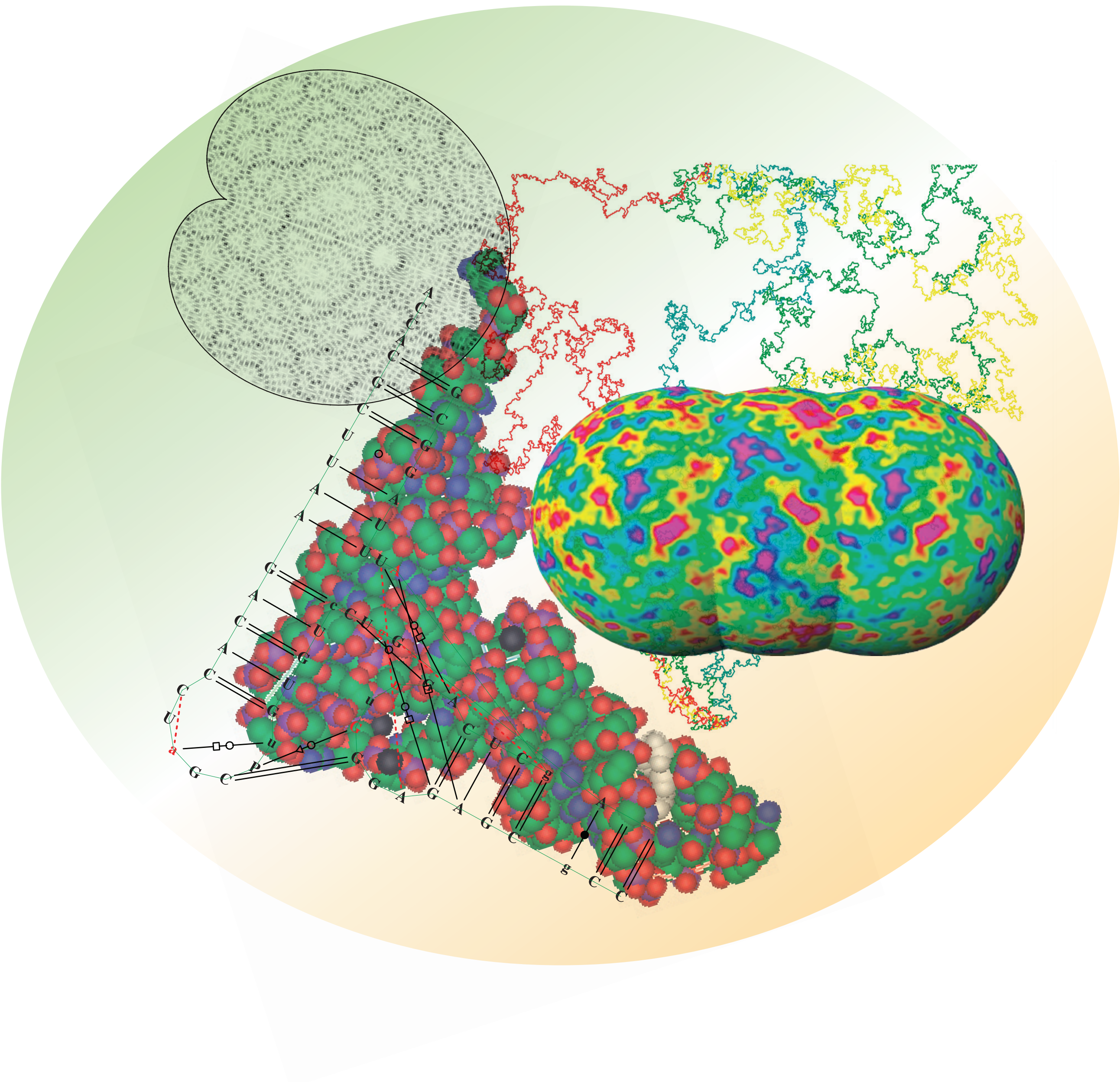
SERVICE DE PHYSIQUE THÉORIQUE

Rapport d'activité juin 2002 - mai 2005



Commissariat à l'énergie atomique
Direction des sciences de la matière
CEA/DSM/SPhT

Centre national de la recherche scientifique
Département des Sciences physiques et mathématiques
CNRS/SPM/URA2306

SERVICE DE PHYSIQUE THEORIQUE

RAPPORT D'ACTIVITE JUIN 2002 - MAI 2005

PHYSIQUE THEORIQUE
SACLAY
CEA/DSM

Centre d'Etudes de Saclay
F-91191 Gif-sur-Yvette Cedex
Tel: +33 (0)1 6908 7385 - Fax: +33 (0)1 6908 8120
URL: http://www-spht.cea.fr/

Contents

CHAPTER A

Introduction

This report presents an overview of the activities of the Service de Physique Théorique (SPhT) from June 2002 to May 2005. It covers a period of three years in order to be in phase with with the biennial evaluation made by the National Committee of the Centre National de la Recherche Scientifique (CNRS). Indeed, our laboratory, which is a department of the Direction des Sciences de la Matière (DSM) of the CEA, has been recognized by the CNRS as a "Unité de recherche associée" (URA) since January 1, 2001, and as such is subject to the biennial evaluation rules of the CNRS.

During the period covered by this report, we have hired two CEA physicists in field theory and in string theory, two in particle physics and one in statistical physics, and we have been assigned one junior CNRS physicist in statistical physics and one more senior CNRS physicist in string theory. Let us emphasize that the main criterion for hiring in SPhT is the scientific excellence of the candidates. During that same period, four physicists have retired from the laboratory. The total population of permanent physicists at SPhT now comprises 31 CEA and 15 CNRS. Thanks to a reasonable budget and external funding, we have been able to host on the average 6 post-docs per year, about 9 students, and numerous long and short term visitors. These physicists who stay temporarily in our lab are a constant source of inspiration and collaboration and participate actively in the success and the very high standards of the SPhT. In recent years, the SPhT has received lots of requests from physicists from the Paris area, in particular academics, to spend part of their time in our lab. We are particularly happy to welcome these high level scientists in our lab, but we are starting to suffer from a lack of offices. We have thus urged the DSM to allocate us new offices.

For many of us, Physics is a passion which does not die out the day of our retirement, which takes place at the very early age of sixty in CEA (this age is going to change in the coming years). Therefore, many of our senior scientists are given the status of "Conseiller scientifique" (CS) for several years, to allow them to pursue their scientific activity beyond retirement, while enjoying the possibility to travel and invite visitors. We have presently 10 CS in the laboratory. However, this status cannot be given forever, since our total number of CS is limited by the DSM. Under the initiative of J.-P. Blaizot and C. De Dominicis, we have created the "Association pour la Science" in 2004, which allows our most motivated seniors to have a secure jurisdictional status in the laboratory, and to pursue their scientific activity and share their experience with us. At present, three physicists retired from SPhT belong to this Association.

One of the main strength of our laboratory is its multidisciplinary character: Most of the major subjects of modern theoretical physics are represented in our lab, at the highest international level. Thanks to our scientific policy, we have been able, in the last few years, to reinforce our activities in QCD and small x physics, in the physics beyond the standard model and in the statistical physics of disordered systems, establishing world leading groups in these fields. The more recently created string theory and condensed matter groups are following the same route and should soon reach the same level of visibility and international recognition.

Following some well established tradition which started with quantum field theory, we are one of the world center of expertise in conformal field theories (CFT), random matrix theory, random geometries and their applications to statistical physics, and we have to warrant this leading position by making sure that we renew (at least partially) the positions of physicists who retire or leave the laboratory, and that we keep up our activity at the highest level in these domains. In the coming years, to avoid isolation and to promote internal and external collaborations, some groups will have to be reinforced, in particular the group of biological statistical physics, the group of cosmology and astroparticle, and that of hard processes in QCD. We are also seriously considering the possibility of introducing some new themes of modern theoretical physics which are absent from our laboratory, in particular cold atoms and their relations to condensed matter, and quantum information. In the long term life of a laboratory, subjects come and go, and it seems that traditional Nuclear Physics is slowly disappearing from the lab, due to retirements and non-renewal of the positions. This trend is not specific to our laboratory, but Nuclear Physics seems to undergo some revival, in particular with the upgrade of SPIRAL2, which should allow to explore nuclei in extreme conditions. To keep up with this potentially very interesting physics, we have agreed to host a nuclear physicist in our lab. In such an environment, he will be confronted to the most recent and sophisticated methods of condensed matter and particle physics and will be able to stay at the highest level in theory.

I want to emphasize again that in my opinion, in addition to excellence, multidisciplinary research is the main justification for the existence of a large theoretical physics laboratory. It acts in the laboratory as a melting pot in which ideas and concepts of various fields are confronted, similarities are identified and methods from one field can be imported to another. Two recent such examples of successful transfer can be found in high energy QCD: the QCD processes of gluon radiation and recombination can be analyzed in terms of reaction-diffusion processes thoroughly studied in non-equilibrium statistical physics, in particular about ten years ago at the SPhT. This analogy has allowed the explanation of such important phenomena as geometric scaling in high energy processes. Similarly, sophisticated methods developed (in particular at SPhT) for perturbative calculation in gauge theories have suggested a deep relationship between gauge theories and topological string theory in twistor space; this conjecture has led to important new developments in the field, in which SPhT is playing a prominent role.

Three other examples can be found in mathematical physics: The Razumov-Stroganov conjecture, which relates the components of the ground-state vector of some dense-loop model to the number of configurations of the fully-packed loop model on a square lattice, has been proved, establishing the link between the integrability of the model and the algebraic geometry of some matrix varieties. In a different context, it has been shown that some properties of the harmonic measure (electrostatic potential) near any conformally invariant boundary can be computed exactly using methods initially developed in the context of 2d quantum gravity (Knizhnik-Polyakov-Zamolodchikov formulas). Another spectacular example of such transfer of knowledge is given by the SLE (stochastic Loewner equations). These equations were initially introduced and studied by mathematicians to describe the statistics of geometrical critical lines in 2d (such as polymers, boundaries of percolating clusters, etc.). The reinterpretation of SLE as random processes on the Virasoro group has allowed a deep connection of these stochastic equations with CFT. This in turn has allowed the calculation of new quantities, and the generalization of SLE to unexplored geometries.

A beautiful example of transfer of highly sophisticated methods can be found in condensed matter: Methods of low dimensional integrable field theory have been succesfully applied to the problem of transport in nanosystems, to the scattering of Laughlin quasi-particles in the fractional quantum Hall effect, and to quantum dissipation in small junctions, resulting in active discussions and collaborations with experimental physicists of the nearby SPEC (experimental condensed matter laboratory).

A last example of such cross-fertilization can be found in biological physics. Methods from random matrix field theories have been used in the problem of RNA folding. As a result, a new classification of RNA pseudo-knots according to their topological genus has been proposed, resulting in a new and powerful Monte Carlo method for predicting RNA folds in real biological sequences.

Many other important results have been obtained during these last 3 years in the lab. They are thoroughly described in this report. The scientific activity of the lab has been grouped under twelve different chapters, rather than three in the previous reports. Indeed, it seemed more natural to group scientific activities according to their scientific proximity, rather than to try to stick to the three groups of the lab (Mathematical Physics, Particle Physics and Astrophysics, Statistical Physics and Condensed Matter). These groups are convenient for administrative purposes (choice of post-docs, of invitations, etc...) but have no strict boundaries and should be viewed primarily as management tools.

The scientific life of the SPhT is punctuated by five specialized weekly seminars and one almost-weekly colloquium. In addition, five to six high-level courses for graduate students and researchers are given at SPhT. They are very much appreciated by the physics community of the Paris area, and are recognized by the Universities of Paris as a credit for second-year graduate students. Finally, the Claude Itzykson meetings have become well established and prestigious international conferences, covering a large variety of subjects. The 2002 meeting was devoted to biology, 2003 to cosmology and astrophysics, and 2004 to QCD. The meeting of

2005, which took place just after the period covered by this report, did commemorate the 10th anniversary of the death of our friend and colleague Claude Itzykson, and was devoted to all the subjects in which Claude was active.

Although the lab was created in 1963, we have celebrated its 40th anniversary in 2004. This was the occasion for a very warm and friendly party where many of the people who passed through SPhT where brought together.

All these scientific activities bring in many external visitors and students to the lab, and contribute to its life, visibility and high quality.

The high quality of the research performed at the SPhT has been rewarded by 6 prizes or distinctions, including the prestigious "Médaille d'argent du CNRS" awarded to D. Bernardand the "KBS Science Prize" awarded to M. Rho.

The sociology of research in France has considerably changed in the last years. All research laboratories used to be funded mostly by the organisms to which they would belong (CNRS, CEA, etc.). Nowadays, the funding is increasingly coming from external agencies, such as the European Union (EU), the European Science Foundation (ESF), the newly created Agence Nationale pour la Recherche (ANR modeled after the American NSF), etc... As a result, researchers have to look for their own funding, write proposals, administer networks, etc... This trend seems irreversible and will probably tend to generalize in the future. In addition to research, physicists will have to become administrators, a task for which most of us are not prepared and that some of us do not wish to do. Competent administrative support will become crucial in dealing with these matters.

To conclude this introduction, I would like to express my warmest thanks to the members of our External Scientific Committee who agreed to spend two days with us, in our lab, to evaluate its scientific value and give us some advice on how to improve it. Jean-Yves Ollitrault has been coordinating the preparation of this report, together with Loïc Bervas, Marc Gingold and Laure Sauboy; I thank them warmly. The presentation of the twelve chapters has been prepared by Christiane Normand and Stéphane Nonnenmacher (Chap. B), Emmanuel Guitter (Chap. C), Hubert Saleur (Chap. D), Didina Serban and Pierre Vanhove (Chap. E), Patrick Valageas (Chap. F), Philippe Brax (Chap. G), Robi Peschanski (Chap. H), Cécile Monthus (Chap. I), Grégoire Misguich (Chap. J), and myself (Chap. K). Finally, I would like to express my gratitude to all the members of the SPhT for being so helpful in the preparation of this report, and for keeping the scientific quality of this lab at such high standards.

Henri Orland

CHAPTER B

Dynamical Systems, Chaos and Turbulence

Contents

Although any physical system is a "dynamical system" of its own, by that denomination one generally has in mind a system of differential equations with respect to the time variable: ordinary differential equations (ODEs) in the case of finitely many degrees of freedom, partial differential equations (PDEs) in the case of infinitely many d.o.f. or discrete-time maps. These equations are explicit, but their solutions are not in general. The theory of dynamical systems consists in characterizing these solutions, as precisely as possible.

The simplest models consists in maps or ODEs describing the evolution of a particle in 1 or 2 dimensions. Such models can already lead to various types of behaviors, ranging from "regular" to "chaotic" motion. Interval-exchange maps constitute simple one-dimensional systems which can yet exhibit a rich variety of ergodic properties. A special class of such maps has been analyzed by P. Moussa and his collaborators.

These different types of behaviors can only be observed in (real or numerical) experiments if they are sufficiently *stable* with respect to small variations of the parameters. It is therefore crucial to study the stability of these different motions if one adds some "noise" in the dynamical equations, the noise modeling random fluctuations in the parameters, due to the environment or to unknown internal variables. The noisy dynamical system keeps memory of the original (noiseless) motion, but the evolution can qualitatively change: the input of noise can lead to phenomena such as noise-induced phase transitions, pattern formation and stochastic resonances.

Some of these phenomena were described and analyzed by K. Mallick and P. Marcq in a series of papers. They studied one-dimensional (possibly damped) nonlinear oscillators, and showed that different types of noises (namely, white noise versus time-correlated noise) may induce different behaviors, like anomalous diffusion, delocalization phase transition etc.. On the other hand, S. Nonnenmacher *et al.* considered time-discrete maps on the torus, perturbed by a (small) additive noise after each step. Such a noisy system always relaxes to an equilibrium density, but the speed of relaxation strongly depends on the underlying noiseless motion: chaotic systems relax much faster than regular ones.

One connected problem is the analysis of *quantized* low-dimensional dynamical systems, with an emphasis on chaotic systems (this topic is generally called "quantum chaos"). One is interested in both the time-dependent behavior and the stationary quantities (eigenvalues and eigenstates) of the quantum system, which cannot be described in closed form (no WKB-type formula is available). One generally focuses on the semiclassical limit, in order to use some form of correspondence between quantum and classical systems. The discrepancies between both frameworks are mainly due to interference effects; the latter are strongly reduced in the presence of noise, which explains why the quantum-classical correspondence is "cleaner" for noisy quantum systems (S. Nonnenmacher). During the years 2001–2003, two postdocs (B. Gutkin and R. Schubert) together with A. Voros and S. Nonnenmacher held regular meetings to discuss various aspects of the subject, mainly on the structure of eigenstates of quantum billiards and quantum maps. The discussions and subsequent works have focussed on mathematically rigorous statements, like the existence of strongly localized eigenstates for a certain quantum chaotic map.

The methods applied to study quantum billiard problems (boundary operators, expansion into classical paths) can also be used in the study of the Casimir effect in arbitrary geometries, the interest of which was renewed by recent experiments. Indeed, to compute the Casimir effect in a "cavity", one is led to compute the density of electromagnetic modes in the cavity, which is more or less given by the spectral density of the Dirichlet Laplacian (R. Balian and B. Duplantier).

Beyond systems with finitely many degrees of freedom, one enters the "turbulent" world of nonlinear PDEs. Ch. Normand collaborates with researchers from the Condensed matter group in Saclay (SPEC) on specific problems of instabilities in (magneto)hydrodynamical flows, like the the dynamo action in the von Kármán geometry, which is at the experimental stage in Cadarache. Although the experimental flow is believed to be turbulent at the onset of dynamo (and therefore out of theoretical reach), it is possible to estimate the threshold value of the dynamo action for a steady velocity field "close to" the turbulent one, also in presence of a time-dependent small modulation. Replacing this modulation by a random noise, one is lead to the problem of intermittency in stochastic bifurcating systems, which can be analyzed in the (model) case of a 1-D oscillator (K. Mallick).

Finally, another approach to study complex PDEs, like the Boltzmann equation, consists in discretizing the phase space. H. Cornille studies discrete-velocity models on the plane, in search for stationary distributions which capture the features of the continuous Boltzmann equation, including the case of binary mixtures.

B.1 Interval-exchange maps (P. Moussa)

P. Moussa, S. Marmi and J.-C. Yoccoz have obtained for the first time some explicit diophantine conditions which assert the existence of solutions of the cohomological equation associated with interval-exchange maps [T03/033] [T04/146].

Those maps are interesting examples of dynamical systems, since they generalize rotations on a torus to the case of Riemann surfaces of higher genus. They are also associated with rational (pseudo-integrable) billiards. Interval exchange maps have interesting ergodic properties, which have been widely studied and belong to the family of weakly ergodic systems.

Generally speaking, the cohomological equation displays the simplest small-divisors problem, since it is essentially linear in nature. Nevertheless, its generalisation from the torus to higher genus surfaces leads to important difficulties, although it is only the first step to nonlinear problems. It is here useful to recall that the stability of quasiperiodic orbits in Hamiltonian mechanics is one example of such nonlinear problems on the torus, and the corresponding diophantine conditions have been the subject of the classical works of Siegel, Arnold, Kolmogorov, Moser, Herman et Yoccoz during the second part of the twentieth century.

For interval-exchange maps, the authors have only reached the first step. In particular the diophantine conditions they obtain for the linear case are far from optimal, so the amount of remaining work is tremendous.

B.2 Noisy dynamical systems

Randomness in the external conditions of a dynamical system makes its parameters fluctuate. External randomness may appear as a multiplicative or additive noise in the dynamical equations.

B.2.1 Noisy nonlinear oscillators (K. Mallick)

In a series of works, K. Mallick and P. Marcq have investigated the effect of *parametric noise* on the long-time behavior of a nonlinear oscillator. They have shown in particular that energy transfers from the noise source to the internal degrees of freedom of the oscillator give rise to anomalous growth exponents that can be exactly calculated [T02/126] [T02/149]. As opposed to most earlier works, the authors have investigated the case when the noise is "colored" by a non-vanishing correlation time τ (Ornstein-Uhlenbeck noise). They show that this new time parameter strongly modifies the long time scaling behavior found for the white noise case, even when τ is vanishingly small. Their analysis is based on a recursive adiabatic elimination scheme that generalizes a method previously used for deterministic dynamical systems: a reduced effective Langevin dynamics is derived for the slow variable (the action), so as to obtain an analytical expression for the phase space distribution in the long time limit. This distribution provides the anomalous scaling exponents and generalized diffusion constants. The method is genuinely non-perturbative: the colored noise behavior can only be (partially) recovered through a *resummation to all orders* of the perturbative series for small τ; this resummation also yields the crossover function between white noise and colored noise scalings [T03/134] [T03/206] [T04/003].

If the oscillator contains a damping term, it relaxes to the equilibrium point. However, adding enough noise can make that point unstable. In [T02/189], K. Mallick and P. Marcq have obtained the exact phase diagram of the damped Duffing oscillator subject to white noise, by deriving a closed formula for the Lyapounov exponent (the growth rate of $\langle \log E \rangle$, where E is the energy). The system has two phases: an absorbing phase (for small noise) and a non-equilibrium steady state. In the vicinity of the transition line, the observables exhibit a *multifractal scaling*: this behavior contradicts previously known results on the stochastic Hopf bifurcation, based on incorrect perturbative expansions. The noise can also *stabilize* a phase that is deterministically unstable, as a stochastic analogue of the classical Kapitza oscillator [T03/185]. Recently, the same authors have investigated the effect of the noise correlation time on the stochastic Duffing oscillator; an exact formula for the Lyapounov exponent is not available anymore, but various approximations allow to draw a fairly complete picture of the phase diagram [T05/007].

B.2.2 On-Off intermittency (K. Mallick)

Motivated by experiments on the effect of internal noise on the onset of magnetohydrodynamic instabilities (such as the dynamo effect, see Sec. B.5.1), K. Mallick*et al.* have investigated the intermittent behavior of stochastic bifurcating systems. For a simple model, they find that the intermittent behavior is extremely sensitive to the nature of the noise: it is controlled by the ratio between the departure from the bifurcation and the value of the noise spectrum at zero frequency. Reducing that part of the noise spectrum drastically shrinks the intermittency regime and modifies the time-distribution spent by the system in the off phase. These features are confirmed by simulations of more complex systems, and are believed to be quite general: on-off intermittency is controlled by zero modes of the noise. This may explain why many experimental investigations on the effect of a multiplicative noise on an instability do not display on-off intermittency, contrary to theoretical expectations. Indeed, if the noise is high-pass filtered, as often required for experimental reasons, then the intermittent regime disappears [T05/003] [T05/033].

B.2.3 Noisy classical and quantum maps (S. Nonnenmacher)

The influence of noise on discrete-time dynamical systems (maps) on a compact phase space (the torus) has been investigated in [T03/174]. The noise acts additively on the system after each step of the map, independently of the past, with typical "strength" ϵ. Such a noise effectively transforms the unitary propagator for densities into a contracting (noisy) propagator, of Fokker-Planck type. As a result, any initial density will eventually relax to the equilibrium density after a certain time scale, called the relaxation time τ_R. The aim of the paper was to study how the small-noise behavior ($\epsilon \to 0$) of this relaxation time depends on the dynamical properties of the deterministic map. Roughly speaking, two different regimes were identified: for a "regular" deterministic map, the relaxation time behaves algebraically in the small-noise limit, $\tau_R(\epsilon) \sim \epsilon^{-\beta}$. (the relaxation is *slow*). On the opposite, for a "chaotic" map (with an exponential decay of correlations), the dissipation is *fast*, and $\tau_R(\epsilon) \sim \log(1/\epsilon)$. In certain cases, these two types of behaviors can be related to the *spectrum* of the noisy propagator.

The above study was extended to *quantized noisy maps* on the torus, as a model for decoherence. Two parameters are now relevant: the noise strength ϵ and Planck's constant $\hbar$. In [T03/005] the *spectra* of noisy quantum maps were analyzed and compared with their classical analogues, while the relaxation (or "decoherence") time of the noisy maps was investigated in [T04/083]. In the semiclassical regime ($1 \gg \epsilon \gg \hbar^\gamma \epsilon$), the quantum spectrum converges to the classical one, while quantum and classical relaxation times have the same asymptotics. On the opposite, in the "deep quantum regime" ($\epsilon \ll \hbar$), the quantum spectrum remains quasi-unitary and the quantum relaxation is much slower than the classical one: the noise strength ϵ is thinner than the "quantum mesh" $\hbar$, so that the quantum system barely feels the noise.

B.3 Quantum chaos

The aim of quantum chaos is to investigate the properties of quantum systems with a chaotic classical limit. A first family of models consists in some 2-dimensional Euclidean billiards with certain well-defined shapes (e.g. the "cardioid" billiard of Fig. B.1). A second family of models is provided by some area-preserving maps on a compact phase space (e.g. the 2-dimensional torus). The chaotic properties of these systems (ergodicity, decay of correlations) are precisely known, and their quantized versions are easy to study numerically.

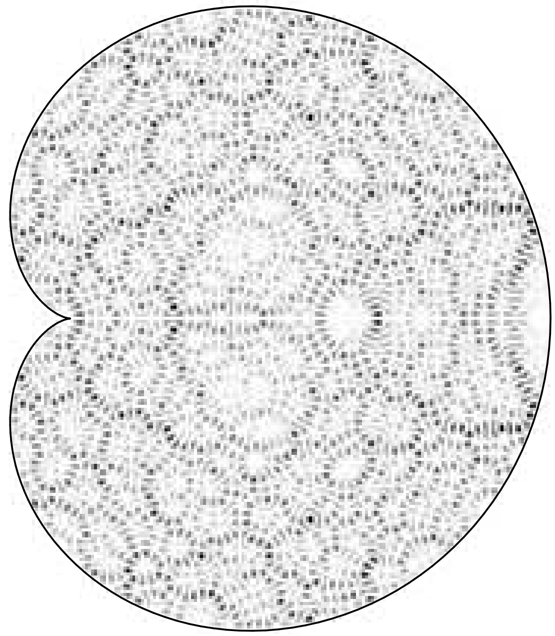


Figure B.1: High-energy eigenstate of the cardioid billiard.

B.3.1 Two-dimensional billiards (B. Gutkin, R. Schubert)

The quantization of the free evolution inside a 2-D billiard is the Laplace operator inside the billiard, with Dirichlet boundary conditions. The first numerical method used to compute the (discrete) spectrum of the Dirichlet Laplacian (equivalently, of the Helmholtz equation) consists in expanding eigenfunctions into linear combinations of plane waves of identical energy: the quantization condition is the requirement that the combination vanishes on the billiard boundary (this method is the Plane Wave Decomposition Method). In [T03/169], B. Gutkin rigorously proves that, if the billiard is *non-convex* (as the cardioid billiard in Fig. B.1), this method generically fails to compute correct eigenenergies and eigenstates. Although any eigenfunction can be represented as a sum of plane waves inside a *convex* domain, semiclassical arguments show that, in general, this expansion cannot be extended without singularities throughout the nonconvex billiard. As a corollary, the author shows that the exact eigenfunction cannot be smoothly continued into the full plane.

It is therefore desirable to use a different representation for billiard eigenfunctions. One alternative is provided by the normal derivative of the eigenfunction at the boundary (or "boundary function"), which contains all the relevant information about the eigenfunction. First, the latter can be reconstructed from the boundary function. Second, the quantization condition can be expressed through a boundary integral equation, which can be used for numerical studies without the above-mentioned problems. In [T02/098], Schubert *et al.* define a "Green's function" in terms of the boundary functions, and study its high-energy (i.e. semiclassical) asymptotics: the dominant term is found to be universal, while the first-order term depends on the curvature of the boundary. This Green's function is studied numerically for several billiards.

The use of boundary functions to describe stationary waves is generalized in [T02/103] to the case of a dielectric interface: now the "boundary" separates two media of different refractive indices (typically, one "optical microresonator" inside free space). Although the spectrum of the Laplacian is continuous, the Green's function has poles at complex resonances, corresponding to (non-normalized) resonant eigenfunctions. To study the phase space structure of such eigenfunctions, the authors introduce four types of *Husimi functions* living on the "reduced phase space" of the interface, which represent the incident vs. emitted waves on both sides of the interface. At a high non-resonant energy, these Husimi functions reproduce the laws of ray optics; at resonant energies, they are sensitive to the interference patterns of the resonant eigenfunctions.

B.3.2 Quantum ergodicity for quantum maps (S. Nonnenmacher)

Quantum maps on the torus have been investigated, in order to study the localization properties of their eigenstates. For any quantized ergodic map, a general theorem ("quantum ergodicity") states that *almost all* eigenstates are "equidistributed" over the torus in the semiclassical limit, meaning that their Husimi functions converge to the Lebesgue measure. The baker's map is a simple chaotic map on the torus, which is linear by parts and easy to quantize. However, discontinuities create diffraction problems at the quantum level, which impede any rigorous analysis. Using propagation of coherent states, the authors of [T04/169] manage to prove quantum ergodicity for the quantized baker's map.

Quantum ergodicity does not prevent the existence of "exceptional eigenstates", whose Husimi functions would converge to an invariant measure different from the Lebesgue measure. The existence of such eigenstates is unknown for a general ergodic system. In [T02/123] [T03/070] an answer to this question is given for a specific family of chaotic maps on the torus, the "generalized Arnold's cat maps". The authors explicitly construct eigenstates which are half-localized on a given periodic orbit, half equidistributed (see Fig. B.2). This type of localization is called a *strong scar* of the periodic orbit, as opposed to a weaker form of "scarring" featured by eigenstates of most quantum chaotic systems. The existence of these exceptional eigenstates is due to

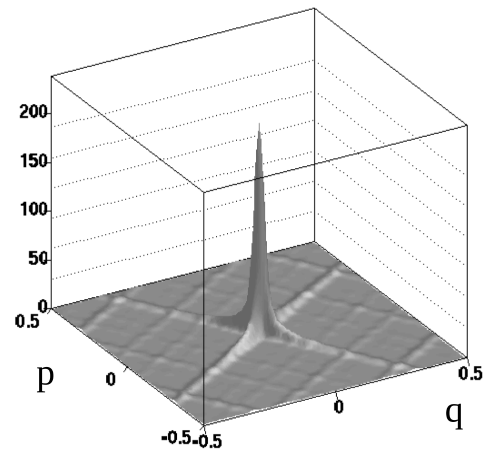


Figure B.2: Husimi function of one eigenstate of the quantum cat map, "strongly scarred" on a fixed point [T02/123].

non-generic algebraic properties of the quantum cat maps, responsible for very high spectral degeneracies.

B.3.3 Resonances in open quantum maps (S. Nonnenmacher)

Quantum maps on the torus can also serve as models for a scattering quantum system (e.g. an open "quantum dot" in mesoscopic physics), especially when the classical scattering is chaotic. In [T05/070], an "open" version of the baker's map is quantized; its spectrum consists in "resonances" similar to those of scattering systems. Within this model, the authors are able to numerically check a *fractal Weyl law* for the density of shallow resonances, which has been conjectured for chaotic scattering systems. Briefly speaking, the density of shallow resonances grows like $\hbar^{-\nu}$ as $\hbar \to 0$, where ν is simply related with the dimension of the set of classically trapped trajectories. The authors also construct a modified quantum baker's map, for which this law is derived analytically, as well as several quantities relevant in mesoscopic physics (conductance, shot noise).

B.4 Geometry of the Casimir effect (B. Duplantier, R. Balian)

In [T02/090] [T02/092] [T03/091] the authors review results published more than 25 years ago, motivated by the present intense interest in the Casimir effect, both experimentally and theoretically.

When the vacuum is partitioned by material boundaries with arbitrary shape, one can define the zero-point energy and the free energy of the electromagnetic waves in the geometry: this can be done in the limit where the walls are perfect conductors, provided their curvature is finite, and consists in a sum over electromagnetic eigenmodes inside the "cavity". For arbitrary geometries, an explicit 'multiple-scattering' expansion is obtained for the zero-point energy and the free energy; more precisely, an integral kernel on the boundaries can be expanded in a convergent series interpreted as a succession of scatterings. The quantum and thermal fluctuations of the vacuum then result from purely geometrical or topological properties. Various applications are reviewed: low temperature; high temperature, where wrinkling constraints appear; stability of a plane foil; transfer of energy from one side of a curved boundary to the other; forces between distant conductors; a few special shapes are studied (Casimir's original parallel plates, the experimental situation of a sphere in front of a plate with the Derjaguin approximation, cylinder, honeycomb).

B.5 Instabilities in magnetohydrodynamical flows

Dynamo theory is concerned with the generation and maintenance of magnetic fields by the motion of a liquid conductor. The dynamo action has been invoked to explain the magnetism of planets and stars and its renewed interest is motivated by recent realizations of a homogeneous dynamo in the laboratory.

B.5.1 Kinematic dynamos (Ch. Normand)

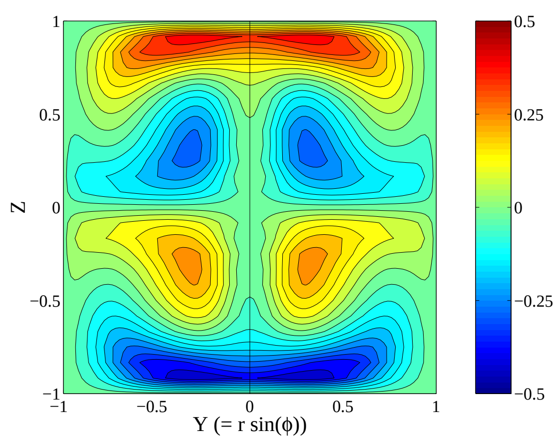


Figure B.3: Azimuthal component of the magnetic field generated by the dynamo effect in a cylinder [T04/049].

Close to us, the team "Instability and Turbulence" of the condensed matter group in Saclay (SPEC) is working on the von-Kármán-Sodium (VKS) experiment. The flow, driven by two impellers at each end of a cylindrical container, is turbulent in the regime where the dynamo action is expected. Concurrently, a Galerkin method was implemented to solve the kinematic dynamo problem, for steady velocity fields modeling the experimental mean velocity. The best candidate yields a critical value of the magnetic Reynolds number ($Rm_c = 58$) which is within reach of the VKS experiment [T04/049]. An important question (not yet answered in the case of the von Kármán geometry) is to compute the shift of the threshold value produced by a time-dependent perturbation of the velocity field. This shift has been calculated in the case of the Ponomarenko dynamo driven by a helical flow modulated periodically in time [T02/136]. In the limit of small perturbation, modulating the two velocity components either in-phase or out-of-phase leads to opposite effects: the onset of dynamo is either decreased or enhanced.

B.5.2 Instability of rotating stratified shear flows (Ch. Normand)

The simplest model of an astrophysical accretion disk is that of a rotating shear flow with a Keplerian velocity law. According to the Rayleigh criterion governing its stability with respect to axisymmetric perturbations, Keplerian flows are centrifugally stable, which contradicts observational evidence they are turbulent. A possible source of turbulence is the presence of a vertical magnetic field, which is known since Chandrasekhar to have a paradoxical effect: it destabilizes (resp. stabilizes) centrifugally stable (resp. unstable) flows. The authors of [T03/100] show that a similar effect is at play when the magnetic field is replaced by a stable vertical stratification and non-axisymmetric perturbations are considered.

B.6 Discrete planar kinetic Theory (H. Cornille)

In the last ten years, important progress was made in understanding the links between Discrete Boltzmann equations (BE with discrete velocities) and the continuous Boltzmann equation. The only invariant quantities in the discrete models must be the physical ones (mass, momentum and energy), with the exclusion of any *spurious invariant*. Discrete models should contain an infinite number of velocities (as opposed to a finite number as done previously). H. Cornille was mainly interested in binary mixture models with light particles (mass $m = 1$) and heavy particles (mass $M > 1$). In such a model, all integer sites (x, y) of the velocity plane are filled with either heavy or light particles; the filling is performed step by step, by constructing finite models in larger and larger square-grid domains, making sure that no spurious invariant appears. Some results were also obtained for the case of a single gas.

Models where heavy particles sit on the odd sublattice ($|x| + |y|$ odd) have been constructed for the cases $M = 2, 3, 3/2, 4$ [T02/190], then for any M of the form $2p$ or $(2p+1)/2^n$ ($p \geq 1$, $n \geq 0$ integers) [T03/060] [T03/145] and finally for any rational $M > 1$ [T03/200].

Concerning finite DBE versus continuous BE for a single gas, Cercignani showed in 1994 that the energy-to-mass ratio (linked to the temperature) does not behave correctly in discrete models with a finite number of velocities, and therefore criticized the validity of such models. An answer to this criticism (suggested by R. Balian) was to study a *sequence of models* with finite numbers of velocities N_v, which grows along the sequence [T02/143]. One can then study how N_v grows with respect to the maximal velocity V. Only those sequences for which $N_v \sim V^2$, as $V \to \infty$ should be considered "physical".

Another case of DBE consists in models where the heavy particles sit on the corners of *polygons* embedded in the integer lattice, and the light species fill the remaining sites. This was done previously for particular values of M and octagons, in [T03/200] for hexagons with any rational $M > 1$ and in [T03/060] for dodecagons and $M = (2p+1)/5$, $p \geq 5$. More recently, models were constructed for any rational $M > 1$ and heavy particles sitting either in octagons [T04/101], decagons or dodecagons. One open problem is whether similar models could exist for other polygons.

B.7 Thermodynamics and quantum mechanics (R. Balian, A. Allahverdyan)

B.7.1 Thermodynamics of small systems

The development of nanophysics has stimulated studies aimed at extending to small systems the concepts and laws of thermodynamics, which apply in principle only to macroscopic matter. In particular, the extensions of the various formulations of the second law are not equivalent. The articles [T03/122] and [T03/237] (see also [T02/199]) study the work that may be extracted from a microscopic system, initially in a given off-equilibrium state and interacting with work sources. For macroscopic sources, the upper bound for this work, named ergotropy, has been explicitly evaluated; due to the discreteness of the spectrum of energies of the system, it is smaller than the amount inferred from the second law. For finite sources, the existence of correlation energies may raise the available work.

B.7.2 Quantum measurements

The theory of quantum measurements is still a subject of debate, and one should master it to understand the foundations of quantum physics. Two points have been cleared up. (i) At first sight, determining the full density matrix that characterizes a statistical ensemble of quantum systems seems to require several different apparatuses, which measure non-commuting observables. However, it has been shown [T03/184] that, by letting the considered object interact with an auxiliary object, the density matrix of which is known, one can map the unknown initial density matrix onto an ordinary set of probabilities for commuting observables that pertain to the pair of systems. Thus, rather unexpectedly, it is possible to determine a full density matrix by means of repeated experiments involving a single apparatus. (ii) In the prospect of understanding the general properties of quantum measurements, it is enlightening to work out exactly solvable models so as to analyze the dynamics of the process. Being a macroscopic object, the apparatus should be treated in the framework of quantum statistical mechanics. In the article [T04/183] (see also [T03/163]), the z-component of a spin is measured by interaction with an Ising system, which is a model for a magnetic dot. Various time scales are exhibited. The reduction of the wave packet appears as a relaxation process, very rapid owing to the macroscopic size of the apparatus; it should not be confused with decoherence, as currently done. The registration by the apparatus of the outcome, which obeys Born's rule, behaves in each sector as a phase transition triggered by the system; it takes a much longer time.

CHAPTER C

Random Geometries and Statistical Physics

Contents

Since the pioneering works of Wigner and Dyson, random matrices (Sec. C.1) have provided much insight into many physical problems. Indeed, the universality properties for the distribution of eigenvalues in random matrices are shared by many different systems, in condensed matter physics, particle physics, biology or even economics. On the other hand, the expansion of random matrix integrals allows to enumerate random surfaces made of polygons (tessellations), thus providing discrete models for membrane physics, 2D quantum gravity, string theory, or conformal field theory. Finally, random matrix models can be viewed as a typical example of integrable systems and are a good toy model to get insight on integrability, with close relations to algebraic geometry. Many members of the laboratory are actively working on the field of Random Matrix Theory (RMT), both as a tool for applications and in its own right.

The intimate link between statistical physics of discrete systems and combinatorics (Sec. C.2) can be used in both ways: give a purely combinatorial solution to some statistical problem in physics or, conversely, apply physical methods to combinatorial puzzles. This interplay, used a few years ago to address the famous "meander problem", was applied in the laboratory in two new directions of interest. The first issue concerns statistical models of random graphs where bijective techniques of enumeration were constructed, reducing these models to a combinatorial problem of decorated trees, therefore making a link from the field of discrete 2D quantum gravity to that of branching processes. A second issue concerns variations around the so-called Razumov-Stroganov conjecture relating some highly constrained enumeration problems (such as fully-packed loop on a square lattice or tilings of domains in the plane) to the ground state of some physical integrable model (typically the O(1) dense loop model). A number of related conjectures were actually proved already and interesting links with algebraic geometry were also discovered.

C.1 Random matrices

A third edition of the widely used standard book "Random Matrices" by M.L. Mehta has been published. It contains many additions that reflect recent developments in the field, such as the theory of skew-orthogonal and bi-orthogonal polynomials [T04/021].

C.1.1 Random matrices: theory

C.1.1.1 Determinants of random matrices (M.L. Mehta, J.-M. Normand)

In any statistical theory, one would like to know the average value or the probability density of any quantity. We have been interested in the probability density of the determinant of $N \times N$ random matrices. The method is based on the use of the Mellin transform. The study of the still unknown cases for Gaussian ensembles is under way. For real symmetric matrices ($\beta = 1$) with N even, the probability density is found to be a complicated combination of Meijer G-functions and the error function; for real quaternion self-dual matrices ($\beta = 4$), it is a linear combination of several Meijer G-functions. This requires the evaluation of determinants with ratios of gamma functions as elements. This leads to define the s-shifted factorial as a generalization for non-negative integers of the power function z^n, namely the rising factorial $(z)_n = z(z+1)\cdots(z+n-1)$ and the falling factorial $[z]_n = z(z-1)\cdots(z-n+1)$, as well as their analytic continuation to complex values. Combinatorial properties, mainly multiplication laws, Pascal triangle property, generating function and binomial formulae, are given. These are used to evaluate families of generalized Vandermonde determinants with s-shifted factorials as elements [T03/208].

C.1.1.2 Correlations in RMT: bi-orthogonal polynomials and graph expansions (M. Bergère)

Most results on spectral properties of random matrices are encoded in the correlation functions for the invariants of the matrices like traces or determinants. Although most of the interesting results are expected only in the limit of infinitely large matrices, exact results can nevertheless be obtained for finite matrices using the technique of orthogonal polynomials. The correlation functions can be obtained from the introduction of external sources both at the numerator and at the denominator of the ratio of matrix integrals. Following Christoffel and Uvarov, we constructed bi-orthogonal polynomials for potentials of two variables with external sources at the numerator [T03/180] and at the denominator [T04/042] and we described the correlation functions from a determinant of kernels attached to the different sources. In the case of the Gaussian potential, we developed this determinant in terms of graphs and we determined for each graph the large-N expansion and the so-called BMN limit introduced to test the duality between supersymmetric Yang-Mills theory and string theory (see Sec. E.9).

C.1.1.3 Random matrices and integrable differential equations (B. Eynard)

Random matrix integrals can be computed using families of orthogonal or bi-orthogonal polynomials. These obey systems of differential equations, which can also be put in the form of a Riemann–Hilbert problem, namely: find a function by knowing only its discontinuities and behavior at infinity. In the case of (bi-)orthogonal polynomials, the discontinuities turn out to be constant (isomonodromic property). To any isomonodromic system is associated an "isomonodromic" τ function. In [T04/019], it was proven that this τ function for orthogonal polynomials coincides with the matrix model's partition function. In [T02/097], the Riemann-Hilbert problem for systems of bi-orthogonal polynomials was derived, and many of its properties were computed in [T03/139]. This is the starting point for a rigorous proof of the large-N asymptotics of the two-matrix model, which is considered a great challenge for mathematicians. The long-term goal of this study is to connect integrability in the sense of isomonodromic systems to other notions of integrability (KP, Toda). Another important goal is to prove the universality of large-N random matrix laws, and to classify the universal behaviors (review article [T02/111]).

C.1.1.4 Random matrices, surfaces, CFT and algebraic geometry (B. Eynard)

The large-N expansion of RMT, a useful tool for generating random surfaces, is best obtained by the Schwinger–Dyson's equations, also called loop equations. Such loop equations for chains of matrices and generalized semi-classical matrices (i.e. whose eigenvalues are constrained on paths in the complex plane), were derived in [T03/125] and [T05/038].

In this context, the most studied model is the one-matrix model which, to leading order, involves an equation of degree 2. This corresponds to a so-called hyperelliptic algebraic curve, and most properties of the large-N expansion can be expressed as geometric properties of this curve. The next simplest case is that of the two-matrix model which enumerates discrete surfaces carrying an Ising spin. Its leading behavior involves a general algebraic equation (not necessarily of degree 2), and allows to understand the properties of matrix models and integrable systems more generally. Before 2002,

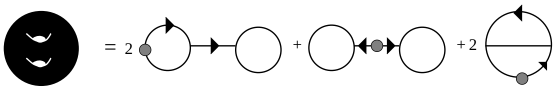


Figure C.1: Graphical representation of the $1/N^2$ correction to the free energy of the one-matrix model.

only the leading large size behavior was known. A first step was achieved in [T02/128], [T03/106], [T04/010] and [T04/020], with the computation of the density of eigenvalues and the free energy to next to leading order. The result involves the "Bergmann *tau*-function", previously introduced in algebraic geometry, and known to be related to the determinant of the Laplacian on the algebraic curve.

Then, in [T04/086] we invented a new method for solving loop equations, which simply consists in applying the Cauchy formula and moving the integration contours. It proved very powerful and allowed to solve exactly loop equations to all orders, for all correlation functions of the one-matrix model. The solution is non-recursive, and is expressed in terms of residues on the algebraic Riemann-surface. It displays a clear separation between the part coming from the geometry of the surface (i.e. its complex structure, represented by some moduli) and the specificities of the model (the potential). The solution is best represented in a diagrammatic way (see Fig. C.1), and hints that there is an underlying 2D field theory, yet to be found. The method is striking by its simplicity and its universality, and it is likely to be applicable to most other integrable matrix models.

C.1.1.5 The Harish-Chandra Itzykson–Zuber integral revisited (J.-B. Zuber)

The integral over the $U(N)$ unitary group $I = \int DU \exp \mathrm{tr} AUBU^\dagger$ plays an important role in random matrix theory. It has been known for many years to be computable by a variety of methods, heat equation, character expansion, *exact* steepest descent method (Duistermaat-Heckman localization theorem). These methods and some generalizations of the integral have been reviewed in [T02/132]. The integral is also related to the Toda lattice hierarchy of integrable equations. The large-N limit of the former corresponds to the so-called dispersionless limit of the latter. The resulting equations enable one to compute successive terms in the large-N limit of $\log I$, which are confronted to those obtained by a novel diagrammatic expansion of $\log I$.

C.1.1.6 Enumeration of surfaces with boundary conditions (B. Eynard)

Mixed correlation functions in matrix models, were considered as a difficult problem before 2003, because they are the average of traces of products of non-commuting matrices, and thus they cannot be written in terms of eigenvalues of the various matrices involved. Moreover, they cannot be computed as derivatives of the free energy. In the application of random matrices to the description of random surfaces, mixed correlation functions play the role of boundary operators. In the context of orthogonal polynomials and related integrable systems, these correlators appear in the computation of the spectral curve and in the isomonodromic τ function. A simple mixed correlation was first computed in [T03/028], with a surprisingly simple result in the form of a single determinant. Then, the most general correlation function was computed in [T05/011], with, as an unexpected byproduct, a generalization of Harish-Chandra Itzykson–Zuber integral.

In the large-N limit, the mixed correlation functions were first computed in [T05/037]. Again, the answer is amazingly simple, and reminds of a Bethe wave function. Indeed, the $2k$-point function is a linear combination of products of 2-point functions with universal rational coefficients independent of the matrix model at hand. Integrability seems to play a key role here, yet to be understood.

C.1.2 Random matrices: applications

C.1.2.1 Constrained random matrices and resonance spectra of impedance networks (J.M. Luck)

Most investigations have dealt with random ensembles of Gaussian matrices with appropriate symmetries dictated by physical considerations. There are however cases where constraints on the matrix elements must be taken into account. Examples of direct physical interest include the matrices corresponding to random master equations and random impedance networks. In both cases the random matrices obey the constraint that the row sums of matrix elements should be zero. We have derived the density of eigenvalues of a modified ensemble of symmetric Gaussian random matrices incorporating this constraint. The universal limiting distribution law thus found lies somewhat halfway between the Gaussian law and Wigner's semicircle law. The corresponding result for banded matrices is also derived, and compared with numerical results on random impedance networks with quasi one-dimensional topology [T02/165].

C.1.2.2 Application of random matrices to QCD and supersymmetric Yang-Mills theory (G. Akemann, G. Vernizzi)

An exciting field of applications of RMT is a particular limit of Quantum Chromodynamics (QCD). It is known that at low energies in the confined phase with broken chiral symmetry, QCD is well described by an effective theory of its pseudo-Goldstone bosons, the chiral perturbation theory. In a finite volume and zero mass limit this effective theory is further simplified to a finite group integral, which is equivalent to a random matrix model. This link becomes particularly interesting when a chemical potential is switched on, leading to complex Dirac operator eigenvalues and thus a complex phase in the action. While the case of real eigenvalues has been intensively studied, much work had to be done to compute RMT predictions for complex eigenvalues. The problem seemed particularly rewarding since numerical QCD lattice simulations are very hard in the presence of such a complex phase [T03/006] [T03/111] [T03/132] [T04/191]. In this context we developed the corresponding complex RMT using complex orthogonal polynomials and saddle point techniques. Both partition functions and new complex eigenvalue correlations were computed for different symmetry classes, the question of universality was addressed, and the analytic predictions were successfully compared to 2 and 3 color QCD [T02/053][T02/066] [T02/155] [T02/175] [T03/036] [T03/103] [T03/177] [T04/029] [T04/047]. We also formulated a new class of random matrix models (with an action containing non-polynomial terms) which allowed the study some aspects of the temperature induced chiral phase transition in QCD. Furthermore we applied RMT in a different context, in the study of Wilson loops and Polyakov lines [T03/129] in Supersymmetric Yang-Mills theory or matrix models, which include the IKKT model of IIB string theory.

C.1.2.3 Matrix Integrals and the generation and counting of virtual tangles and links (J.-B. Zuber)

Matrix integrals have a large size expansion in terms of Feynman graphs drawn on surfaces of increasing genus. As such, they may yield generating functions of objects of a given topology. This is for example the case of knots, links and tangles, which may be represented in projection as planar graphs with under- and over-crossings. The subclass of *alternating* links and tangles, for which one encounters alternatively under- and over-crossings as one circulates around each thread, had been previously shown to be enumerated by the large-N limit of the integral $\int D(M, M^\dagger) \exp -N\mathrm{tr}(MM^\dagger + \frac{g}{2}(MM^\dagger)^2)$ over $N \times N$ complex matrices. Counting topologically independent objects requires to quotient by the "flypes", a special variety of moves which preserve the alternating character of the links and tangles.

In [T03/032], the subdominant terms in the large-N limit have been shown to count "virtual" alternating links and tangles. Virtual links are generalizations of classical links that can be represented

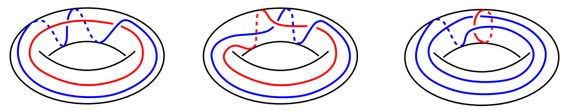


Figure C.2: A genus 1 virtual link in Kaufmann's notation, with virtual crossings in addition to under- and overcrossings; the same link as a Feynman diagram wrapped around a genus 1 surface, in three equivalent representations.

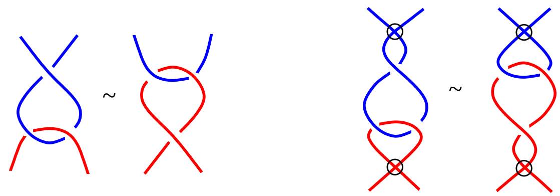


Figure C.3: The flype of an ordinary and of a virtual tangle.

as embedded in a "thickened" surface $\Sigma \times I$, product of a Riemann surface of genus h with an interval (see Fig. C.2). The generating functions of virtual links up to 10 crossings and up to genus 5 have been computed, under the assumption that it is necessary and sufficient to quotient by the action of the planar "flypes" (see Fig. C.3). This assumption has been tested by computing several independent invariants, but it remains an open conjecture.

C.2 Combinatorial statistical physics

C.2.1 Combinatorial approach to statistical models on random graphs

C.2.1.1 Enumeration of planar graphs using trees (J. Bouttier, Ph. Di Francesco, E. Guitter)

Two-dimensional random graphs have been extensively used as discrete models for fluctuating surfaces both in the context of soft condensed matter (membranes) and of 2D quantum gravity. As opposed to the traditional physicists' approach using matrix integrals as tools for generating random graphs, we have developed an alternative, *purely combinatorial and bijective* technique of enumeration. This approach, initiated by G. Schaeffer in 1998, relies on a general cutting procedure that produces out of each planar graph a so-called blossom tree, i.e. a tree with charged decorations (Fig. C.4). This reduces the enumeration of planar graphs to that, much simpler, of these decorated trees. A first application concerned tricolored planar triangulations [T02/075], also enumerated in [T02/096] via a rectangular matrix integral. The bijective technique has been successively generalized to the cases (i) of planar graphs with arbitrary vertex valences

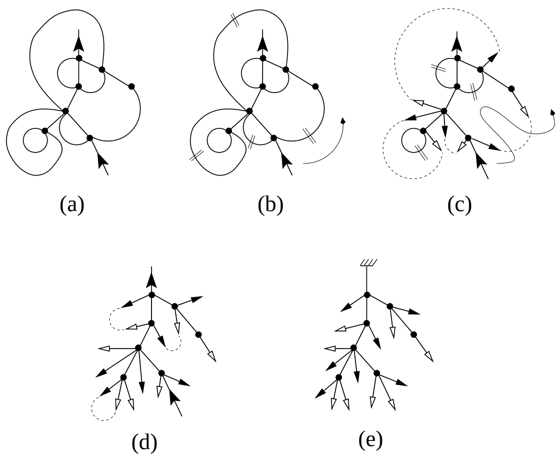


Figure C.4: The cutting of a planar two-leg diagram (a) into a blossom tree (e).

[T02/093], (ii) of hard particles on arbitrary planar tetravalent graphs [T02/160] and finally (iii) of hard particles on bipartite planar trivalent graphs [T05/013]. In the matrix integral language, case (i) corresponds to the general Hermitian one-matrix model, case (ii) to a particular instance of Hermitian two-matrix model with AB interaction and case (iii) to a particular but archetypical instance of the general Hermitian multi-matrix model with chain-like interaction. At this stage, we are therefore now able to apply the bijective approach to *all* planar graph enumeration problems previously amenable to a matrix model solution via orthogonal polynomial techniques. One advantage of the bijective method is to provide a simple interpretation for the auxiliary functions of the orthogonal polynomial solution of matrix models as generating functions for planar decorated trees, and to make clear the algebraic relations they satisfy.

More interestingly, the bijective approach allows to address other questions beyond reach of matrix models such as the *intrinsic geometry* of planar graphs. For instance, we can keep track of the geodesic distance between faces on the graph and thus have access to refined generating functions with prescribed distances between marked points [T03/029] (see also [T03/148] for a review). The latter obey recursion relations on the distance, which turn out to be integrable and to have explicit soliton-like solutions. These yield for instance explicit universal expressions for (possibly multi-critical) two-point functions in the continuum. Beside blossom trees, it is possible to construct a different bijection between planar graphs and trees with now labeled vertices. This was achieved in all generality in [T04/060] for the graphs corresponding to the one- and two-matrix models where planar graphs with prescribed face valences were shown to be in bijection with so-called labeled *mobiles* (after Calder). In this framework, the labels correspond directly to the geodesic distance from an origin. This alternative interpretation gives access to local statistical properties of large graphs [T03/104] such as the distribution of neighbors at a fixed distance from a given vertex. Viewing labels as discrete positions on a target line, labeled mobiles may be reinterpreted alternatively as *spatial branching processes*, i.e. probabilistic models for the evolution and spreading of a population. This creates a surprising link between graph enumeration problems and spatial branching processes. This correspondence was used in [T03/086] to obtain from the above soliton-like solutions explicit expressions for various probabilities for branching processes in the presence of particular boundary conditions. In the continuum, generic branching processes are described by Aldous' Continuous Random Tree (CRT) and their spatially extended version by the Integrated Superbrownian Excursion (ISE). The existence of multi-critical points for statistical models on random lattices should translate into new interesting universality classes of continuous branching processes, hence to multi-critical CRT and ISE.

Lecture notes on these developments are gathered in [T04/078].

C.2.1.2 Geometrically constrained systems on fixed and random lattices: from folding to meanders (Ph. Di Francesco, E. Guitter)

A number of reviews [T02/170] [T03/161] [T04/005] [T05/069] cover a series of earlier works on two-dimensional statistical models with strong geometrical constraints. These include folding problems of regular and random lattices, fully packed loop models as well as the famous meander problem of enumerating the topologically inequivalent configurations of a meandering road crossing a straight river through a given number of bridges. All these problems are described in a unified field-theoretical framework, based on Coulomb gas descriptions and two-dimensional quantum gravity.

C.2.2 Loop model combinatorics: from tilings of the plane to algebraic geometry (Ph. Di Francesco, J.-B. Zuber)

At the border between statistical physics and combinatorics, but with deep connections to the physics of integrable systems on one hand and the mathematics of algebraic varieties on the other hand, a new research activity at SPhT has focused on the discussion of the so-called Razumov-Stroganov (RS) conjecture (2001): the latter relates the components of the ground-state vector of the O(1) dense loop

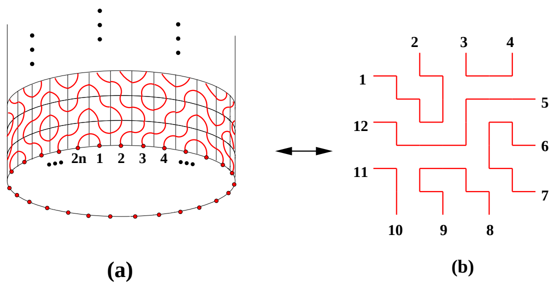


Figure C.5: Sample configurations of (a) the O(1) loop model on a cylinder of perimeter $2n$ and (b) the FPL model on a 6×6 grid. The RS conjecture connects the configurations of the O(1) model and those of the FPL model which realize the same connection between labeled boundary points (here for $n = 6$).

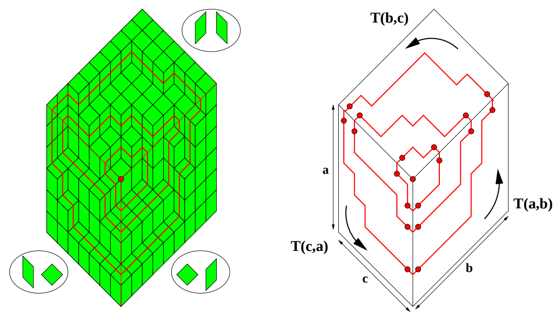


Figure C.6: The number of rhombus tilings of an hexagon of size $a \times b \times c$ is expressed as $\det(I + T(a,b)T(b,c)T(c,a))$, where $T(i,j)$ is the transfer matrix for non-intersecting lattice paths in a parallelogram of size $i \times j$.

model on a semi-infinite cylinder (dense gas of non-intersecting loops with a weight $n = 1$ per loop) to the numbers of configurations of the Fully-Packed loop (FPL) model on a square grid (see Fig. C.5), realizing the same loop connectivity pattern between boundary points. Our developments may be classified into three main topics: (i) pure combinatorics in which we have found and proved connections to other combinatorial problems, such as tilings of domains of the plane, (ii) integrability in loop models, which we have used to actually compute ground states of loop models and eventually prove weaker versions of the RS conjecture and (iii) relations to algebraic geometry.

A first paper [T03/153] established among other things a conjectural connection between some classes of FPL and tilings of hexagonal domains of the plane with three elementary rhombi. This was proved in [T03/186] and extended in [T04/030] to other classes of FPL and rhombus tilings of domains with conic singularities, by identifying the underlying fermionic degrees of freedom in the FPL, in the form of non-intersecting lattice paths. The counting of such paths involves determinantal formulas familiar to combinatorialists, which we have used and extended in [T04/120], where we performed the exact enumeration of a number of classes of FPL (see Fig. C.6) for the example of the rhombus tilings of an hexagon of size $a \times b \times c$). Finally, in [T04/100], we presented some refinements of the RS conjecture, involving the numbers of FPL configurations subject to extra boundary conditions, and also established a conjectural connection between these objects and yet another class of combinatorial objects, namely plane partitions, a 3D generalization of Young tableaux, also used to model crystal melting or even topological strings.

A first attempt to use the underlying integrable structure of the dense O(1) loop model has led to a number of new conjectures relating partition functions of the O(1) loop model on cylinders with dislocations (resulting into an indented boundary) and with inhomogeneous Boltzmann weights [T04/100] and [T04/117] to the inhomogeneous versions of FPLs made of configurations of the six-vertex model with domain wall boundary conditions on the same square grid, and with different spectral parameters in each line and column. The complete mechanism underlying this connection was unearthed in [T04/133], where the integrable structure of the O(1) model was fully applied to the computation of the ground state of the fully inhomogeneous loop model on a cylinder. This was done by turning intertwining relations for the inhomogeneous transfer matrix of the model into local relations between the components of the ground state, allowing for their direct computation. This has led to a proof of a weaker version of the RS conjecture that identifies the total number of FPLs on a given grid with the sum of components of the properly normalized ground-state vector of the O(1) loop model on a cylinder. Analogous techniques were developed to treat the case of the O(1) crossing loop model [T04/158] and also extended so as to include different (open) boundary conditions as well [T05/044].

The paper [T04/158] actually proved earlier conjectures of De Gier and Nienhuis relating the ground state of the O(1) crossing loop Hamiltonian to the degrees of some varieties related to the so-called commuting variety. These varieties are simple algebraic matrix varieties defined by quadratic relations, such as for instance the commuting variety, made of the pairs of complex $n \times n$ matrices (X, Y), such that $XY = YX$. The counting of solutions to such equations, possibly supplemented by generic affine conditions in order to make the set of solutions finite, leads to the notion of degree, easily generalized to that of multidegree by weighting differently the matrix elements, using spectral parameters. What we proved is that the multidegree of various components of these varieties obeys the same local relations as the entries of the ground state of the loop model, thus establishing a direct link between the integrable structure of the loop model and the algebraic geometry of some matrix varieties. This may be viewed as a non-trivial extension of some standard work of Fomin and Kirillov relating solutions of the Yang–Baxter equation to the Grothendieck and Schubert polynomials appearing in the cohomology of flag varieties. The subsequent results of [T05/044] certainly have an algebro-geometric meaning as well, yet to be understood.

CHAPTER D

From Conformal Field Theory to Random Geometries

Contents

SPhT has traditionally had a strong presence at the interface of quantum field theory and statistical mechanics, with particularly visible works in the area of critical phenomena. The related expertise in renormalization group and *epsilon*-expansion became gradually replaced and completed after the explosion of conformal field theories (CFT) in the early eighties. The latter, spurred in part by progress on the theory of infinite dimensional Lie algebras, had extremely profound influences, and branched out in a variety of directions of physics and mathematical physics to which there seems to be almost no limit. Recent activity at SPhT reflects this history In the last few years, it concentrated on geometrical problems, although there has also been a fair amount of work at the interface of conformal field theory and condensed matter physics, described in Sec. J.7 of this report.

In the early nineties, methods of conformal invariance had been applied to the determination of critical exponents in geometrical problems such as polymers, percolation, or interfaces in spin systems. These results were justified and generalized by the use of quantum gravity methods, which involves first the exact solution of the problems coupled to a random metric, and then derivation of results for the plane by use of Knizhnik–Polyakov–Zamnolodchikov type formulas. This technique was used recently to determine the multifractal function $f(\alpha, c)$ of the harmonic measure near any conformally invariant fractal boundary as a function of the central charge c of the associated CFT.

Independently, mathematicians tackled the problem of critical exponents for interfaces by the introduction of random conformal mappings, and the associated Stochastic Loewner Evolution (SLE). This idea, and the potential connection with the initial conformal-field-theory approach, were in turn reconsidered by physicists in the service, bridging ever deeper quantum field theory and probability theory. It was shown how SLE can be reinterpreted as a random process on the Virasoro group, leading to a reinterpretation for instance of the velocity of the Brownian motion in terms of the central charge of the CFT, or a reinterpretation of geometric probabilities in terms of CFT correlation functions. This led to the introduction of chordal and dipolar SLE, and the solution of problems in previously unexplored geometries.

In another direction, it was proposed that many properties of geometrical optimization problems could be addressed using techniques of conformal field theory. The minimum spanning tree and the traveling salesman problem (TSP) were considered. In the latter case it was argued that optimal tours were conformally invariant objects in the limit of a large number of cities, and described by a conformal field theory for which the (minimum) length plays the role of the free energy. The relevant CFT was identified, and related to sigma models on supergroups described below. As a result, detailed predictions for new critical exponents, finite size effects (eg, solution of TSP on a cylinder) and correlation functions (multi-salesmen problem) were made, which are currently under investigation.

Several members of the group also pushed the exploration of random geometries beyond conformal field theory, with general contributions on random graphs (leading to exciting interfaces with biology) the spectrum of random trees, or the development of a field theory and renormalization group formalism to address self-avoiding polymerized membranes.

Another area of progress concerns lattice models and quantum field theories with supergroup symmetries. The study of this topic stems from interest in the phase transitions of non-interacting disordered electronic systems, such as the transition between plateaux in the integer quantum Hall effect, which are described, in the supersymmetric approach, by σ-models on superspaces. These models typically exhibit non-hermitean "hamiltonians", and present considerable difficulties to analyze non perturbatively. Important results were obtained on the conformal field theory fixed points (some are also described in Chapter E on string theory), on the nature of the related S matrices and bootstrap, and on the applicability of the thermodynamic Bethe Ansatz (TBA) approach. Applications to geometrical problems were also discovered: for instance, the reformulation of the arboreal gas model as a σ-model on the supersphere, and the subsequent analysis of its critical point.

Other aspects of conformal and perturbed conformal field theory have been studied, such as relations between the TBA and ordinary differential equations, the analysis of universal ratios, or the development of applications in the study of transport in nanosystems, as described in Sec. J.7.

In conclusion, the last few years can be characterized most of all by their interdisciplinarity — while some of the activity focused on quantum field theory *per se* (conformal field theories with supergroup symmetries), other works established deep connections with soft condensed matter physics (membranes), hard condensed matter physics, probability theory (SLE project), optimization problems (CFT and TSP) and biology (random graph theory), showing more than ever the relevance and power of mathematical physics to modern theoretical physics.

D.1 Random geometries

D.1.1 Conformal random geometry and quantum gravity (B. Duplantier)

In [T03/041], a comprehensive description of the universal fractal geometry of conformally-invariant (CI) scaling curves or interfaces, in the plane or half-plane, is given. It focuses on deriving critical exponents associated with interacting random paths, by exploiting an underlying quantum gravity (QG) structure. The latter relates exponents in the plane to those on a random lattice, i.e., in a fluctuating metric, using the so-called *Knizhnik, Polyakov and Zamolodchikov* (KPZ) map. This is accomplished within the framework of conformal field theory (CFT), with applications to well-recognized critical models, like the $O(N)$ or Q-state Potts models, and the Schramm's Stochastic Löwner Evolution (SLE_κ).

Two fundamental ingredients of the QG construction are: the relation of bulk to Dirichlet boundary exponents, and additivity rules for QG *boundary* conformal dimensions associated with *mutual-avoidance* between sets of random paths. These relation and rules, used in former publications, are established in detail in this work from the general structure of correlation functions of arbitrary interacting random sets on a random lattice, as derived from random matrix theory.

The additivity of boundary exponents in quantum gravity for *mutually-avoiding* paths is in contradistinction to the additivity of exponents in the standard complex plane $\mathbb{C}$ or half-plane $\mathbb{H}$, where the latter additivity corresponds to the statistical independence of random processes, hence to possibly *overlapping* random paths. Therefore, with both additivities at hand, either in QG or in $\mathbb{C}$ (or $\mathbb{H}$), and the possibility of multiple, direct or inverse, KPZ-maps between the random and the complex planes, any entangled structure made of interacting paths can be resolved and its exponents calculated.

From this, non-intersection exponents for random walks or Brownian paths, self-avoiding walks (SAWs), or arbitrary mixtures thereof are derived in particular.

Next, the multifractal function $f(\alpha, c)$ of the harmonic measure (i.e., electrostatic potential, or diffusion field) near any conformally invariant fractal boundary or interface, is obtained as a function of the central charge c of the associated CFT. It gives the Hausdorff dimension of the set of frontier points w_α, where the potential varies with distance r to the said point as r^α. From an electrostatic point of view, this is equivalent to say that the frontier locally looks like a wedge of opening angle $0 \leq \theta \leq 2\pi$, with a potential scaling like $r^{\pi/\theta}$, whence $\alpha = \pi/\theta$. Equivalently, the electrostatic charge contained in a ball of radius r centered at w_α, and the *harmonic measure*, i.e., the probability that an auxiliary Brownian motion started at infinity, first hits the frontier in the same ball, both scale like r^α.

In particular, we find that Brownian paths, SAWs in the scaling limit, and critical percolation clusters all have identical spectra corresponding to the same central charge $c = 0$. This result therefore states that the frontiers of a Brownian path or of a critical percolation cluster are just identical with the scaling limit of a self-avoiding walk (or loop).

Higher multifractal functions, like the double spectrum $f_2(\alpha, \alpha'; c)$ of the double-sided harmonic measure, or the n-uple spectrum of the multiple-sided harmonic measure near n multiple random paths or SLE's, are similarly obtained.

As a corollary, the Hausdorff dimension D_{H} of a *non-simple* scaling curve or cluster *hull*, and the dimension $D_{\mathrm{EP}} = \sup_\alpha f(\alpha, c)$ of its *simple frontier* or *external perimeter*, are shown to obey the (superuniversal) *duality* equation $(D_{\mathrm{H}} - 1)(D_{\mathrm{EP}} - 1) = \frac{1}{4}$, valid for any value of the central charge c.

For the SLE_κ process, this predicts the existence of a $\kappa \to \kappa' = 16/\kappa$ duality which associates simple ($\kappa' \leq 4$) SLE paths as external frontiers of non-simple paths ($\kappa > 4$) paths. This duality is established here via an algebraic symmetry of the KPZ quantum gravity map. An extended *dual* KPZ relation is thus introduced for the SLE, which commutes with the $\kappa \to \kappa' = 16/\kappa$ duality.

Quantum gravity allows one to "transmute" random paths one into another, in particular Brownian paths into equivalent SLE paths.[1] Combined with duality, this allows one to calculate any SLE exponent from simple QG fusion rules.

Besides the set of local singularity exponents α introduced above, the statistical description of the random geometry of a conformally invariant scaling curve or interface requires the introduction of *logarithmic spirals*. These provide geometrical configurations of a scaling curve about a generic point that are conformally invariant, and correspond to the asymptotic logarithmic winding of the polar angle φ at distance r, $\varphi = \lambda \ln r, r \to 0$, of the wedge (of opening angle $\theta = \pi/\alpha$) seen above.

In complex analysis and probability theory, this is best described by a new multifractal spectrum, the *mixed rotation harmonic spectrum* $f(\alpha, \lambda; c)$, which gives the Hausdorff dimension of the set of points possessing both a local logarithmic winding rate λ and a local singularity exponent α with respect to the harmonic measure.

The spectrum $f(\alpha, \lambda; c)$ of any conformally invariant scaling curve or interface was thus obtained as a function of the central charge c labeling the associated CFT, or, equivalently, of the parameter κ

[1] This may be why some authors like to label it as "magic".

for the SLE_κ process. Its original derivation, based on quantum gravity and Coulomb gas methods, was given in the Letter [T02/124], and in [T03/090]. The details of the theory are given in the aforementioned survey [T03/041].

Recently, with Ilia Binder, we have been able to derive rigorously these results, including their various probabilistic senses, from first principle calculations within the SLE framework.

D.1.2 The SLE project (M. Bauer, D. Bernard, and more recently J. Houdayer and K. Kytölä)

Random curves have been a subject of investigations for more than one century, motivated by their occurrence in physics and finance. A central role is played by Brownian motion – a clean mathematical definition took decades – due to some deep facts relating it to the much vaster class of continuous Markov processes, via stochastic integrals. However, the understanding of many random curves of interest for physics and mathematics seemed to be out of reach. The continuum limit of geometric objects such as self-avoiding random walks, loop-erased random walks, percolation interfaces and so on were the subject of challenging questions and conjectures.

In 2000, Schramm made a breakthrough: he observed that, in two dimensions and under the hypothesis of conformal invariance, random curves satisfy a new type of Markov property and independence of increments. At the heart of these observations is the description of random curves via conformal maps. The tool to describe one parameter families of conformal maps is the so-called Loewner equation, which involves a source term. Schramm's result is that conformal invariance of a random curve in 2d imposes that the source term be proportional to a normalized Brownian motion, leaving just one parameter called the "speed". This has led to the elaboration of an impressive body of knowledge. Mathematicians have shown that at low speed the interface is a fractal simple curve, but that two phase transitions occur for larger speeds, leading to changes in the quantitative aspect of the interface. The fractal dimensions have been calculated, and many other geometric probabilities have been computed...

Since the mid-eighties, physicists had been working on other aspects of 2d conformal invariance after a breakthrough of similar importance made by Belavin, Polyakov and Zamolodchikov. They showed that conformal invariance allows to reduce the study of local scale invariant quantum field theories in 2d to algebraic questions related to representation theory of an infinite dimensional Lie algebra, the Virasoro algebra, which also involves a single free parameter, the central charge. Since then, conformal field theory has found applications in many branches of physics from string theory to QCD and condensed matter.

It was immediately clear that those two aspects of conformal invariance were intimately related. By imposing appropriate boundary condition to a 2d statistical mechanics model, one can impose the existence of an interface in the system, and the Boltzmann weights for the full system determine a probability distribution for the interface. At a critical point, the interface is expected to be conformally invariant, and thus conformal field theory applies, though it is much more efficient a priori to describe local objects than non-local ones like interfaces. One can cook up statistical mechanics system to mimic many of the geometric random curves that have been the primary interest in the mathematics community. The mathematical physics community in general, and the SPhT in particular, had in fact studied random curves and obtained deep heuristic results long before Schramm's discovery. But the physicist approach, via conformal field theory and/or quantum gravity, looked like magic.

Our main contributions to the subject have to do with the interplay between SLE and CFT.

We started [T02/086] with a reinterpretation of SLE as a random process on the Virasoro "group", which implements conformal transformation in CFT, and can thus be used to build an "group theoretic interface". Schramm's conformal invariance allows to construct martingales – continuous Markov processes which do not change with time in average – related to the interface. Imposing that the "group theoretic interface" in CFT leads to martingales leads to the identification of a special state in the CFT which when acted on by the "group theoretic interface" gives the physical interface. As a by product, an expression of the central charge of the CFT in terms of the speed of the Brownian motion in SLE is obtained. After this fundamental observation, we proceeded in different directions.

The first one led to the reinterpretation of the explicit computations of probabilities done by by mathematicians – a typical example is "what is the probability that the interface passes to the right of a given point" – in terms of CFT correlation functions [T02/162].

The second was to apply our group theoretic ideas to other geometries. Our first contribution was for interfaces going from one boundary point to another, called chordal SLE. Then we treated the case when the interface goes from a boundary point to a point in the bulk, called radial SLE [T03/154]. We also realized that an interesting case had been overlooked, to which we gave the name "dipolar SLE" [T04/013] [T04/194].

We also spent a lot of energy making our formal consideration on the Virasoro "group" rigorous [T03/081]. Most of the time, physicists had been dealing with infinitesimal conformal transformations. The possibility to build finite ones by iteration had not been seriously addressed, and indeed our construction involves restriction on the type of finite conformal maps that one can describe and compose in CFT. Explicit formulæ for finite transformations and explicit finite commutations rules had not appeared in the literature. This work has had applications to pure CFT and representation theory of the Virasoro algebra. These applications finally had also something to say about SLE and martingales generating functions. First, we could identify a useful martingale with a partition function. Second, we obtained, via the representation theory of the Virasoro algebra, a deep generalization of the classical relationship between martingales polynomial in a Brownian motion and the Fock space of simple harmonic oscillators [T03/012].

It was a long maturation process until we realized that there is a fundamental reason to the relationship we discovered between CFT and SLE [T04/194]. CFT describes a full system, but SLE describes what happens when only (part of) the interface is observed, and the other degrees of freedom have been averaged. The fact that Boltzmann weights are relative probabilities can be reinterpreted very simply in terms of martingales: if one averages over certain degrees of freedom, one finds effective Boltzmann weights for the remaining ones. If one computes a correlation function with the remaining degrees of freedom fixed, and then averages of the remaining degree of freedom, one recovers the correlation function when one averages over all degrees of freedom at once. This essentially says that correlation functions when the remaining degrees of freedom are fixed are martingales for the probability distribution describing the remaining degrees of freedom. A central role in this is played by conditional partition functions.

Trivial as the above observation seems, it is the clue that allowed us to define the correct extension of Schramm's construction when several interfaces are present, which we called "multiple SLEs" [T05/101]. This led us to a systematic answer to general questions which can be illustrated by the simplest non trivial example. In the Ising model on a rectangle, put boundary condition $+$ on the vertical sides and $-$ on the horizontal sides, so that two interfaces have to connect the four corners, either connecting the top to the bottom or the left to the right (interfaces cannot cross); in the continuum limit at the critical point, what is the relative probability of top-bottom and left-right, depending on the aspect ratio of the rectangle ?

More recently, we have focused our attention to more general, non conformally invariant, growth processes like diffusion limited aggregation [T04/193].

D.1.3 Traveling salesman problem and conformal invariance (H. Saleur)

NP complete problems such as the Traveling Salesman Problem (TSP) have so far resisted the sort of analytical progress that has transformed our understanding of simpler problems, such as percolation or polymers. The situation might however improve in the thermodynamic limit (eg, large number of cities for the TSP problem) where aspects of NP completeness might become, in a sense irrelevant. In a collaboration with Jacobsen and Read [T04/222], Saleur has argued recently that optimal tours become conformal invariant in this limit. He identified the (minimal) length with the free energy of the associated conformal field theory, and argued that this CFT is close to the one describing dense polymers (and best understood using a super-group σ model approach, see below). Saleur and coworkers introduced non trivial microscopic operators (not unlike the fuseau operators in polymers) for which they conjectured critical exponents, and made predictions (which should be amenable to numerical checks) for the length of optimal tours in the presence of various constraints, such as a cylinder geometry, or several 'folds' (equivalent to several travelers). Saleur and coworkers have proposed extensions of these results to other optimization problems, such as the minimum spanning tree problem.

D.1.4 Aspects of random graphs (M. Bauer, D. Bernard, S. Coulomb, S. Dorogovtsev and M.-C. Marsolier)

Since the pioneering work of Erdös and Renyi in the late 50's, random graph theory has become a well-established part of mathematics and has found applications in various branches of science. The Erdös-Renyi model starts from an empty graph on a fixed number of vertices and adds edges one at a time, at random, uniformly among the remaining edges. By looking at the time when the number of edges has reached a certain value, one gets a model of random graphs with given number of edges and vertices. The Erdös-Renyi model has been studied in considerable details, but it is still the subject of very active research.

However, in recent years, other random graph models of interest have emerged. This is mainly due to the explosion of the scale of (bio)technological networks. People have started to study a whole collection of realistic graphs, from the Internet to the large scale protein-protein interactions networks with the same statistical tools. They have observed that they share common features. As we shall stress in a moment, biological studies are still biased by several artifacts, and many spectacular observations in this area should be taken with a grain of salt. But there is one feature for which the evidence is overwhelming: the degree distribution, i.e. the statistics of the number of neighbors, is incompatible with the Poisson statistics predicted by the Erdös-Renyi model. In typical realistic networks, most vertices have a very small number of neighbors, and a few have a very large number of neighbors.

To construct models having these new features, several options are possible. Anything that leads to edge correlations is a candidate. One possibility is to look at evolving graphs. Starting from an Erdös-Renyi random graph with a fixed number of edges and vertices, one can apply evolution rules that reorganize the edges at each time step, leading in the long term to a graph which can have qualitative and quantitative characteristics markedly from those of the original graph. In social networks for instance, preferential attachment is a reasonable assumption, which says that the more people you already know, the more new people you are likely to meet in the near future. Another evolution model is to start from a graph on a small number of vertices and then add new vertices and edges at each time step, with rules which may depend on time. Then the graph is inhomogeneous by construction [T02/084] [T02/188]. Still another possibility is to include edge correlations and/or degree distribution by hand from the beginning and see what comes out [T02/085] [T03/149]. On top of that, one can also add more degrees of freedom to the graph, say, by coupling it to an Ising model [T05/018]. Tracing over the new degrees of freedom leads to an effective random graph model; or re-weighting each graph by the number of ground states leads to new models of random graphs [T04/223] [T04/224].

Except for preferential attachment, we have made contributions to all the above mentioned aspects. At the same time, we have tried to keep practical problems in mind, in particular those emerging from large scale studies in biology. We proposed a general way to attack the problem of finding relevant features of realistic (biological, say) interaction networks [T02/085]. The idea is to use maximal entropy methods. Choose a family of observables on the real graph, say the two edge correlation function or the degree distribution. Choose the probability law on graphs which maximizes the entropy under the sole constraint that the selected observables take the correct value. Then look for systematic deviations between features of the real graph and typical graphs in the constructed statistical ensemble. This must be done numerically in general. This approach relies on thermodynamical ideas, so it makes little sense if the real graph is too small or if one observes too many things. However, we tried to apply it to the Yeast protein interaction network. With its $\sim$ 6000 vertices, this is a reasonably large graph. To decide which observables to use, we made an analysis of previous studies and discovered that apart from the large degree distribution, all the previous spectacular features proposed to relate mutational resistance for instance to pure graph theoretical features are in fact washed out when biases are controlled. Among the obvious biases are the oversampling of certain proteins, fake interactions due to poor experimental precision, to experimental protocols and in particular the signature chosen to decide whether two proteins interact. Also, it turns out that as soon as a too detailed observable is chosen, the statistics on the real graph becomes too poor to be relevant. This reassessment has led to our first publication in a journal of biology [T05/103].

However, this means that it is too early to try to apply our general maximal entropy method fruitfully.

On the other hand, as theoretical physicists, it is remarkable that the random graphs models motivated by biology turn out to be very interesting for their own sake, if not for biology. As byproducts, we were led to discrete analogs of the famous continuous random matrix models, to strange phase transitions very similar to Kösterlitz-Thouless, to asymptotic freedom analogs in random graphs, to a new combinatorial decomposition of trees with applications in mathematics and optimization...

From that point of view, the interaction between theoretical physics and biology that we have tried to build has proven a very fruitful one.

D.1.5 Spectral density of large random trees (O. Golinelli)

In [T03/008], we analyze the spectral density of large random trees. We prove that there is an infinity of δ peaks at all real numbers which are eigenvalues of finite trees. By exact enumerations and Monte-Carlo simulations, we have numerical estimations of the heights of peaks. In the large tree limit, the sum of their heights is 0.19173 ± 0.00005. Moreover, all associated eigenvectors are strictly localized on a finite number of nodes. The rest of the spectral density is a function which vanishes at all positions of peaks, which are a dense subset of real numbers: so this function is almost everywhere discontinuous.

D.1.6 Field theory for polymerized membranes (F. David)

The study of non-local field theories for self avoiding polymerized membrane (a 2D generalization of flexible polymers) has been actively pursued in collaboration with K. Wiese. We have been especially interested in the development of non-perturbative methods to study the large orders of perturbation theory for these models. Although the self avoiding manifold model (SAM) model is known since the '90, and is a generalization of the Edwards' model for SAW and polymers, it is notoriously more difficult to study, since it cannot be mapped onto a local field theory in the bulk, and since the upper critical dimension for membranes is $d = \infty$.

We have developed instanton calculus for this model, and have been able to show how to relate the large orders of perturbation theory for the SAM to the contribution of instantons (complex solutions with finite action) for another non-local model for a composite field (playing the role of an effective background potential $V(r)$ in bulk space for the membrane).

Our recent works focused on the calculation of the contribution of the quantum fluctuations around the instanton in the effective theory. This calculation is needed to normalize the large orders asymptotics, and several new issues had to be addressed. (1) The functional determinant (Hessian) is ultraviolet (UV) divergent. We have analyzed these divergences and shown that the renormalization procedure used to make the perturbative SAM model UV finite makes also this determinant UV finite. This provides a first non-perturbative consistency check for the model (1-loop renormalizability in a nontrivial background). (2) New variational methods have been developed to study the instanton contribution in a large d expansion. (3) New kind of IR divergences have been discovered, analyzed and shown to be associated to the singular behavior of the unstable eigenmode of the instanton (global dilation) in the large d limit. (4) We have also checked for consistency that in the special case of a 1-dimensional manifold we recover with our formalism the known results for polymers. This ensemble of new results is presented in a long paper [T04/122].

Further studies should focus on better resumations of IR divergences at large d, and on the applications of these results to practical perturbative estimates of scaling exponents and amplitudes for the SAM model.

Another project is to apply our renormalization methods to models of heteropolymer folding used for instance to study the secondary structure of RNA strands (work in progress).

D.2 Quantum field theories with supergroup symmetries (H. Saleur)

Considerable effort has been devoted to the study of lattice models and quantum field theories with super group symmetries. This stems from interest in the phase transitions of non-interacting disordered electronic systems, such as the transition between plateaux in the integer quantum Hall effect, or the spin quantum Hall effect, which are described, in the supersymmetric approach, by σ models on super spaces. More recently, several problems in string theory have also been mapped to such σ models.

While the topic may look like a mere extension of the ordinary case, it is much more complicated, for fundamental reasons: supergroups do not possess positive definite metrics, and they admit indecomposable (ie not fully reducible) representations. This means that the quantum field theories with such symmetries have non-hermitean 'hamiltonians', non-fully reducible operator product expansions, and also exhibit many features of the theories based on ordinary, but non compact groups such as $SL(2, R)$.

D.2.1 Wess–Zumino–Witten models

In Wess–Zumino–Witten models, the supergroup symmetry turns into a current algebra. Saleur, in collaboration with Essler and Frahm, has argued [T05/006] that $SU(2,1)_1$ is obtained in the continuum limit of the integrable superspin chain with alternating 3 and $\bar{3}$ representations. Careful analysis of the Bethe equations does prove the existence of a continuous spectrum of critical exponents, which manifests itself numerically as very large (infinite in the thermodynamic limit) degeneracy of scaled gaps. This behavior is very different from the one of the $SU(2,1)$ spin chain supposed to describe the spin quantum Hall effect and percolation, and the potential flow between the two theories is now a topic of active interest.

By using information from integrable lattice models, as well as from the conformal field theory side, Saleur has put forward typical features of WZW models on supergroups, such as the existence of a continuous spectrum of exponents (even in the "compact" case), which is moreover unbounded from below; the crucial importance of spectral flow; and the subtle difference between characters and character functions. These results rely partly on simultaneous works of Saleur, Lesage, Mathieu and Rasmussen [T02/223] [T03/207] on $SU(2)_{-1/2}$ and $\beta\gamma$ systems, and are currently being completed by minisuperspace calculations carried out in collaboration with V. Schomerus. They are also related with works described in the string theory section.

D.2.2 Goldstone phases

The Mermin Wagner theorem does not apply to supergroups, and models with such symmetries can exhibit spontaneous symmetry breaking in two dimensions. Jacobsen, Read and Saleur [T03/234] showed that models of self intersecting loops could generically be described by supersphere σ models $OSP(n/2m)/OSP(n-1/2m)$ (where $n-2m$ is the loop fugacity). They constitute one of the first examples where the continuum limit of a lattice model with "compact" target space is described by a non compact CFT. Jacobsen and Saleur have recently exhibited more such examples in the antiferromagnetic Potts model.

Later, Jacobsen and Saleur, in a collaboration with A. Sokal [T04/221], showed that the $OSP(1/2)$ case (the supersphere σ model) has another interpretation in terms of an arboreal gas. This involves a beautiful generalization of Kirchoff's theorem - which states that the number of spanning trees is equal to any minor of the Laplacian - to forests, and a Grassmann integral with four fermion interaction [T05/025].

D.2.3 "Logarithmic current algebras"

Apart from the WZW and the rather trivial Goldstone phases, there seems to exist yet another type of theory with supergroup symmetry, where the local currents are not Kac–Moody (and therefore must have some logarithms in their OPEs) and the spectrum comprises pretty much all rational numbers. In a paper with N. Read, Saleur [T01/197] was able to solve several such theories (such as super CP^n models with $\theta = \pi$) and discovered, on top of a very rich spectrum, a pattern of very large degeneracies, reminiscent of but different from, Yangian symmetries. Read and Saleur are currently studying the algebra responsible for these degeneracies, both at the level of lattice discretizations, and at the level of field theories.

D.2.4 S matrices and flows

Flows within theories with supergroup symmetries play a crucial role in applications to discordered systems. To get an understanding of the possible flow patterns, Saleur, in collaboration with B. Wehefritz Kaufmann, has investigated [T02/222] [T03/023] the S matrix and bootstrap approaches to solve the orthosymplectic Gross Neveu and σ models. They found that such an approach is formally possible, in particular that the thermodynamic Bethe Ansatz does gives meaningful results, despite the non unitarity of the S matrix (ie, the non hermiticity of the hamiltonians). Saleur is currently finishing a work on the $OSP(2/2)$ case, with potential applications to the disordered ising model and the fractional quantum Hall phase diagram. This uses other results of Fendley and Saleur on the simpler $O(n)$ case [T02/220].

D.3 Perturbed conformal field theory and thermodynamic Bethe Ansatz (P. Dorey, R. Guida, A. Voros)

D.3.1 Exact WKB analysis (A. Voros)

In continuation of earlier works (e.g., [T01/146]), the exact resolution of the polynomial 1D Schrdinger equation has been reviewed and brought in closer contact with the Bethe Ansatz methods for the exact resolution of 2D statistical mechanical models and quantum field theories. However, a deep connection between those two areas remains wholly mysterious [T04/159].

The transition from that exact framework to a singular quantum perturbative regime (coupling constant $g \to 0$) has also been understood for binomial potentials, such as the anharmonic oscillator $V(q) = q^2 + gq^4$: the $g \to 0$ behavior of certain global spectral functions (zeta functions, spectral determinants) has thus been determined [T03/192].

D.3.2 Aspects of thermodynamic Bethe Ansatz (P. Dorey)

P. Dorey worked on aspects of integrable models during a three-month stay in SPhT in 2004. These are certain theories defined in two space-time dimensions, which have the special feature of being exactly solvable, at least in principle. Turning the "in principle" into practice has led to the discovery of many interesting mathematical structures in the past few years, and also to the development of novel techniques for the study of physical problems.

The first paper [T04/037] concerned the behavior of these theories when defined on spaces with boundaries, a subject of much recent activity. A particular quantity - the "g-function" had been defined many years ago by Affleck and Ludwig, and its applicability in more general circumstances - to "off-critical" theories - had been the subject of much debate. In [T04/037] the question was settled by finding an exact expression for a fully off-critical g-function using techniques from the thermodynamic Bethe Ansatz.

In [T04/048], written with L. Miramontes, another visitor to SPhT, a set of exactly-solvable examples were used to study the general properties of unstable particles in quantum field theories, using the thermodynamic Bethe Ansatz method to probe their properties in finite volumes.

The so-called "ODE/IM correspondence" links problems in quantum mechanics, and techniques developed by André Voros in his study of exact WKB methods (see above), to integrable models. In [T04/050] the correspondence was used to investigate some novel perturbative and non-perturbative features of non-Hermitian (PT-symmetric) quantum mechanics.

D.3.3 Universal ratios in perturbed CFT (R. Guida)

A new class of universal amplitude ratios which involve the first terms of the short distance expansion of the correlators of a statistical model in the vicinity of a critical point has been proposed [T03/049]. The critical system was described by a conformal field theory (UV fixed point) perturbed by an appropriate relevant operator. In two dimensions the exact knowledge of the UV fixed point allows for accurate predictions of the ratios and in many nontrivial integrable perturbations they can even be evaluated exactly. In three-dimensional O(N) scalar systems feasible extensions of some existing results should allow to obtain perturbative expansions for the ratios. By construction, these universal ratios are a perfect tool to explore the short distance properties of the underlying quantum field theory even in regimes where the correlation length and one point functions are not accessible in experiments or simulations.

D.4 Critical phenomena and renormalization group (C. Bervillier, R. Guida, J. Zinn–Justin)

D.4.1 Perturbative evaluation of RG functions (R. Guida)

In collaboration with P. Ribeca, a framework for the automatic evaluation of Callan–Symanzik Renormalization Group functions is under construction. This framework will consist of three stages, generation of diagrams, parametrization of amplitudes and numerical evaluation of integrals. While the first two steps are under control, the problem of finding a capable high-dimensional integration routine is under active development.

D.4.2 Supercritical fluids (C. Bervillier)

Measurements of small-angle neutron scattering in supercritical krypton have been carried out in order to study the behavior away from the critical point. Comparison of these data with theory [T03/075] is a difficult exercise for the following three reasons:

1. data (intensity of scattered neutrons) involve three relevant physical parameters: deviations to the critical temperature and density and transfer wave number. The analysis requires the knowledge of the critical behaviors of the correlation function, the correlation length, and the susceptibility.
2. theoretical calculations (by Guida and Zinn–Justin) of pure scaling forms are available only for the susceptibility.
3. the accurately known theoretical results (pure scaling form of the susceptibility, of the correlation length and correlation function) do not include corrections to scaling laws.

We thus had to rely on general features of the theory to find theoretical functions that allow to reproduce experimental data.

D.4.3 Exact renormalization group (C. Bervillier)

It was commonly admitted that the historical formulation by Wilson (in 1971) of the exact renormalization group (using a specific regularization schime named "incomplete integration") and the later formulation by Polchinski (in 1984) which assumed a general regularization scheme, were equivalent. This equivalence relation, however, had never been clearly expressed before Golner (1998). Further more, in the latter paper (unpublished), the exponent η was introduced in a non-natural way through "anomalous" dimensional analysis. As recalled in [T04/058], this introduction is an essential point of the renormalization-group technique. It assumes the existence of fixed points suited to the problem under consideration. It is shown how, following the steps defined by Wilson, one may construct the exact equation of state relevant to the physics under study. Then, this Wilson–Polchinski equation is analyzed by expanding it to order ∂^2.

As an illustration of this method, the exact equation corresponding to the Lifshitz critical point is obtained [T04/059]. This result is completely new. This system has two correlation lengths: this peculiarity makes it more difficult to obtain the equation of state, because of the anisotropy it induces in the scaling behavior.

We show that the expansion of this equation in powers of the field derivatives is equivalent, to leading order, to the order ∂^2 of the ordinary critical point. This leading order of the Lifshitz critical point is studied, and the corresponding estimates of the Lifshitz-type critical exponents are obtained. We also show that one can also study the assumed "tricritical" point associated with a fixed point which differs from that which governs the critical behavior. The numerical study gives a result which is not foreseen by the usual approach using perturbative expansion around 4 dimensions: the point is not critical. We explain why this result could not be obtained by a perturbative approach.

In the case of $O(N)$ symmetry, the expansion to order ∂^2 involves three ordinary differential equations, instead of two in the case of Z_2 symmetry (Ising). In this respect, it is similar to an intermediate step between the ∂^2 and ∂^4 orders of the Ising model These three equations are studied in [T05/009] for the first time. We obtain estimates of the critical exponents. Results are compared to those of previous works (to order ∂^2, but based on a class of exact renormalization-group equations of the which differs from the Wilson-Polchinski class). The interest of this study does not lie in the estimates of critical exponents, but rather in the study of the convergence of the expansion in powers of the field derivative, which had never been undertaken before. We show that by varying the parameter N, a few effects appear which might hint at convergence. The study of the next-to-leading order will be essential in answering this question.

D.4.4 Quantum field theory in the large-N limit (J. Zinn–Justin)

In [T02/110] [T02/119], some $O(N)$-symmetric supersymmetric models in three dimensions at finite temperature are investigated. These models are known to have an interesting phase structure. In particular, in the limit $N \to \infty$ one finds spontaneous breaking of scale invariance with no explicit breaking. Supersymmetry is softly broken at finite temperature and the peculiar phase structure and properties known at $T = 0$ are studied at finite temperature.

In [T03/144], a review is given on the solutions of $O(N)$ and $U(N)$ quantum field theories in the large N limit and as $1/N$ expansions, in the case of vector representations.

CHAPTER E

Strings and Quantum Gravity

Contents

String Theory along with other approaches to Quantum Gravity is one of the important directions of research of the SPhT. The main activity of the laboratory in this area covers string theory in time-dependent background and the associated Liouville models, $c = 1$ and large-N matrix models, various aspects of the AdS/CFT correspondence and the integrability of $\mathcal{N} = 4$ gauge theories, the compactifications of string theory, the structure of $\mathcal{N} = 1$ and $\mathcal{N} = 2$ low energy limits and their relation with pure spinor formalism and Hitchin functionals and finally some new formulation of Loop Quantum Gravity.

Since 2002, the group had one post-doc (Bénédicte Ponsot); one graduate student (Sergei Alexandrov) has received his PhD in string theory, and two students (Yann Michel and Vincent Pagès) are doing a PhD in string theory. Two new post-docs in string theory will start next September (Michael Chesterman and Kazuo Hosomichi). A young string theorist (Mariana Graña) was hired and will join the SPhT from October, 1st 2005. Ruben Minasian joined our group in 2005. We invited many visitors, and where involved in organization of major conferences and workshops in Paris and Europe.

The recent results in the structure of our universe have prompted a renewed interest in the study of time-dependent models in string theory. Unfortunately, the evolution of strings in a time-dependent background is hard to analyze, especially since our understanding of the behavior of string theory in a curved background relies on the world-sheet renormalization group flow, which is not guaranteed to be valid in this case. However in the case of localized closed-string instabilities, such as the case of decaying D0-branes, a time-dependent Liouville model has been written down, and this will hopefully lead to the resolution of the problem.

The low-dimensional string theories and their matrix models, which enjoy renewed interest, are good laboratories for the current topics in string theory as open/closed string duality, D-branes and vacuum instabilities. In particular, the time-dependent backgrounds and the non-perturbative effects in the bosonic $c = 1$ string theory have been studied using the exact solution of the large-N matrix quantum mechanics perturbed by chiral sources. In the open string theories, the basic observables are the correlation functions of boundary operators. The latter were studied using the loop gas and Liouville theory approaches and were shown to satisfy a set of functional identities.

Some of the newest developments in string theory concern the duality between the gauge and string theories. On the string side, they concern the study of strings in curved backgrounds, the prototype being the AdS-type backgrounds. This is a difficult and so far unsolved problem, and progress in understanding the basic features has been made by considering simplified models. The group is concentrating presently on understanding the non-linear σ-model on supergroup manifolds, and as a preliminary in developing the representation theory for supergroups, which is notably more sophisticated than that of Lie groups. On the side of gauge theories, significant progress has been made in recent years for the planar case, due to the property of integrability. The dilatation operator of the $\mathcal{N} = 4$ gauge theory was identified with the Hamiltonian of an integrable spin chain, at least for the first few orders in perturbation theory. The group succeeded, using the Bethe Ansatz and classical integrability techniques, in obtaining a detailed comparison between the gauge and string results, which unraveled a discrepancy starting with the third order in perturbation theory. The ongoing activity is dedicated to understanding this spin chain to all order in perturbation theory.

The structure of string compactification to 4d dimension is not yet completely under control. Despite the knowledge of the general structure of the effective theory with $\mathcal{N} = 1$ or $\mathcal{N} = 2$ supergravities in four dimensions, the goal of obtaining the superpotentials and the quantum corrected metric for the moduli is far from being complete. Members of this group have studied both the cases with $\mathcal{N} = 1$ and $\mathcal{N} = 2$ supersymmetries and showed the relevance of SU(3)-structure. All the string quantum corrections should respect this geometrical characterization. One particularly interesting aspect of this description is the action of mirror symmetry on these geometries, which takes a clearer interpretation when described in terms of special formal series of forms or so called pure spinors. Its was shown that pure spinors are the correct variables for describing the structure of the low-energy effective action but as well for formulating a first-quantized approach to 11-dimensional supergravity. These two results, although not immediately connected, should in fact be two aspects the importance of pure spinors for the description of string vacua with fluxes and the construction of a new underlying topological model.

Other works of this group are on a better formulation of loop gravity, another promising approach to quantum gravity. The most popular formulation of loop quantum gravity uses a SU(2) connection which has the main drawback of not being Lorentz covariant. A new approach based on a Lorentz covariant formulation was found. With this approach many standard results of SU(2) quantization were rederived, and the origin of many ambiguities and inconsistencies in the traditional approach could be spelled out precisely. The Lorentz invariant quantization was as well related to the spin foam approach, and model for the Hilbert of this new formulation of loop quantum gravity approach was given.

E.1 Strings and conformal field theory (V. Schomerus)

Current problems in String Theory often require to go far beyond the supergravity approximation. The microscopic techniques of (boundary) conformal field theory were developed to investigate systems in which the extension of strings can no longer be neglected (see [T04/055] for a non-technical introduction).

E.2 Strings in AdS-like geometries (V. Schomerus)

Some of the deepest recent developments in string theory are in one way or another related to a novel set of non-perturbative dualities between string and gauge theories, the so-called AdS/CFT dualities. They have triggered significant progress in our understanding of certain gauge theories. Unfortunately, the input from string theory is still rather limited. In fact, it is restricted to semi-classical studies or weak curvature approximations since string theory on AdS backgrounds has not been constructed yet.

Throughout the last years we have addressed this issue departing from a lower dimensional toy model [T03/146]. In particular, we demonstrated how information on the exact closed string spectrum in an AdS-like geometry may be recovered using no more than a few basic principles. We also constructed a number of instantonic objects (branes) which play some role for the study of so-called little string theory, a 6-dimensional non-gravitational string theory.

A next step toward more realistic theories requires to study (RR-) deformations of our toy model. Such deformations become particularly natural once the theory is rewritten in terms of a non-linear σ-model on the supergroup PSL(2|2). We have started to investigate the latter. So far, we completed two papers with necessary mathematical preliminaries on the representation theory of the Lie superalgebras SL(2|1) [T05/062] and PSL(2|2) [T05/080]. These will be applied in a forthcoming publication.

E.3 Strings in time dependent backgrounds (V. Schomerus)

The study of string theory in time dependent backgrounds has received some attention recently, partly because of its obvious relevance for cosmological applications of string theory. Unfortunately, evolving string backgrounds are extremely hard to deal with and most of our ideas about stringy time dependence are based on a conjectured link with world-sheet renormalization group flows. In [T03/251] we tested such ideas for decay processes that are triggered by localized instabilities in closed string theory. A more ambitious aim was then to prove the conjectured relation at least for the very simplest process, namely for the decay of an unstable D0 brane in type IIB theory. In two papers [T03/074] [T03/121] we succeeded to construct a Euclidean version of the relevant background from Liouville theory. But in contrast to a widespread believe we also showed that a naive Wick-rotation of this model is impossible and we suggested a new continuation procedure. With some guidance from a related quantum mechanical model [T04/121] we now expect to bring this program to a conclusion.

E.4 Asymmetric cosets (V. Schomerus)

A general theory of WZNW coset models G/H in which different left and right actions of H on G are gauged. These asymmetric cosets corresponds to exactly solvable backgrounds, like the the base of the conifold and the time dependent Nappi-Witten background in which a 3-dimensional universe passes through a series of big-bang big-crunch singularities. In [T02/173] [T03/250] we derive a formula for modular invariant partition function, the construction of a large set of boundary states and a general description of the corresponding brane geometries is given for general asymmetric coset models.

E.5 Matrix models and two-dimensional string theory (S. Alexandrov and I. Kostov)

The spectacular progress achieved recently in Liouville theory encouraged string physicists to reconsider the correspondence between large-N matrix models and noncritical string theories, or solvable models of 2D quantum gravity. In particular, it became possible to give a world-sheet interpretation of the non-perturbative phenomena in matrix models in terms of the so-called ZZ branes discovered by A. and Al. Zamolodchikov. In [T03/013] it is shown that the non-perturbative corrections to the free energy of the two-matrix model are associated with the vanishing cycles of the algebraic curve that defines the saddle-point solution. This statement applies for any perturbation off the critical points of the matrix model, which describe the rational $c < 1$ string theories, and generalizes a result previously obtained for these points. The non-perturbative effects in the compactified 2D string theory are studied in [T04/137]. The leading and the sub-leading factors in the non-perturbative corrections to the free energy are calculated in an arbitrary time-dependent background generated by a tachyon source. The result is interpreted in terms of the one-point (disk) and two-point (annulus) correlation functions of the bosonic field associated with the tachyon source.

In [T02/158], it was shown that a particular type of tachyon perturbation, which gives the so called sine-Liouville theory, can be given a thermodynamic interpretation. Namely, one of the parameters of the perturbation plays the role of temperature and the system possesses a non-trivial entropy. This is interesting due to the fact that the sine-Liouville theory is T-dual to a system (2d string theory with a winding perturbation) which is supposed to describe string theory on a black-hole background. Thus, one might hope to get a new insight into the thermodynamic properties of the theory and to better understand the dynamics of black holes within string theory.

In [T03/058], the problem of deducing the structure of the background of 2d string theory, corresponding to a particular perturbation of Matrix Quantum Mechanics (MQM), directly from the matrix model solution was addressed. Using the collective field theory of Das and Jevicki, some results for the tachyon perturbations were obtained. In particular, it was shown that there exist coordinates in which the metric of an effective two-dimensional space-time is always flat. These coordinates were expressed in terms of the solution of the perturbed MQM at the quasiclassical level. It was suggested that, although the tachyon perturbations always lead to the trivial local structure of the two-dimensional space-time, the global structure may become non-trivial.

The work [T03/079] is devoted to non-perturbative effects in non-critical string theories. Recently, a great progress in understanding of these effects has been achieved mainly due to the discovery of conformally invariant boundary conditions in Liouville theory, which give rise to the so called FZZT (Neumann type) and ZZ (Dirichlet type) branes. In particular, MQM was interpreted as an open string theory living on N ZZ branes. Thus, the representation of 2d string theory in terms of MQM provides a simple example of open/closed string duality which is quite interesting due to its integrability.

A particular kind of non-perturbative effects, which can be calculated exactly using the matrix model technique, is given by non-perturbative corrections to the string partition function. In critical string theory they are given by exponentiation of disk amplitudes representing an open string ending on a D-instanton. In [T03/079], the same interpretation was found for non-critical strings, and the branes responsible for the leading correction in both $c < 1$ and $c = 1$ cases were identified. In the latter case, the integrability of the matrix model allowed to find the non-perturbative correction also in the theory with a non-trivial condensate of either winding or tachyon modes. This provided a prediction for a series of correlation functions in Liouville theory on a disk, which still remain unachievable in the CFT formulation.

E.6 Boundary correlation functions in 2D quantum gravity (I. Kostov and B. Ponsot and D. Serban)

The progress achieved the recent years in boundary Liouville theory allowed to extend the correspondence between the world-sheet and matrix-model descriptions to boundary phenomena. In [T03/004] and [T03/102] the boundary correlation functions in solvable statistical models of 2D quantum gravity are calculated and compared with those in Liouville theory. Functional identities are derived for all fundamental boundary structure constants, similar to the one obtained for the boundary two-point function by Fateev, Zamolodchikov and Zamolodchikov. The same equations are obtained in the microscopic realization of 2D quantum gravity as a height model on a dynamically triangulated disc. In [T03/214] [T04/015] it is shown the correlation functions of any number boundary operators satisfy similar functional identities, which stem from an integrable structure, the boundary ground ring. The ground ring in quasi-rational theories of 2D quantum gravity is studied in [T05/068].

E.7 Lorentz covariant loop quantum gravity (S. Alexandrov)

Loop quantum gravity is a canonical approach to quantization of 4-dimensional general relativity. It realizes the idea that the physical excitations of quantum space are concentrated on one-dimensional structures. Within this idea, a kinematical framework for quantum gravity, based on an SU(2) connection, has been constructed and some information about spectra of geometric operators, like area of two-dimensional surfaces, have been found. However, even without taking into account the problems of the implementation of dynamics and extracting the classical limit, which is non-trivial for any canonical quantization, the constructed formalism was supplied with a number of puzzles. Due to this, recently, an alternative approach based on the use of the full Lorentz gauge group was developed. In particular, it was found that it resolves several problems and identifies their origin with some serious internal inconsistencies of the standard loop quantization.

In the work [T02/129] the analysis of the new covariant approach was continued. It was shown that in the new framework it is possible to reproduce the kinematical setup of the SU(2) quantization, including the structure of the Hilbert space. This is achieved by resolving in a certain way of some quantization ambiguity existing in the covariant approach. However, it was argued that in this way one breaks the diffeomorphism symmetry at the quantum level, which is the origin of all problems. At the same time there exists a quantization preserving all symmetries. In [T02/129], a connection of this quantization to another approach to quantum gravity called spin foam models was established and a model for the Hilbert space of the covariant loop quantum gravity was proposed.

E.8 Integrability and the AdS/CFT conjecture (D. Serban)

In the recent years, progress was made towards understanding the details of the AdS/CFT correspondence, which constitutes the prototype of gauge/string duality. This progress was fostered by the discovery that the dilatation operator of the $\mathcal{N}=4$ super Yang-Mills theory can be put in correspondence with a spin chain. In the planar limit, in the first few orders in the 't Hooft coupling constant, this spin chains proved to be integrable. It was conjectured that this property will hold to all orders in perturbation theory. On the other hand, the σ model describing the strings on $\mathrm{AdS}_5\times\mathrm{S}_5$ is at least classically integrable and there are arguments that is will remain integrable when quantized. We face therefore the possibility to find a complete solution of these two problems, using the methods of integrable systems, and to compare the two solutions. In the paper [T04/002] we used a long range spin chain, namely the Inozemtsev model, to match the second and the third order in the dilatation operator. In the limit of sufficiently long operators, we were able to write Bethe Ansatz-like equations and compare their solution with the corresponding strings solutions. Our method allowed to uncover that, starting with the three-loop order, there is a systematic difference between the gauge-theory result and the string result. There are several directions in which we pursue this approach: first, the Inozemtsev model can presumably be deformed into a family of integrable models, with interactions which involves more than two spins, and some of these spin chains may solve the problem of quantizing the string σ model. Also, it is of great importance to understand the finite-size effects, which may be at the origin of the mismatch between the gauge and string results.

E.9 BMN limit and matrix models (B. Eynard)

The AdS/CFT conjecture can be tested in the particularly simple BMN limit. In this case, the field theory side is reduced to a gaussian complex matrix model, where one has to compute mixed correlation functions of the form $\langle TrZ^k\phi(Z^\dagger)^l\phi^\dagger\rangle$, and other similar types. The work done in [T02/120] consisted in applying the loop-equation method in this framework. This allowed us to check the validity of the AdS/CFT conjecture to the next order.

E.10 $\mathcal{N}=1$ Supersymmetric compactifications with fluxes (R. Minasian)

String theory on non-trivial backgrounds with fluxes, known as flux compactifications, and their underlying topological models are have received much attention recently. Turning on fluxes allows to fix certain continuous parameters (moduli) of the theory, thus limiting the arbitrariness of the vacuum; fluxes may also explain the observed hierarchy between the Planck and the electroweak scale. These novel features make the flux compactifications attractive for constructing semi-realistic stable Standard-Model-like vacua, and their systematic study is definitely needed both for phenomenological and theoretical reasons. Systematic analysis of the supersymmetry in flux compactifications was the subject of some recent work including the paper [T05/079]

Up to now, only a few supersymmetric backgrounds are known explicitly, and their low-energy actions have been only partially worked-out, and this project is aimed at constructing explicit solutions and systematically exploring the physical implications of these vacua and their theoretical structures. An important recent development that serves as a starting point for this project has been the development of the generalized Calabi-Yau structures and the classification in their terms of supersymmetric string backgrounds. Without fluxes, consistent four-dimensional string backgrounds require a special class of Ricci-flat six dimensional internal geometries, known as Calabi-Yau manifolds. Due to particularly nice features amenable for both physical and mathematical analysis, these have been the favored background of string theory for the last twenty years. When fluxes are turned on, the geometry back-reacts and is no longer Ricci-flat, and much of the intricate Calabi-Yau structure is lost. However some of the topological structure special to the Calabi-Yau manifolds can survive inclusion of fluxes, making these new set-ups richer yet calculable. New differential-geometric conditions sensitive to the incorporation of fluxes can be described in the framework of newly developed generalized Calabi-Yau structures, which in the last two years have been in the centre of attention of both string theorists and mathematicians. A particular attraction for string theorists lies in the special role played in the formalism by an antisymmetric tensor field (B-field) and the potential ability of this geometry to give a unified description of complex and symplectic structures, which arise in IIB and IIA flux compactifications, as well as in A and B topological models.

E.11 Quantum corrections to $\mathcal{N} = 2$ supergravity vacua (R. Minasian and P. Vanhove)

The spectrum of $\mathcal{N} = 2$ supergravity theories is composed of vector multiplets and hypermultiplets. The structure of $\mathcal{N} = 2$ supersymmetry implies the factorization of the moduli space of vectormultiplets and hypermultiplets for neutral couplings in the Einstein frame. This factorization is at the heart of many non renormalization theorems in string theory. The σ model metric of the vectormultiplets has to be Special Kähler and the one for the hypermultiplet has to be Quaternionic-Kähler. Not many explicit Quaternionic-Kähler metric are explicitly known despite the importance for the low-energy physics of superstrings. In particular understanding how quantum corrections (given by string loops) affect this metric is of great importance. In 2001, Calderbank and Pedersen wrote a relatively general Quaternionic-Kähler metric (but not the most general one) which we could match, in [T03/088] with the one predicted by string theory and identify the parameters of this metric in terms of string datas. We showed that the string one-loop correction to this metric is physical and affects the geometry of the hypermultiplets (correcting a previous claim by Strominger) and that higher-loop corrections do not affect the metric. These results are important for the relation between the A and B topological models and the black hole entropy calculation.

E.12 Structure of the low-energy effective action for type II superstrings (P. Vanhove)

In the article [T03/199] we continue the study, started in [T00/116], of the structure of the higher-derivative corrections to the low-energy action of type II string. We study in particular the effect of these corrections on the self-duality constraint of the RR 5-form field-strength of type IIB string. This self-duality relation is a necessary condition for having the correct spectrum for type IIB string. The higher-order derivative corrections to the effective action imply higher-order corrections to the equation of motion and consequently to the Bianchi identity by self-duality, which poses problems for quantizing the theory. We show that the self-duality constraints has to be imposed on a modified RR 5-form field-strength corrected by α'-corrections.

E.13 Topological M-theory (P. Vanhove)

In [T04/102] and [T04/141] a systematic construction of multiloop amplitude computation for the superparticle in 11d is presented. The M-theory conjecture states that 11d dimensional supergravity is the low-energy approximation of the more fundamental microscopic theory. This fundamental theory is not known but some informations about the structure of it low-energy effective action can be derived by considering multiloop amplitudes in the superparticle formalism. This approach was started in [T97/192] in collaboration with M. Green and M. Gutperle and was pushed up to two-loop amplitude in [T99/100] with M. Green and H. Kwon using the unitary technics of Bern, Dixon and Kosower to $\mathcal{N} = 1$ 11d supergravity. These unitary technics allowed to derive some important results on the structure of the low-energy effective action for M- and string theory (some non-renormalization theorems obtained this way were recently confirmed by explicit superstring two-loop amplitude computation by D'Hoker, Phong and Gutperle), but too cumbersome at 3-loop order and higher. In order to circumvent these difficulties we presented, in [T04/102] and [T04/141], a first quantized formalism for computing multiloop amplitude for the superparticle in 11d. The path integral is formulated in terms of constraints variables called pure spinors, which arise after gauge fixing the κ-symmetry of the world-volume action. In [T04/141] we shown that the bosonic dimension of the moduli space at g-loop order is $7(g-1)$, which we conjecture to be giving the dimension of the topological M-theory in the same way that the bosonic dimension of the string perturbation moduli space gives the dimension 6 where the topological A and B models are defined. A few checks of this conjecture are presented in this paper, and this proposal is under more studies in some work in progress with P.A. Grassi.

CHAPTER F

Cosmology

Contents

Cosmology is a strong research field at SPhT which covers a broad range of topics, from studies of inflationary scenarios for the early universe to works on clusters of galaxies observed in the present universe. Three permanent researchers specialize in this field but other SPhT physicists from other groups (mathematical physics, statistical physics) also contribute to it. Besides, the subjects at the interface between particle physics and cosmology are also studied by the particle physics group. Since 2002 one postdoc has worked in SPhT and one student has started his PhD.

This field has undergone a tremendous growth in recent years as various data of increasing precision have shown that the universe is almost flat but contains an important dark energy component responsible for its recent acceleration. On the theory side, string theory and physics beyond the standard model have opened the way to new scenarios (for instance involving extra dimensions) while numerical simulations quickly strengthen the relationship between theory and present observations.

A key theme of modern cosmology is the study of the generation of primordial fluctuations in the early universe, which eventually gave rise to the large scale structure of the present universe. The generic properties predicted by the simplest inflationary scenarios, e.g. adiabatic initial metric fluctuations with Gaussian statistics with an almost scale-invariant power-spectrum, agree very well with observations of the large scale structure and of the Cosmic Microwave Background (CMB) ruling out some theoretical models. Still non-minimal models of inflation are worth investigating if one wants to eventually shed light on the nature of the inflaton field. For instance a family of such non-standard models can be obtained in a string theory or supergravity framework where it is possible to have coupling constants depend on some scalar fields. This leads to modulated fluctuations with novel properties, a scenario presented and studied in details. The case of multiple field inflation has also been explored actively. In this case, non only can a mixture of adiabatic and isocurvature fluctuations be produced; it is also possible to generate primordial fluctuations with significant non-Gaussian couplings. Those investigations are crucial to better understand the constraints forthcoming CMB observations can pose on the physics of the early universe. On the other hand, the analysis of current CMB data has already allowed one to obtain stringent constraints on the properties of primordial fluctuations and to rule out some theoretical models.

The study of quantum fluctuations in the cosmological context has also led to interesting mathematical problems when one wants to compute quantum radiative corrections or when unconventional modes (which grow at large distances) appear in the case of negative spatial curvature. Although present observations suggest that the universe is (almost) flat, the latter studies are actually relevant to other fields of theoretical physics (such as string theory).

In recent years the combination of various observations (CMB, high redshift supernovae, clusters) has shown that 70% of the present energy content of the universe ought to be in the form of a dark energy to account for its current acceleration. This dark energy may be understood conservatively as a cosmological constant or as the potential energy of some quintessence field. Several works have shown that departure from a mere cosmological constant can only be modest. An alternative to such scenarios is provided by the Chaplygin gas models which involve a fluid with a negative pressure given by the equation of state $p = -1/\rho$. This can be connected to a string theory model and may have the advantage of unifying dark matter and dark energy. Thus recent studies have investigated the properties of such scenarios and the associated relationship between tachyon and scalar field models. More radical solutions to this observational puzzle are suggested by super-string theories where the current expansion of the universe could be due to the evaporation of the graviton into extra dimensions, modifying the gravitational interaction at cosmological distances. Although this approach is promising it has been shown that the simplest models lead to too many chiral fields and are not realistic.

On a global scale, the topology itself of the universe is not predicted by current theories and many possibilities exist for three-dimensional spaces of constant curvature. Motivated by CMB observations (and in particular by the large-scale anomaly detected by the WMAP satellite) the tools needed to study the impact of topology on the CMB have been developed. Although no definite conclusion can be drawn from current data they will be useful to analyze the future PLANCK data.

Another aspect of cosmology which is a strong activity at SPhT is the study of the formation and statistics of large-scale structures in the late universe. In the standard scenario the primordial quantum fluctuations of the inflaton lead to density fluctuations in a Cold Dark Matter (CDM) component, which are later amplified by gravitational instability to form galaxies. If the interactions of these particles cannot be neglected one obtains a Warm or Hot Dark Matter scenario which may improve the agreement with observations at small scales thanks to damping effects. Detailed studies of such scenarios have been performed, investigating the damping lengths associated with various interactions and their impact onto structure formation. This also enables one to derive constraints on the dark matter properties.

The dynamics of these CDM density fluctuations is still an important issue in the non-linear regime. Current simulations can show discrepancies of the order of 10% which will be a limiting factor for the measure of key cosmological parameters from future observations. On the other hand, numerical simulations are still too expensive to investigate in details the constraints which can be derived from such surveys. A simple model for the evolution of these fluctuations which shows a significant improvement over previous ones has been developed. On the other hand, a theoretical analysis in terms of a path-integral formalism has opened the way to systematic approaches such as large-N expansions.

An important probe of these large scale structures is provided by weak gravitational lensing surveys which are directly sensitive to the matter content of the universe (while galaxy surveys mainly trace stars). Several works have shown how the statistical properties of weak lensing observables (including their full probability distribution function) can be related to the statistics of the underlying matter distribution. Inclusion of various sources of errors allows one to investigate the results which can be expected from future space based missions like SNAP. On the other hand, weak lensing can be used to test gravity at very large scales. It has been shown that current data already yields tight bounds on deviations from Newton's law below 2 Mpc.

Finally, the link to astrophysical objects like clusters of galaxies remains a topic of research at SPhT. Although the ΛCDM scenario shows a good agreement with numerous observations, a few puzzles remain such as the low amount of baryons observed today and the properties of small clusters of galaxies. A shock-heating process which can simultaneously explain both discrepancies has thus been put forward.

It should be noted that these various subjects, which reflect many aspects of modern cosmology, are more and more closely related. With the arrival of the awaited LHC and Planck data, and possible new surprises, this trend should be strengthened in the forthcoming decade.

F.1 Inflationary models (F. Bernardeau, T. Brunier)

The observation of the Cosmic Microwave Background anisotropies and polarization offers a unique window on the physics of the early Universe and in particular on the physics of inflation. Generic properties of single field inflation have been widely explored. They provide us with a set of predictions, namely primordial curvature fluctuations obeying Gaussian statistics with a nearly scale-free power spectrum, that to a large extent have been verified in the current observations.

However, extensions of the high-energy physics standard model like supergravity provide us with a framework in which it is possible to build new classes of inflationary models, such as the so-called modulated inflationary model proposed in [T04/032]. This is a particular case of multifield inflation, that is of inflationary models in which there exist more than one light scalar degree of freedom. Those can lead to rich new phenomenologies as explored in a series of papers. An efficient mechanism for transferring initial isocurvature modes into adiabatic modes is detailed in [T02/115] and an explicit model in which this mechanism works is presented in [T02/116]. As shown in those two papers such models open the possibility of having primordial non-Gaussian metric perturbations. These investigations led to fundamental issues regarding the behavior of self-coupled scalar fields in an inflating Universe. A complete quantum calculation of its high order correlation functions at tree order is presented in [T03/182] and in [T05/002] we investigated the effects of radiative corrections. In particular we have shown that, provided the scalar degrees of freedom are embedded in a chiral supermultiplet, radiative corrections do not induce large masses to minimally coupled scalar fields. Similar calculations have been recast in a different formalism in [T04/103], in which corrections to the masses of bosons have been investigated to two-loop order, providing a deeper insight into quantum effects during inflation. Such models led also to observation related investigations. Specific finite volume effects due to the non-Gaussian nature of the primordial metric fluctuations are examined in [T03/183]. They provided us with a possible explanation for statistical anomalies detected in the current CMB data though it was not confirmed in a detailed examination of the data we performed [T04/109].

F.2 Constraints on isocurvature perturbations (A. Riazuelo)

One of the usual assumptions in scenarios of large-scale structure formation in the universe is that of the adiabaticity of the cosmological perturbations. By adiabaticity, one means that although there are some density fluctuations in the universe, they were initially describing a homogeneous mixture of fluids: the densest regions, i.e. those with baryonic or dark matter overdensities, were also the hottest ones, i.e., with more photons. It happens that this assumption is not well justified when one looks at the mechanisms (inflation) which presumably produced these perturbations in the very early universe. We therefore studied some of the constraints one could put on various non adiabatic models of cosmological perturbations in [T02/179] and [T03/076]. The main result we obtained is that although the most general models of non adiabatic cosmological perturbations are not easily constrained by CMB data only, the most realistic ones are fairly well constrained, which in turn allowed us to put the first constraints on various inflationary models.

F.3 Quantification and fluctuations in curved space (R. Schaeffer)

The primordial fluctuations were generated at an epoch when their wavelength may be comparable to the curvature of space. In the case of open universes this raises mathematical problems as one needs to deal with modes which do not decay sufficiently rapidly at large distances, and which thus are not normalizable in the quantum sense. We have found in the 90's a way to deal with these modes and have developed the tools to handle them. This however turned out to be of only moderate astrophysical interest to calculate the primordial quantum fluctuations since the universe was found to be nearly -if not strictly- flat. Our knowledge however turned out to be useful in a frame that goes much beyond our initial motivation. Thus it is relevant to cases which bear no direct relation with astrophysics, for instance in models which consider the space curvature at the Planck scale, or in the frame of the AdS $\leftrightarrow$ CFT conjecture and more generally when decomposing fields into "bulk" and "brane" parts. Under the kind pressure of the scientific community, we have undertaken to write up everything we know on these matters. This should lead to a series of papers gathering old and new results. A first paper is under way [Quantum fluctuations in curved space: open de Sitter universe, U. Moschella, R. Schaeffer en preparation]

F.4 Dark energy models (V. Pasquier, A. Riazuelo)

F.4.1 Quintessence models (A. Riazuelo)

Dark energy is probably the most mysterious component of the universe. It represents around 70% of the current energy density of the universe and is thought to be responsible of the recent acceleration of its expansion. One of the most popular models of dark energy is the so-called quintessence model, where dark energy is supposed to be a scalar field whose kinetic energy is sufficiently small to allow the scalar field to behave as a negative pressure fluid. The constraints of these models were not well done in 2002-2003 and we performed one of the first detailed study on the constraints one could put on quintessence models using various sets of cosmological data [T02/180] [T03/092]. Another issue which arises in these models is that the initial amplitude of the cosmological perturbations is not related by any simple formula to the large scale power observed in the CMB data. We gave some numerical estimate of this relation in the paper [T03/094].

F.4.2 Chaplygin gas (V. Pasquier)

An alternative to quintessence models is provided by the Chaplygin gas scenario. The work done during the past two years, in [T03/212], [T04/054] and [T05/085], continues the initial proposal [T01/185] to study a universe filled in with a Chaplygin gas, defined by the equation of state $p = -1/\rho$. This model has recently attracted a lot of attention among cosmologists for the following reasons. It is a very simple model which has a negative pressure and thus, can predict a cosmological constant and an acceleration of the present universe. The model is exactly soluble in (1+1) dimensions. It interpolates between a dust universe and a pure cosmological constant universe and therefore can possibly unify dark matter and dark energy. In the regime close to the cosmological constant, it is a mixture of pure cosmological constant and stiff matter ($p = \rho$) and our recent progress indicates there are good reasons to believe that stiff matter is an important ingredient of our universe. Finally, It can be obtained in two different ways if we view our universe as embedded in in a five dimensional universe. The relativistic version is the simple Born-Infeld action for a (3+1) membrane embedded in a (4+1) universe. The non relativistic version can be derived from the light cone gauge choice for the action of the membrane.

F.5 Modification of gravity at long distances (P. Vanhove)

The current acceleration of the expansion of the universe might also be explained by the presence of extra dimensions, without the need for a cosmological constant, as in the DGP model which entails a modification of Newton's law at cosmological scales. In this model the 4d graviton is a quasi-localized state which decays in the non-compact extra dimension of the bulk. The decay scale parameter is determined by the bulk Planck mass, the 4d Planck mass and the UV cutoff scale of the theory. At this scale, fixed with respect to the size of the Hubble radius of our universe, the gravitational interactions are modified and become weaker and of higher-dimensional type, and late-time self-inflationary cosmologies (without a cosmological constant or dark energy) can be found. Following the previous setup of [T02/035] and [T03/054] for a string theory realization of the DGP model, we investigated with E. Kohlprath in [T04/115] whether weakly coupled gauge interactions can be as well localized in 4d and give the Standard Model type of constructions. By studying a huge class of type IIB orientifolds, we showed that the hierarchy between the 4d (localized) Planck mass and the bulk Planck mass always gives strongly coupled models with huge rank for the gauge groups and are therefore not realistic.

F.6 The topology of the universe (A. Riazuelo)

It is well established that the universe can be locally described by a locally Friedmann-Lemaitre-Robertson-Walker homogeneous and isotropic metric, but the large scale structure of space-time is unknown. In particular, it is not known whether the universe is simply connected. In order to constrain the topology of the universe, it is of course necessary to scan the largest scales available. In practice, this is done using the cosmic microwave background as these photons were emitted by a region — called the last scattering surface — which is now around 45 billion light years away. The imprint of the topology on the CMB is two-fold. First, if the spatial sections of the universe are of finite extent, there should be a maximum wavelength in any process, as nothing can be larger than the size of the universe itself. Second, one expects to see multiple images of various objects, similarly to what one would see if put in a room filled with mirrors. For the CMB, this amounts to look for various unusual correlations in the temperature patterns in various directions. We performed the first detailed computation of this effect in most if not all relevant topologies in a number of papers between 2002 and 2003 [T02/182] [T03/035] [T03/093] [T03/253]. We also contributed to raise the scientific community's interest to these issues thanks to a somewhat provocative paper published in Nature, where we suggested that the lack of large scale power in the CMB maps revealed by the WMAP experiment might be due to a finite size of the universe [T03/155].

F.7 Nature of dark matter (A. Riazuelo, R. Schaeffer)

In the 80's, when the "Cold Dark Matter" scenario was brought up, we had the opportunity to write one of the very first papers on these matters, having found a credible approximation to derive from the initial conditions the distribution of objects (galaxies, clusters) according to their mass. It was obvious at the time that this new scenario was in danger to predict too many small galaxies. We suggested at the time that the Dark Matter could be "Warm" rather than "Cold", having found this may alleviate the problem. Our findings however could only be confirmed quite recently by numerical simulations since the latter lacked for years the needed resolution. This "Warm Dark Matter" conjecture has since become a classic scenario and we have contributed to its renewal by suggesting there may be a new type of "Cold Dark Matter" which is moderately collisional so as to generate a final fluctuation spectrum that looks like "Warm Dark Matter" despite the initial conditions are of the "Cold" type. Our first papers on the matter were published in 2001, more recent publications being [T01/147] and [T02/205]. In 2004, we have completed a quite general work on these matters, with results -in particular bounds on the Dark Matter interaction rates- valid whatever the possible nature of the Dark Matter [T04/211].

F.8 Formation of large-scale structures (P. Valageas)

The one-point probability distribution function of the large-scale density field is an important tool to follow the evolution of cosmological structures. We have built in [T04/052] a new simple model which is consistent with all known rigorous results. We have checked with results from numerical simulations that it works significantly better than previous models.

In order to develop a systematic approach to the formation of large-scale structures through gravitational instability in the expanding universe we have recast the problem in terms of a path-integral formalism [T03/172]. We have derived the action $S[f]$ which gives the statistical weight associated with any phase-space distribution function $f(\mathbf{x},\mathbf{p},t)$. This action describes both the average over the Gaussian initial conditions and the Vlasov-Poisson dynamics. Next, applying a standard method borrowed from field theory we have generalized our problem to an N-field system and we have described three methods based on expansions over powers of 1/N. These systematic schemes match the usual perturbative expansion on quasi-linear scales but may also be able to handle the non-linear regime.

F.9 Gravitational lensing (F. Bernardeau, P. Valageas)

Cosmic shear surveys that are now under construction are direct probes of the mass distribution at large scales. They thus offer a unique way of testing the gravitational instability paradigm thought to be at the origin of the large-scale structures. They also probe the background dynamics of the universe. Earlier studies have shown that it is possible to model the statistics of the lensing convergence field on small angular scales by suitably modeling the statistics of the underlying density field in the highly non-linear regime. We have extended such methods to model the complete probability distribution function of the cosmic shear and of related observables as a function of smoothing angle [T03/130] [T03/142]. We have obtained an excellent agreement with the results of numerical simulations for different cosmological scenarios. Besides, we have shown that an observable built from a compensated filter allows one to probe both the amplitude and the detailed angular behavior of the many-body correlations, and to rule out some simple models [T04/006]. Next, we proposed new unbiased estimators for low-order cumulants which have less scatter than the usual estimators of non-Gaussianity based on the moments themselves and we studied the statistical measures which can be extracted from future surveys like the SNAP experiment [T04/053]. Finally, we investigated the additional information which can be brought up by cross-correlating different angles or redshift bins [T04/175] [T04/176].

On the other hand, as proposed in [T04/110] weak lensing surveys could be used to test gravity laws at cosmological scales. As shown in this paper deviations from Newton's law can already be strongly constrained below 2 Mpc.

F.10 Properties of small X-ray clusters (R. Schaeffer, P. Valageas)

The ΛCDM cosmological scenario suggested by data such as the CMB and high redshift supernovae has also been checked to agree reasonably well with many astrophysical observations, like galaxy or Lyman-α cloud statistics. However, some puzzles associated with large-scale structures still remain unresolved, like the low amount of baryons observed today and the departure of the properties of X-ray clusters from expected scaling laws. We have argued in [T03/063] that these two problems could be closely related. Indeed, as shown by recent studies the shock-heating associated with the formation of large-scale structures heats part of the intergalactic medium (IGM). This warm IGM component, which is difficult to observe, can explain the low amount of baryons detected at low redshift. Then, we suggested that the intracluster medium could be fueled by this intergalactic gas, shock-heated by the collapsing much larger scales. We have shown that the entropy of the warm IGM is sufficient to explain the observed entropy of small clusters and their departure from simple scaling laws. The advantage of this mechanism is that it is a natural outcome of hierarchical cosmological scenarios and it removes the need to invoke specific pre-heating sources.

CHAPTER G

Particle Physics beyond the Standard Model

Contents

Particle physics beyond the standard model is a very active research subject in Saclay. The group comprises six permanent researchers (Ph. Brax, M. Chemtob, C. Grojean, S. Lavignac, G. Servant and C. Savoy). In the past 3 years, 3 post-docs have worked in Saclay (I. Masina, L. Pilo and M. Thormeier) and 3 PhD students have been supervised (N. Chatillon, C. Delaunay and P. Hosteins). The group covers most areas of research beyond the standard model, from electroweak physics to string phenomenology. Some aspects of cosmology linked to high energy physics are under close scrutiny.

One traditionally strong aspect of the work carried out in Saclay is the physics of flavour and CP violation, especially in the framework of supersymmetric extensions of the Standard Model. In the last three years, most efforts have been concentrated on the lepton sector, which after the discovery of neutrino oscillations has become the new Eldorado of flavour physics. Indeed, experimental searches for processes which violate lepton flavour, such as muon to electron transitions, offer a golden opportunity to test not only the flavour structure of supersymmetry breaking, but also the mechanism responsible for neutrino masses. This has motivated the study of flavour and CP violations in the lepton sector, both in the supersymmetric version of the seesaw mechanism and in a more general supersymmetric framework. A related and challenging line of research concerns the construction of supersymmetric flavour models which can simultaneously reproduce the observed hierarchies of fermion masses and mixing angles together with giving constraints on the flavour structure of their scalar superpartners; the aim being the suppression of the associated flavour violating processes up to an acceptable albeit experimentally accessible level. In addition to the above-mentioned issues, neutrino physics stimulates further work on non-standard effects in neutrino oscillations, which could be due to mechanisms explaining their masses, and on the possibility of generating the baryon asymmetry of the universe through leptogenesis. S. Lavignac, C. Savoy with one student P. Hosteins, and two new post-docs, M. Frigerio and M. Thormeier, work in this field.

Attempts to assess the status of the standard models have flourished in the last few years. Indeed and despite the amazing success of the Standard Model in describing high energy physics, we are still missing experimental information about its main ingredient: the mechanism of electroweak symmetry breaking. While we know from flavour and CP violation physics that in the standard model the cutoff scale Λ cannot be below a few TeV, the fact that, within the standard model , the ratio of the Higgs mass to the cut–off scale receives large quantum corrections, points out that the standard model matter content is incomplete and that new physics at the TeV scale is required. It has been assumed in the last 20 years that the new physics at the TeV scale is embedded within a class of supersymmetric models such as the MSSM. Recently there has been a reappraisal of this paradigm and numerous new models have been proposed which make the supersymmetric hypothesis less compelling. To name a few, the little Higgs models springing from deconstruction of extra-dimensional gauge theories or the Higgsless models where boundary conditions in extra dimensions induce the electroweak breaking have been particularly studied in Saclay. These last models which appear as a resurgence of old technicolour models seem particularly promising in view of testing alternatives to the MSSM at the LHC. C. Grojean and G. Servant with a new student C. Delaunay work in this field.

Of course the supersymmetric idea remains a valid option as a possible extension of the standard model. Together with providing a natural solution to the hierarchy problem, supersymmetry is naturally embedded in more fundamental theories such as string theory. The subject of string phenomenology has recently received a new boost with the advent of new classes of constructions involving branes and flux compactifications. In such a framework, the stability problem for moduli, which plagues attempts to confront string theory with experiments has been partially overcome. This allows one to envisage scenarios involving new ways of breaking supersymmetry leading to valuable predictions for particle spectra. A new string theorist, M. Grana, specialist of flux compactifications, has been recruited by the laboratory. Ph. Brax and M. Chemtob are already working on this subject.

Another central theme of our activity is the connection between particle physics and cosmology/astrophysics. Three main subjects have been actively developed. First of all, there has been a renewed interest in the construction of models of inflation. Indeed inflation is a paradigm in search of a model, and flux models of string theory are promising candidates. This is all the more crucial as the Planck satellite experiment will soon give precise data. Ph. Brax works in this area in close connection with F. Bernardeauand a student T. Brunier. Secondly, the origin of the acceleration of the universe is certainly one of the greatest puzzles in our field. Traditional approaches have involved scalar fields. Recently, more drastic approaches where gravity is modified, either through the interaction with matter as in scalar-tensor theories or even truly altered at large distances have been proposed. Ph. Brax and C. Grojeanhave been working in this field.

Finally, dark matter is a time-honoured subject. Despite our ignorance of its nature, numerous techniques have been developed in an effort to detect it. Indeed, if dark matter consists of Weakly Interacting Massive Particles (WIMPs), it should have a tiny probability of interacting with ordinary matter. In addition to collider searches, direct and indirect detection techniques have been devised to search for dark matter. Direct detection consists in searching for WIMP elastic scattering off target nuclei in underground detectors while the goal of indirect detection is to observe a flux of cosmic rays resulting from the annihilation of WIMPs in the Galactic centre, the Galactic halo, or the interior of the Sun. All these efforts may finally reconcile supersymmetry with experiments as a likely candidate for dark matter arises in the form of a stable supersymmetric particle. As an alternative, dark matter may result from Kaluza-Klein particles appearing in extra-dimensional models. Such models are close in spirit to the one developed to describe alternatives to the standard model electroweak breaking. This highlights the sharp relationship between particle physics and cosmology. C. Grojean and G. Servant together with R. Schaeffer work in this field

It is worth emphasizing that these subjects are not disconnected but almost impossible to disentangle. Moreover, the prospect of having new discoveries at the LHC renders the efforts of understanding physics beyond the standard model even more worthwhile. It is an exciting few years which lie in front of us.

G.1 Electroweak symmetry breaking, deconstruction and modification of gravity (C. Grojean, L. Pilo, G. Servant)

Fermion masses are protected by chiral symmetry and scalar fields can inherit this protection if a symmetry relate them to fermions as in supersymmetry. Gauge invariance forbids any radiative mass terms for spin one fields. Again this protection can be extended to scalar fields if a symmetry relates spin zero and spin one fields: this is what higher dimensional Lorentz invariance is precisely achieving. After compactification of the extra dimensions, the higher dimensional gauge field decomposes into a 4D gauge field (the components along our 4D world) and 4D scalar fields (the components along the extra dimensions) which we could try to identify as the SM Higgs doublet. Both 4D vectors and 4D scalars originating from higher dimensional gauge fields belong to an adjoint representation of the gauge group, while the SM Higgs boson is a fundamental representation of the weak symmetry. In order to identify the Higgs as components of a gauge field in extra-dimensions we thus need to enlarge the $SU(2)\times U(1)$ gauge symmetry into a bigger group G, which by compactification on an orbifold can be broken to the EW symmetry. In [T02/127], we construct such a model based on a 6 dimensional G_2 gauge theory compactified on T^2/Z_4. This model can naturally produce the SM Higgs fields with the right quantum numbers while predicting the value of the weak mixing angle $\sin^2\theta_W = 0.25$ at the tree-level, close to the experimentally observed one. The quartic scalar coupling for the Higgs is generated by the higher dimensional gauge interaction and predicts the existence of a light Higgs. Fermions are introduced at orbifold fixed points, making it easy to accommodate the standard model fermion content. Yukawa interactions are generated by Wilson lines. However, we point out that one can write a quadratically divergent counter term for Higgs masses localized at the orbifold fixed point. This operator corresponds to a localized tadpole for the 6D gauge theory. See [T03/055] for an introductory review to this approach to EW symmetry breaking.

In [T03/061] we investigate the nature of gauge symmetry breaking via general boundary conditions (BC's). The possible set of BC's includes the commonly considered orbifold BC's but there are more possibilities. For example, it is easy to reduce the rank of the gauge group with more general BC's. The question that such theories raise is whether such a breaking of the gauge symmetries via BC's yields a consistent theory above the gauge boson mass. In order to verify that such a breaking is indeed soft, we have investigated the issue of unitarity of scattering amplitudes. We derived the general expression for the amplitude for elastic scattering of longitudinal gauge bosons and we derived some sum rules, inherited from 5D Ward identities, among the Kaluza–Klein and couplings that ensure the cancelation of all the terms growing with the energy, despite the absence of any scalar exchange. This opened up the possibility to break EW symmetry without a Higgs. We proposed a Higgsless model based on a $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ 5D gauge symmetry on an interval with appropriate BCs to only keep $U(1)_{em}$ unbroken. In [T03/112], we argued, inspired by the AdS/CFT correspondence, that a warping of the background would yield a double advantage: a custodial symmetry protects the correct M_Z/M_W ratio and the warping raises the resonance masses to a realistic level. In [T03/147], we showed that fermion masses can also be easily generated by boundary conditions. Such models show several similarities with technicolor models, in particular large oblique corrections are expected. We carefully computed these oblique corrections in [T04/009] and we showed how most experimental constraints can be alleviated by delocalizing the light fermions in the bulk [T04/170]. The only serious difficulty is to raise the top quark mass without disturbing the coupling of the bottom quark to the gauge bosons and to circumvent it, we proposed [T05/061], in analogy to topcolor models, a scenario with two TeV branes that aims to disentangle the EWSB scale from the top mass scale. The model predicts the presence of new particles that would give rich and very distinctive signals at LHC and future colliders [T04/081] [T04/171] [T04/172].

A few years ago, it was argued that it might be possible to translate many higher dimensional effects into a purely 4D construction by using a set of 4D theories which in the IR reproduce the dynamics of extra dimensional theories. Following this spirit, in [T03/152], we calculated the one-loop corrections to the Kaluza-Klein gauge boson excitations in the deconstructed version of the 5D QED. In particular we calculated the cut-off-dependent non-leading corrections that may be phenomenologically relevant for collider physics. We also discussed the structure of the operators that are relevant for the quantum corrections to the gauge boson masses in 5D and in deconstruction.

Hoping to alleviate dark matter and dark energy problems, there has been a renewed interest in theories of gravitation which deviate from Einstein's gravity at very long distances. In [T03/194] we consider a brane world setup in warped AdS spacetime and we investigate the consequences of writing a mass term for the graviton on an infrared brane where the local cutoff is of order a large (galactic) distance scale. The advantage of this setup is that the low cutoff for physics on the infrared brane does not significantly affect the predictivity of the theory for observers localized on the ultraviolet brane. For such observers the predictions of this theory agree with general relativity at distances smaller than the infrared scale but go over to those of a theory of massive gravity at longer distances. A careful analysis of the graviton two-point function, however, reveals the presence of a ghost in the low energy spectrum corresponding to the radion field. It would be of interest to consider whether there are simple modifications of this theory that could evade this problem.

G.2 Neutrino oscillations, lepton flavour and CP violation (S. Lavignac, C. Savoy, I. Masina)

There is a rich phenomenology of flavour issues for the quark sector where the masses, flavour mixings and CP phases are relatively well-known. The measurement of neutrino oscillations gives definite evidence for lepton flavour violations, actually with almost maximal flavour mixing angles in the neutrino mass matrix. In the charged lepton interactions instead, there are very strong experimental limits on flavour and CP violations. E.g., in electromagnetic interactions, the (neutrinoless) muon to electron transitions are less than 10^{-9}, and the CP violating part of the electron magnetic moment is bounded by 10^{-15} Bohr magneton - both limits are to be improved soon. Actually these phenomena are forbidden to a much higher level in the Standard Model with neutrino masses, and would signal new physics beyond that theory. In particular, in supersymmetric models they are generically expected to be as large as to become a main challenge in the construction of realistic models. These facts motivated research along three main lines.

Firstly it has been shown that data prefer models with a double hierarchy in the neutrino mass eigenvalues [T02/138] using statistical simulations. This backed up a previous analytic analysis.

Secondly a quite model independent re-analysis of the experimental limits on the flavour patterns of scalar lepton masses in supersymmetric theories was performed [T02/159] [T02/130] which completed, generalized and improved the previous ones. The limits on the CP violating lepton electric dipole moment have been translated into limits on the seesaw model and grand-unified theory couplings and scales through the calculation of their radiative corrections in a supersymmetric framework [T03/053] [T03/114].

Finally and by analogy with the quarks, one expects CP violation in the decays of the heavy neutrinos which are plausible candidates to generate lepton excess, hence baryon excess in the early universe. The relations between leptogenesis and CP violation at low energy were analyzed in the minimal seesaw framework searching for the necessary conditions to establish a direct link between these different manifestations of lepton CP violation [T02/144].

The complementarity of these various constraints on flavour models were demonstrated by the case study of the model with one abelian flavour symmetry, which would even be excluded by the expected improvement in the bounds for lepton flavour violation [T05/008]. A short general review was published in the proceedings of Neutrino 04 [T04/215].

Another approach to the fermion mass and mixing hierarchies is based on extra space-time dimensions, and makes use of the localization of fermions belonging to different generations in the extra dimensions. In [T03/059], A hierarchical spectrum is obtained from order one dimensionless parameters of a six-dimensional orbifold model.

G.3 Fermion mass hierarchy and supersymmetric flavour problems (S. Lavignac, C. Savoy, I. Masina)

Horizontal symmetries – symmetries which, contrarily to the gauge symmetries of the Standard Model, act in a different way on fermions belonging to different generations – have been proposed long ago as a possible origin to the fermion mass hierarchy. Since such symmetries also have implications for flavour changing neutral currents (FCNC) and CP violating processes in extensions of the Standard Model, it is useful to have benchmark models available which accurately account for the quark and lepton masses and mixings. This motivated us to reconsider supersymmetric fermion mass models based on a string-inspired anomalous horizontal abelian symmetry, with its anomalies compensated for by the Green-Schwarz mechanism [T05/053]. We have identified the few viable models compatible with simple reasonable assumptions, and fitted the order one parameters left unconstrained by the horizontal symmetry so as to obtain a precise description of the quark and lepton data. We then studied the properties of the corresponding Yukawa couplings relevant for flavour and CP violation in the presence of non-universal masses for the squarks and the sleptons, the supersymmetric scalar partners of the quarks and of the leptons. We found large effects in the kaon sector, especially for CP violation in K^0-$\bar{K}^0$ mixing, due to the large phases generically present in the down-type quark Yukawa couplings, as well as in the B meson sector, for B_s^0-$\bar{B}_s^0$ mixing and $b \to s$ transitions.

Supersymmetric extensions of the Standard Model suffer from a generic flavour and CP problem: the superpartner sector contains new sources of flavour and CP violation (e.g. the phases of the gauge fermion mass terms, or the flavour changing sfermion mass terms) which can give unacceptably large contributions to FCNC and CP violating processes. In particular, heavy meson mixing, most notably in the kaon sector, experimental upper limits on lepton flavour violating decays of charged leptons and on electric dipole moments put strong constraints on the flavour structure and on the phases of the squark and slepton mass terms [T03/160].

G.4 Phenomenology of supersymmetric theories with R-parity violation (M. Chemtob, S. Lavignac)

Supersymmetric extensions of the Standard Model allow for new renormalizable interactions that violate lepton number and baryon number. If all such interactions were simultaneously present in the Lagrangian, they would induce proton decay through the tree-level exchange of a squark at an unacceptable rate. For this reason, it is generally assumed that supersymmetric extensions of the Standard Model respect a discrete symmetry called R-parity, a remnant of a continuous R-symmetry present in supergravity. This symmetry forbids baryon and lepton number violation from renormalizable operators, and thus prevents the proton from decaying through tree-level squark exchange. Another advantage of R-parity is that it ensures the stability of the lightest supersymmetric partner (LSP), hence providing a candidate for the dark matter of the universe. In spite of these virtues, however, it is legitimate to consider the possibility that R-parity be violated by small couplings. In fact, if the combinations of operators leading to proton decay are absent from the Lagrangian, some of these couplings may be relatively large. The violation of R-parity then gives rise to a rich phenomenology, with distinctive signals at colliders such as single superpartner production, new contributions to FCNCs and CP violating processes, the automatic generation of neutrino masses and mixings, and new cosmological scenarios for dark matter and baryogenesis. We wrote a comprehensive review on the phenomenology of supersymmetry with R-parity violation [T04/186].

G.5 Phenomenological constraints on broken R-parity symmetry in supersymmetry models (M. Chemtob)

The existence of an approximate R-parity symmetry would affect in a deep way the conventional supersymmetric models where an exact R-parity symmetry is built-in by assumption. Indeed, the R-parity odd Yukawa interactions of quarks and leptons with the scalar superpartners have the ability to violate the baryon and lepton numbers, change the hadron and lepton flavours and make the lightest supersymmetric particle unstable. We review the direct experimental constraints set by the low and intermediate energy physics processes on the bilinear and trilinear R-parity violating interactions. We also discuss the constraints imposed by the renormalization group scale evolution and the cosmological and astrophysical phenomenology [T04/070].

G.6 Brane cosmology, brane SUSY breaking and string phenomenology (Ph. Brax, N. Chatillon)

The possibility that our universe could be the boundary of a five dimensional space–time has been thoroughly studied in the past few years. The cosmology of the resulting models has been reviewed in [T04/038], [T03/038]. The cosmological constant problem has also been reviewed in [T03/162]. When no matter lives in the bulk of the extra dimension, the model becomes the Randall-Sundrum model with a background corresponding to slice of anti de Sitter space. We have concentrated on models with bulk scalar fields. The high energy regime is modified compared to usual general relativity and can be relevant to inflation, in particular modifying the initial power spectrum . The low energy regime can be analyzed using a moduli approximation [T02/108] [T03/166]. Within this framework, one can study the role of moduli to act as quintessence [T02/121] or generate variations of the fundamental constants [T02/118] [T03/164]. The cosmological evolution of the moduli has also an impact on the CMB anisotropies [T03/165] [T03/167]. When the moduli are not stable, possible strong violations of Newton's law and of the equivalence principle can result. A new mechanism coined "chameleon" can alleviate this problem; the moduli picking a mass dependent on the environment [T04/209] [T04/210] [T04/212] [T05/060]. Finally gravity can be modified due to Gauss-Bonnet terms in the bulk and/or brane induced gravity [T04/174]. The nature of cosmological perturbations in brane worlds is still an open subject. Brane perturbations on a moving branes have been investigated [T02/166].

The nature of the mechanism leading to the acceleration of the universe is still a mystery. One proposal is that the acceleration is due to a scalar field, quintessence, rolling along a runaway potential. Supergravity models of quintessence have been investigated [T02/146]. The coupling of quintessence to F-term inflation in supergravity has also been studied [T05/059] [T03/025].

Inflation is a paradigm with no fundamental description yet. One tantalising possibility is that inflation results from the accelerated motion of a brane. We have studied such a model when BPS brane move inside a 10d non-supersymmetric background [T02/048]. The same type of configuration can lead to bouncing branes [T02/094]. It is also particularly difficult to obtain accelerating configurations in supergravity. Some accelerating configurations in half–maximal supergravity were constructed in [T04/192]. Finally, inflation in supergravity after compactification from 10d suffers from the moduli stability problem and the flatness problem of the potential. Combining the KKLT stabilisation of moduli and chaotic inflation leads to models alleviating these problems [T05/110].

The building of concrete models of supergravity combining the warping of extra–dimensions and the stabilisation of moduli is one of our main goals. We have studied susy breaking due to tilted brane [T03/133] and moving brane [T02/089] [T03/039] configurations. From the 4d point of view, the soft breaking terms of brane configurations with bulk scalar fields have been computed [T04/065]. The low energy action depends on moduli fields whose geometry depends on a Kahler potential that we have described for an arbitrary number of moduli [T04/104].

Non-supersymmetric field theories suffer from quadratic divergences. We have analyzed the quiver models of string theory and shown that they do not have quadratic divergences. The link with deconstructed models has been studied too [T02/010] [T02/117]. The strong coupling regime of deconstruction has been analyzed using the AdS/CFT correspondence [T03/027]. Non-supersymmetric string theories have tachyonic instabilities. This is also the case of non-BPS branes. We have studied the kinks of non-BPS branes and their stability [T03/069] [T03/168].

G.7 Dark matter (G. Servant)

Given the abundance of experimental activity related to dark matter detection, it is timely to study the distinctive signatures expected in different dark matter scenarios. Such signatures and event rates can vary substantially from one WIMP (Weakly Interacting Massive Particle) model to another. The most studied candidate so far is the Lightest Supersymmetric Particle (LSP) in models of R-parity conserving supersymmetry. Some alternatives to neutralinos and other LSPs do exist, however. Lately, we proposed and explored the possibility of Kaluza–Klein dark matter. While the idea that dark matter could be made of Kaluza–Klein (KK) particles is very tempting, it turns out that in most extra-dimensional models, there are no stable KK states, all being able to decay to SM particles. An exception is the class of models in Universal Extra Dimensions (UED). In this case, all standard model (SM) fields propagate in flat toroidal extra dimensions. Translation invariance along an extra dimension is only broken by the orbifold imposed to recover a chiral SM spectrum. Still, there is a remnant discrete symmetry called KK parity, $(-1)^n$, where n is the KK number. This symmetry insures that interaction vertices cannot involve an odd number of odd-KK states and, therefore, a vertex with two SM particles (with $n = 0$) and one KK state (with $n = 1$) is forbidden. As a result, the Lightest KK Particle (LKP) with $n = 1$ cannot decay into SM particles and is stable. For $\sim\text{TeV}^{-1}$ sized extra dimensions, the LKP can act as a WIMP. Relic density [T03/244], direct [T02/231] and indirect detection [T03/243] [T05/102] studies of this candidate have been carried out. Constraints on these models from radion cosmology have also been studied [T03/241].

The second example of KK dark matter arises in the context of warped geometries and more specifically in the context of warped Grand Unified Theories (GUTs) [T04/119] [T04/139]. To locate these constructions in the landscape of extra dimensional models, recall that the interest in the phenomenology of extra dimensions over the last few years has been motivated by the goal of understanding the weak scale. The only extra-dimensional geometry which really addresses the hierarchy problem is the Randall-Sundrum geometry. Particle physics model building in this framework has been flourishing and a preferred class of models has emerged where all SM fields propagate in the bulk of AdS_5, except for the Higgs (or alternative physics responsible for electroweak symmetry breaking) which is localized on the IR brane. In addition, the electroweak gauge group should be extended to $SU(2)_L \times SU(2)_R \times U(1)$. Those models were embedded into a GUT in [T04/119] [T04/139] and it is in this context that a viable dark matter appears.

In these models, a stable KK fermion can arise as a consequence of imposing proton stability in a way very reminiscent to R-parity stabilizing the LSP in supersymmetric models. The symmetry is called Z_3 and is a linear combination of baryon number and $SU(3)$ color. It actually exists in the SM but SM particles are not charged under it since only colored particles carry baryon number in the SM. In [T04/119] [T04/139], and more generally in higher dimensional GUTs, baryon number can be assigned in such a way that there exists exotic KK states with the gauge quantum numbers of a lepton and which carry baryon number as well as KK quarks which carry non-standard baryon number. These particles carry a non-zero Z_3 charge. The lightest of these, called the Lightest Z_3 Particle (LZP), is stable since it cannot decay into SM particles. The prospects for the indirect detection of this candidate and more generally of right-handed neutrino dark matter have been investigated in [T05/019].

G.8 Baryogenesis (C. Grojean, G. Servant)

There are two distinct favorite models to explain the matter-antimatter asymmetry of the universe: Electroweak baryogenesis and Leptogenesis. Electroweak baryogenesis is a sophisticated mechanism taking place during a first-order electroweak phase transition (EWPT) when the temperature of the universe is of order 100 GeV. It only involves electroweak physics and therefore has the advantage of being testable at colliders such as the LHC. In the Standard Model, the EWPT is of second order and EW baryogenesis cannot take place. However, extensions of the SM can lead to a 1rst order EWPT [T02/232]. Successful EW baryogenesis requires that the Higgs vev, v, at the time of the transition, be larger than the temperature T. The ratio v/T characterizes the *strength* of the transition. Whether the EWPT was first or second order only depends on the precise nature of the Higgs potential, something which we still have not tested experimentally. Thus, EW baryogenesis is crucially tied to the Higgs sector that we expect to disentangle at the LHC. In [T04/084], we used an effective field theory approach to study the EWPT and parametrized the new physics in terms of higher dimensional nonrenormalizable operators in the Higgs potential. We showed that these models, combining a negative quartic coupling for the Higgs and a restoration of stability by order six operators, can lead to a strongly first order phase transition even for large Higgs masses, provided that the scale of new physics is at a TeV. These operators can be generated for example by integrating out a heavy TeV mass singlet scalar field. Interesting physical effects can occur during a very strong first order phase transition, such as the production of gravitational waves which could be observed in the next generation of space interferometers.

CHAPTER H

Strong Interactions

Contents

Looking both to the variety of topics and the number and experience of physicists involved, Physics of the Strong Interactions (SI) is a major subject of research in the SPhT, with a large recognition of the international community. From nuclear states and reactions, the study of hadrons and hadronic matter in various environments, lattice QCD calculations, to the analysis of heavy ion collisions, the behaviour of Quantum Chromodynamics (QCD) in the limits of high density and/or high energy, we have a quasi complete (except perhaps B physics) and modern panorama of Strong Interaction phenomena, models and theory.

The connection with experiments, through phenomenology, is another typical aspect of the domain, where numerous experimental results exist or are expected in the near future. Hence the physicists are working in tight connection with experimentalists working at particle accelerators like GANIL (Caen), RHIC (Brookhaven), HERA (Hamburg), the Tevatron (Batavia) and preparing for the LHC (Geneva). Collaborations with experimentalists from many laboratories including those of DAPNIA/CEA are acknowledged.

In the physics of nuclei and hadronic states, the characteristic features of the studies are the long-term commitment to basic studies by known experts in those fields. The structure of nuclear states has been studied with precision by various methods beyond the mean-field approximation and using a microscopic description of the elementary interactions. Various interesting phenomena appearing at the transition scales between nuclear and hadronic problems have been thoroughly investigated, such as the relevance of hadronic degrees of freedom in the study of matter at high density and high temperature. This may happen at accelerators (RHIC) or in astrophysical conditions.

On a microscopic level, the goal of deriving the properties of hadrons from the confinement properties of quarks and gluons has been a major concern. It has been attacked from the point of view of a "dual" (magnetic) superconductor. Also, understanding confinement starting from the QCD lagrangean motivates lattice calculations. In this spirit, one important development concerns the methods of describing chiral fermions on the lattice avoiding the Nielsen–Ninomiya no-go theorem. QCD at finite temperature and in 3 dimensions has been used as an interesting laboratory for confinement-deconfinement transition in these conditions. At the perturbative (weak coupling) level, self-consistent resummations at finite temperature have been proposed in order to solve the face renormalisation problems. New techniques have been successfully applied to a scalar field theory and in progress for QCD.

An important recent development of SI studies is the extension of perturbative QCD calculations at high density and/or high energy. These kinematical regimes are topical for both experimental and theoretical reasons. New accelerators are extending by far the experimental frontiers in density and energy. For instance the RHIC accelerator allows for the formation of high density states of gluons and quarks while the Tevatron and soon the LHC push forward the limits of high energy. Theoretically, the high-density/high-energy regime opens the way to new and still unsolved problems. Moreover the perturbative/non perturbative interface remains largely unknown.

Heavy-ion reactions, with a very high number of particles produced by event, require new ways of analyzing data. The study of the collective flow of particles, in particular the so-called "elliptic flow" initiated in the SPhT, appears to be one of the main observables for identifying new phases of QCD, such as the quark-gluon plasma and the "color glass condensate". Predictions, in particular for lepton and jet production in such a medium, have been elaborated in order to use them as probes of these new states of matter.

Among the various theoretical results on the high-density/high-energy domain of QCD, it is interesting to mention a domain which makes a link between QCD, particle physics and statistical nonlinear physics, recently emerging from studies for a large part initiated at SPhT. Starting with the derivation of a hierarchy of (JIMWLK) equations, it was remarked that, in the mean-field approximation, the structure of the equation was similar to the paradigmatic "F-KPP" equation of statistical nonlinear physics. Then, this result was enlarged to the whole hierarchy and even beyond, opening the possibility of a quite complete solution of QCD equations in this limit.

In the search for the Higgs boson and new particles or dynamics (Supersymmetry, extra-dimensions, ...) at the LHC, it will be of primary importance to analyse as precisely as possible the "hard" QCD mechanisms of production together with their possible QCD backgrounds. For this sake, the computation of perturbative QCD amplitudes has been developed towards higher number of involved quarks and gluons including their helicity structure and towards the inclusion of one-loop and now two-loop calculations. As a theoretically stimulating extension of these technics, one finds striking simplifications the $\mathcal{N} = 4$ supersymmetric Yang-Mills theory which reveals a possible deep connection to its relation ("duality" properties) with String Theory.

Another aspect of Higgs boson and new particle search is the proposal of a non standard QCD production mode via "hard Diffraction". Due to its interest for its potentially clean signal-over-background ratio it is being studied as a possible complementary process to the standard production. The evaluation of its cross-sections and Monte-Carlo simulations are being developed in cooperation with experimentalists concretely working on appropriate detectors in operation at the Tevatron and foreseen at the LHC.

String Theory is a major theoretical challenge of present times. Interestingly enough, recently, some well-defined properties connecting QCD to strings have been found, via "duality" properties. For instance, it has been recognized that some gauge field theories at strong coupling are dual to superstrings moving in a specific gravitational background. The corresponding AdS/CFT correspondence has been used in studies of the formulation and derivation of high energy amplitudes at strong gauge coupling, which are not reachable by lattice calculations.

Very recently, it was recognized that perturbative multi-leg amplitudes at tree and one-loop levels for the $\mathcal{N} = 4$ theory can be related to string theory using the twistor formalism. Striking simplification and regularities of otherwise complicated multi-leg amplitudes are then obtained and give a new insight on a deep connection between QCD in the perturbative regime and string theory. This field is developing rapidly, and the SPhT is present with fruitful collaborations abroad.

This rapid survey of activities in the field of strong interactions confirms the diversity and large covering of problems investigated in the SPhT. One may discern some broad features of the future activity, taking into account factors like the rapid evolution of the domain in the experimental perspective (e.g. the LHC) and the theoretical context (e.g. the connections with statistical physics and with string theory). It is clear that the SPhT teams are and will be involved in the most recent developments. A concern could be the "savoir-faire" accumulated in nuclear and hadonic physics which could be lost due to the retirement of senior physicists in this domain.

The group of physicists dealing with SI is composed of 11 permanents (among which 9 from the " group B") and had 5 post-docs during the 3 years. Together with the research activity, the SI physics have been a lively domain for the training of students and the formation of young theorists. 4 PhD theses have been completed during the last 3 years. It is interesting to note that 2 of the 4 PhD students and 1 post-doc have found a permanent position after their stay in Saclay.

H.1 Nuclear and hadronic matter

H.1.1 Neutron deficient lead isotopes (P. Bonche, T. Duguet)

Shape coexistence has been recently observed in the most neutron-deficient lead isotopes. We have studied (with M. Bender, P.-H. Heenen) $^{182-194}$Pb by performing, for the first time in such heavy systems, a configuration mixing along the quadrupole degree of freedom of *angular momentum* and *particle number* projected self-consistent mean-field states [T03/057] [T03/229] [T03/227]. In agreement with earlier studies, the spectra are explained in terms of coexisting spherical, oblate, prolate and super-deformed prolate structures. These results are obtained from a purely quantum mechanical method including kinematic and dynamical correlations beyond the mean-field, and with effective interactions as the only phenomenological ingredient, therefore supported the shape-coexistence picture. Also, the evolution of Pb isotopes spectra with neutron number was qualitatively well reproduced. Finally, deficiencies of existing effective forces associated with single-particle spectra were pointed out.

H.1.2 Transfermium isotopes (P. Bonche, T. Duguet)

Recent experimental results for transfermium isotopes brought data in a region close to the domain of super-heavy nuclei, a region where little is known concerning single-particle spectra and of pairing correlations.

To test our model in this extreme case, we performed (with M. Bender, P.-H. Heenen) extensive calculations in the Nobelium region [T03/110]. Predicted quasi-particle spectra are compared with experiment for the heaviest known odd N and odd Z nuclei. Spectra and rotational bands were presented for nuclei around ^{252,4}No for which experiments are either planned or already running. An interesting finding was the sensitivity of the calculated spectra of odd nuclides to the precise location of individual orbitals. In these very heavy nuclei, the density of levels is higher than for lower masses, and small modifications of the spin-orbit strength could result in significant changes in excitation spectra.

H.1.3 Many-body methods (T. Duguet, P. Bonche)

Effective interactions for configuration mixing calculations. Phenomenological effective interactions presently used have been constructed in the mean field framework. In an attempt to include effects byeond that level, an Extended Goldstone-Brueckner Many-Body Perturbation Theory was proposed [T02/139]. Such a perturbative framework allowed the derivation of an effective interaction appropriate to dealing with large amplitude collective motions. This generalized in-medium G-matrix is far too complicated to be used in quantitative calculations of finite nuclei. Thus, its in-medium content was simplified and a generalized form of the Skyrme force for configuration mixing calculations was derived [T02/141] [T02/140]. Testing the new form of interaction is planned for the near future.

Microscopic treatment of pairing correlations in self-consistent mean-field methods. Furthermore, existing phenomenological pairing forces lack a link to the bare nucleon-nucleon interaction. tough they are quite successful in describing low-energy nuclear structure over the (known) mass table. This feature strongly limits the liability of their analytical structure such as their possible density dependence. To improve on that situation, a microscopic effective interaction, explicitly linked and equivalent to the bare force, was proposed to account for pairing correlations in the $^1S_0$ channel [nucl-th/0311065]. It is finite-ranged, nonlocal, total-momentum dependent and density dependent, whereas a natural cut-off naturally emerged through the recast of the gap equation. Such a cut-off makes a zero-range approximation of the effective vertex meaningful. Although finite-ranged and nonlocal, the proposed interaction makes 3D Hartree-Fock-Bogolyubov (HFB) calculations of finite nuclei in coordinate space tractable. Among other features, the isoscalar and isovector density-dependences derived *ab initio* provide the new effective pairing force with a strong predictive power. Differences with existing phenomenological interactions regarding predictions of pairing properties of nuclei close to the drip-line have already been highlighted [T04/143].

Other works in the field of nuclear structure involve a microscopic study of the plutonium isotope ^{240}Pu [T04/140] and a new microscopic determination of the nuclear incompressibility [T04/142].

H.1.4 Collision theory (B. Giraud)

Nuclear theory gives rise to interesting mathematical problems. For instance [T02/106] [T04/134], complete bases of nuclear states have been found to include resonances despite the a priori infinite norms of such states. New families of orthogonal polynomials [T04/075] [T05/001], have been discovered and can be used for the description of nuclear, and atomic and molecular as well, densities [T05/071].

Progress in mean field approximations for the theory of collisions has also been obtained [T02/148]. Fusion processes that might lead to the synthesis of superheavy elements have been studied [T02/233]. Finally a surprising result has been obtained [T04/072]: nuclear friction may stimulate the tunneling effect rather than inhibate it as one might have believed intuitively.

H.1.5 Hadronic matter under extreme conditions (M. Rho)

A unified approach to addressing hadronic matter at high density and high temperature that can treat on the same footing both single-nucleon and many-nucleon properties has been developed [T03/015] [T03/224] [T04/149] in terms of the skyrmion picture. This development is significant in view of the recent re-derivation of the skyrmion description from holographic dual QCD in string theory. In this formalism, BR (Brown-Rho) scaling [T03/047], pion velocity [T03/095], the role of vector mesons [T03/218] and the structure of the pentaquark Θ^+ [T04/068] [T04/196] [T05/032] have been studied. A hidden local symmetry theory implied by the holographic dual QCD has been shown by Harada and Yamawaki to have the "vector manifestation" fixed point at chiral restoration phase transition. This has been verified in dense and/or hot medium [T02/194] [T02/226] [T03/034] and has been exploited for predicting the pion velocity $v_\pi \simeq 1$ [T03/120] which while disagreeing drastically with the sigma model prediction $v_\pi = 0$ at the critical temperature, is supported by the recent STAR data on HBT pion interferometry. The 1993 prediction of Nowak, Rho and Zahed for the chiral doubler splitting (revisited in [T03/109]), confirmed experimentally in 2003 by the BaBar and CLEOII collaborations, was reformulated starting from the vector manifestation fixed point in hidden local symmetry theory [T03/220] [T03/223].

H.1.6 Effective field theories of nuclear systems (M. Rho)

A "more effective effective field theory" (MEEFT) that combines SNPA, the highly sophisticated 'standard' nuclear physics approach and chiral perturbation theory is formulated and used to accurately compute the *hep* process which is the source for the highest energy neutrinos from the Sun [T02/102] [T02/191]. This result is being quoted in the literature as *the* standard *hep* value in the solar neutrino problem. The MEEFT has also been extended – via BR scaling – to nuclear many-body systems connecting chiral Lagrangian mean field theory to Landau-Migdal Fermi liquid theory [T03/073].

H.1.7 New states of astrophysical matter (M. Rho)

The strongly coupled hadronic matter discovered slightly above T_c, the chiral restoration temperature at RHIC (which is conjectured to be present $\sim 10^{-6}$ s after the Big Bang), is described as a perfect liquid state made up of nearly massless color singlet mesons of the quantum numbers of π, σ, ρ and a_1 [T03/116] [T03/219] [T03/225] [T04/066] [T04/089] [T04/150]. This appears to be a new state drastically different from what was formerly believed to be a weakly interacting quark-gluon plasma.
The highly compact $S^0(3115)$, tri-baryon strangeness nugget recently discovered at KEK, is related to a unit cluster of kaon condensed neutron star matter and is argued to provide a further support to the Bethe-Brown maximum stable neutron star mass $M_{max} \sim 1.5 M_\odot$ [T05/056].

H.1.8 Quark confinement (G. Ripka)

The confinement of quarks has been modeled assuming that the physical vacuum is a dual superconductor, caused by the condensation of color magnetic charges. This model has met some confirmation by lattice calculations but remains so far incomplete. It can only be realized in a particular choice of gauge and one is only able to compute the potential between two static quarks. This subject has been treated in a series of lectures published by Springer-Verlag [T03/150].
I have also studied the formation of diquarks inside a nucleon. Following certain models, where the physical vacuum is represented in terms of instantons, the three valence quarks of a nucleon are predicted to possess a strong diquark correlation while other models, such as the chiral soliton, has only a weak correlation [T04/220].

H.1.9 Mesons on the light front (K. Itakura)

The properties of light mesons in the scalar, pseudoscalar, [T04/096] and vector channels [T03/115]. have been computed by using the Nambu-Jona-Lasinio model with vector interaction in the large N_c limit, in the light-front quantization.

H.1.10 Chiral fermions on the lattice (R. Lacaze)

Over the recent years, substantial progress has been achieved in the longstanding problem of constructing a formulation of chiral fermions on the lattice. With the overlap formulation of fermions, the Dirac operator satisfy the Ginsparg-Wilson relation, which defines the anticommutation with γ_5, so that the physical properties related to chirality are represented correctly. The overlap Dirac operator (D) can be defined in terms of $(D_w^\dagger D_w)^{-1/2}$ where D_w is the usual Wilson-Dirac operator. From the Ginsparg-Wilson relation and the γ_5 hermiticity, the overlap Dirac operator satisfies many interesting properties. It is clear that it is non local (escaping to the Nielsen-Ninomiya No-Go theorem) and difficult to compute. We have compared the different methods used to explicitly compute this operator for various quenched configurations, comparing not only the error on the square root but also on the various properties of D. When adaptability is included, the Zolotarev rational approximation appears to be the most efficient method [T02/091].

H.1.11 Finite temperature in QCD_3 (A. Morel)

As compared to QCD in 4D (QCD_4), QCD_3 is simpler in the ultraviolet regime (it is super-renormalizable), while its infrared singularities are more severe, which makes it an interesting laboratory to study long distance properties in non abelian gauge theories. Lattice regularization allows for this exploration, a technically simpler task in one dimension less. Perturbative dimensional reduction then leads to a 2D gauge model for a Higgs field in the adjoint representation, a model which accounts successfully for the low energy spectrum of QCD_3 at high enough temperature (SPhT-report 2000-2002). This latter limitation arises because the Higgs potential is computed perturbatively for small Higgs fields, that is for finite Polyakov loops. Only the broken (deconfined) phase for the Z_3 symmetry of the original model can thus be reached. A Z_3 symmetric lattice gauge model for the Polyakov loops in 2D has been built and studied, both numerically and analytically to one loop in the gauge fields [T03/232] [T04/043] [T04/044] [T04/045]. The phase diagram in the plane of two free parameters describing an undetermined Polyakov loop potential is shown to contain a deconfinement-confinement transition line as the temperature of the original 3D model is lowered. A new Z_3 breaking phase is found where the Polyakov loops have unusual arguments of the form $(2n+1)\,\pi/3$, a fact to be investigated further. The correlation length for the 3D model in the deconfined phase is however recovered inside the expected domain where the arguments have standard values $2n\,\pi/3$.

H.2 Heavy ion collisions

H.2.1 Anisotropic flow and Lee-Yang zeroes (N. Borghini, P.M. Dinh, J.-Y. Ollitrault)

The azimuthal angle of particles emitted in a heavy-ion collision is generally correlated to the azimuthal angle of the impact parameter, or 'reaction plane'. This phenomenon, called 'anisotropic flow', plays a central role at the highest energies presently available, at the RHIC collider in Brookhaven: the reason is that one particular type of anisotropic flow, 'elliptic flow', has been found to be large at RHIC, and this is considered a crucial piece of evidence for the production of quark-gluon plasma.

In recent years, we have developed improved methods to measure anisotropic flow experimentally. This is a non-trivial issue since the direction of impact parameter is not known experimentally, and the only observables are correlations between detected particles. Traditional methods, based on two-particle correlations, are not accurate enough at ultrarelativistic energies. New methods were developed at SPhT during the period 2000-2002 based on multiparticle cumulants [T02/104]. This motivated a new analysis of SPS data by the NA49 Collaboration, in which we participated [T02/105] [T02/227] [T03/050]. Mai Dinh, a PhD student at SPhT, was awarded the Daniel-Guinier prize of the French Physical Society (SFP) in 2002, and by the 'Prix de thèse de l'Ecole polytechnique' in 2003 for this work [T02/073].

Correlations from global momentum conservation are a parasitic effect in analyses of anisotropic flow. Their contribution to cumulants of arbitrary order was explicitly calculated in [T03/017]. Our cumulant methods have been implemented by the STAR and PHENIX collaborations at RHIC. They allowed the discovery of 'directed flow' at RHIC (nucl-ex/0310029).

This led us to further improvements, and we devised a new method of flow analysis which is both more elegant and more accurate than previous ones. It bears a close resemblance to the Lee-Yang theory of phase transitions [T03/097] [T03/098] [T04/017] [T04/056]. It was successfully applied to data taken at the SIS accelerator in Darmstadt by the FOPI Collaboration [T05/043].

One of the recent progress at RHIC is that experimentalists are now able to measure not only the azimuthal dependence of single-particle production, but also the azimuthal dependence of two-particle correlations. This is of interest in studies of jet quenching (energy loss) in a quark-gluon plasma. We have introduced new observables to quantify the azimuthal dependence of two-particle correlations [T04/099], and explained how they can be measured experimentally.

H.2.2 Phenomenology of heavy-ion reactions (J.-P. Blaizot, F. Gélis)

The quark-gluon plasma. Photons or leptons pairs are a potential signature of a quark-gluon plasma, especially at early stages of heavy ion collisions, where the temperature is the highest. It has been known for some time that in order to calculate fully their production rate at leading order, one must resum all the terms corresponding to multiple scatterings of the emitter in the plasma. This resummation can be formulated as an integral equation. In collaboration with P. Aurenche, G. Moore and H. Zaraket [T02/195] [T02/196] [T02/150], we have developed a new method in order to solve this integral equation numerically, which is both faster and more accurate than previously considered methods (in particular, our method is guaranteed to converge towards the exact solution, contrary to a variational Ansatz).

The color glass condensate. The physics of parton saturation is expected to be relevant in heavy ion collisions (HIC). Indeed, even though the longitudinal momentum fraction x probed in HIC at present energies may not be as small as in Deep Inelastic Scattering, the parton distributions are enhanced by the size of the nuclei. The cleanest situation in order to probe saturation physics is in fact provided by asymmetrical collisions, like proton-nucleus collisions.

With J. Jalilian-Marian, we have studied how photon and dilepton emission is affected by saturation effects in the nucleus [T02/192] [T02/193]. We have also shown that there is a correspondence between deep inelastic scattering and proton-nucleus collisions [T02/167]: both processes can be expressed in terms of a more fundamental object, the so called 'dipole cross-section'.

We have studied more systematically, with J.-P. Blaizotand R. Venugopalan [T03/151] [T04/023] [T04/024], the problem of proton-nucleus collisions in the color glass condensate framework, including an explicit solution of the classical Yang-Mills equations, the cross-section for gluon production, and the cross-section for the production of quark pairs. It became clear that $k_\perp$-factorization is invalid for the production of quark pairs in proton-nucleus collisions; one cannot express the cross-section for this process in terms of a single "distribution function" that would describe the gluon content of the nucleus. With H. Fujii [T05/042], we have investigated this problem numerically in order to assess more quantitatively the magnitude of the breaking of $k_\perp$-factorization.

The analytic method we have used in order to solve the case of proton-nucleus collisions cannot be generalized to nucleus-nucleus collisions. With T. Lappi and K. Kajantie [T04/111], we have reformulated the problem of the production of quark pairs in such collisions in a way which is more appropriate for a computer simulation. Our formulation amounts to solving the Dirac equation with retarded boundary conditions, in the presence of a known color background field. Our method has been tested on a simple toy model (1+1 dimensions), and is now being implemented to a more realistic situation.

H.2.3 Resummations in finite–temperature field theory (J.-P. Blaizot, E. Iancu, U. Reinosa)

The physical degrees of freedom of a high–temperature plasma (so like the quark–gluon plasma of QCD) are *quasiparticles*, i.e, dressed excitations which acquire thermal masses via their interactions with the thermal bath. These thermal masses screen the long–range interactions in the plasma, and thus cannot be expanded out in perturbation theory (not even for a weak coupling) without generating infrared divergences. In some previous work, we have shown that a systematic and also efficient way to include the effects of the thermal masses is via *self—consistent resummations* of the perturbation theory. This is however a non–perturbative method, so in general it is afflicted with *ultraviolet divergences*, which are not eliminated by the standard renormalization techniques (as adapted to perturbation theory). We have nevertheless demonstrated the renormalizability of the self—consistent resummation scheme for the case of a scalar field theory with quartic interactions [T03/007] [T03/187]. In doing so, we have established a new method [T04/073] to isolate vacuum amplitudes in Feynman diagrams calculated at finite temperature in the imaginary time formalism. This method exploits a formula derived long ago by Gaudin The generalization of our construction to a gauge theory like QCD remains an important open problem. Also, We have proposed a new strategy for resumming the thermal masses in QCD at high temperature, based on an effective three–dimensional theory (with A. Rebhan, [T03/024]). The loop expansion within the effective theory is rapidly converging (unlike the corresponding expansion in the original theory in four dimensions), and the ensuing results agree rather well with the respective lattice results.

The $1/N$ corrections to the thermodynamic potential in the Gross-Neveu model at finite temperature has been studied [T02/178].

H.3 QCD at high energy/density

H.3.1 Saturation and the Color Glass Condensate (E. Iancu, K. Itakura, D. Triantafyllopoulos)

In a series of previous publications, we have constructed an effective theory for the Color Glass Condensate (CGC) based on a renormalization group analysis in which gluons are 'integrated out' in layers of x. The central result of this analysis is a functional evolution equation — the 'JIMWLK equation' — which shows how the gluon correlations evolve with increasing energy (or decreasing x). This equation predicts the *saturation* of the gluon density, a phenomenon with important conceptual and phenomenological consequences that we have further explored in more recent publications.

On the conceptual side, gluon saturation implies the unitarization of scattering in QCD at high energy. The scattering amplitudes computed in the CGC effective theory respect the 'black disk' limit [T02/181] [T03/124]. Moreover, when saturation is combined with a reasonable assumption about confinement, one finds that the total cross sections obey the Froissart bound [T02/074]. On the phenomenological side, the phenomenon of *geometric scaling*, that we had previously interpreted as a consequence of quantum evolution in the presence of saturation, appears to be consistent with the deep inelastic scattering data at HERA (for $x < 0.01$) [T03/156] and also with the data for particle production in deuterium–gold collisions at RHIC (Brookhaven) [T04/028].

H.3.2 From high–energy QCD to statistical physics (E. Iancu, K. Itakura, D. Triantafyllopoulos)

Returning to conceptual issues, it turns out that the low energy/density limit of the CGC effective theory is also interesting: In this limit, the theory reduces to, and sheds new light on, previous formalisms based on the BFKL evolution, notably, Al Mueller's 'color dipole picture' [T03/124] and the BKP equation describing 'odderon' exchanges [T05/010]. But the recent studies of the low density regime have also revealed some *limitations* of the original formulation of the CGC theory [T03/138] [T04/147], which, once properly understood, have triggered interesting new developments leading to substantial progress.

It has been thus discovered that the high energy evolution in QCD is a *classical stochastic process* which lies in the same universality class — in the sense of having the same asymptotic behaviour at large 'evolution time' (in QCD, the relevant 'time' is the rapidity $\ln 1/x$) and for large occupation numbers — as the *reaction–diffusion process* in statistical physics (which is itself the prototype of a large variety of problems in physics, chemistry, biology, or the theory of information). The QCD processes of gluon radiation and recombination correspond to the dynamics of a one–dimensional gas of molecules subjected to diffusion, splitting ($A \to A+A$) and recombination ($A+A \to A$). The recombination process is important in the high density regime where it leads to saturation. The splitting process is essential in the dilute regime where it induces gluon number fluctuations which act as a seed for higher–point correlations. Using the universal properties of the reaction–diffusion problem, as recently understood by our colleagues in statistical physics, we have been able to deduce exact results about the asympotic behaviour of the scattering amplitudes in QCD [T04/124].

While both fluctuations and saturation are crucial for a correct description of the leading behaviour at high energy, it turns out that the JIMWLK equation does not properly include the effects of the gluon number fluctuations [T04/147]. Inspired by similar methods in statistical physics, we have developed the CGC formalism in order to allow for gluon splitting and particle number fluctuations [T04/147] [T05/012] [T05/031] [T05/057]. The most complete effective theory for QCD evolution at high energy and to lowest order in (resummed) perturbation theory has been recently constructed in [T05/057]. We have subsequently checked that, in the limit where the number of colors is large, the general effective theory is consistent with Mueller's dipole picture, as it should [T05/089]. Further consequences of the effective theory are being actively investigated.

H.3.3 Hunting new particles via diffraction (R. Peschanski)

The Higgs Boson(s) is the missing key for the unification of fundamental interactions and the origin of the mass of particles. New physics at the LHC will also be searched through the opening of new particle thresholds. Among the production modes, the hard diffractive production in the central region of detectors has the interest to provide a good signal/background ratio, even for smaller cross-sections. Initiated in 20001 by a fruitful collaboration with C.Royon and M.Boonekamp from DAPNIA, this search developed in a series of studies, with many collaborators [T03/066] [T05/095]. Higgs boson search [T02/063] [T03/011] [T04/071] and the WW pair (via QED) and $t\bar{t}$ pair (via QCD) diffractive production have been studied in detail [T05/063]. Interestingly, this approach (for which the Saclay group is one of the two recognized experts) is now used for designing dedicated experimental studies and detectors at the LHC. For this sake, it is of primary importance to evaluate precisely diffractive cross-sections and test the models at the Tevatron and LHC [T03/082] [T04/106].

H.3.4 Hard Diffraction studies (C. Marquet, R. Peschanski)

'Hard Diffraction' or Hard Pomeron exchange can be studied either in elastic or inelastic reactions with vacuum quantum numbers exchange, provided it is initiated by a hard probe [T05/020]. Elastic γ^*-proton scattering related to the proton structure function at small Bjorken x allows, using a new method for this sake, a phenomenological test [T03/031] [T03/188] [T04/160] of the QCD evolution kernel in energy at next-leading-log level in x, which is an actual theoretical challenge. Inelastic hard diffraction, unexpectedly discovered at HERA, gives a precious information on the exchange mechanism, the hard Pomeron [T02/131]. Diffractive forward jet production appears to furnish fruitful observables on diffraction mechanisms (C. Marquet [T04/162] [T05/004], C. Marquet with K. Golec-Biernat [T05/064]), in particular for the so-called 'saturation' phenomenon.

H.3.5 QCD, Saturation and nonlinear physics (R. Enberg, C. Marquet, R. Peschanski, G. Soyez)

Saturation studies aim at understanding in fundamental terms, i.e. in relation with QCD, the overlap of gluon fields when their density grows, in particular with the energy of the hard scattering.

In a series of papers with S. Munier (Ecole polytechnique) [T03/137] [T03/158] [T04/011], inspired by previous studies on intermittency in particle production (A. Bialas, R. P., [T88/032]), we have found a deep connection between QCD saturation equations and archetypal nonlinear equations of Fisher-Kolmogorov-Petrovsky-Piscounov universality class. This discovery is at the basis of new approaches to the saturation problems in QCD. Among our subsequent contributions are [T04/094] [T05/021] [T05/024] [T05/049] [T05/030], with the extension of saturation properties, i.e. the so-called 'geometric scaling' to diffractive scattering at non-zero transfer.

The theory and phenomenology of saturation is in full development, represented in our works by the theoretical implementation of correlations (with R. Janik, Cracow, [T04/088]), the analysis of saturation signals at colliders (C. Marquet, R.P. [T03/205] and with C. Royon [T04/087], C. Marquet [T04/076]), the derivation and simulation of the QCD equation in full momentum space (C. Marquet, G. Soyez, [T05/048]), the analysis of fluctuations in QCD dipole splitting (R. Enberg, R.P. [T05/024]). The first available simulation of a stochastic version of the QCD equation including fluctuations (G. Soyez, [T05/098]) has shown that, even if fluctuations induce geometric scaling violations at high energy, there might be a region in the early stages of the evolution where it remains valid. Very recently a new and promising Projectile-Target duality property of the Color Glass Condensate in the dipole picture has been discussed in detail (C. Marquet, with A.H. Mueller, A.I. Shoshi and S.M.H. Wong, [T05/100]).

The saturation equations have also inspired a new mathematical approach to the problem of joint positivity conditions for a function and its Fourier transform in 1 or 2 dimensions (with B. Giraud, [T05/040]).

H.3.6 QCD and AdS/CFT string theory (R. Peschanski)

In the recent years, with R. Janik, Cracow U., we have initiated a program of investigations establishing the link, using correlators of Wilson lines and loops, between the string formalism in AdS space and the high-energy scattering amplitudes in gauge theories, following the so-called AdS/CFT correspondence. This long term program is going on [T02/122] [T03/018]. It has found interesting consequences on an extension of the Lund string model at non-zero impact-parameter [T03/084], and on an application to the AdS/CFT dual of deconstruction (with Ph. Brax, [T03/027]).

H.4 Hard processes in QCD

H.4.1 "Antenna" function in perturbative QCD (D. Kosower)

In constructing numerical NNLO programs, one needs not only the infrared-divergent virtual contributions, but also the corresponding mixed real-virtual and real-emission divergences, in a process-independent form. At NNLO, the latter include both one-loop contributions with one emission, and tree contributions with two emissions. One needs the factorization of the latter, in particular, as two partons independently approach infrared-singular limits (soft or collinear). These various limits were extracted and classified by Campbell and Glover, and by Catani and Grazzini, several years ago. One might proceed by integrating these separately over the corresponding regions of phase space where the singularities arise. At NNLO, however, there are numerous subregions with rather complicated boundaries. It is therefore a much better idea to try to combine these limits, analogous to the way that Catani and Seymour were able to combine the soft and collinear limits using their so-called dipole formalism. I was able to do so, giving a general formalism for constructing a single function capturing all singular limits, which I call an *antenna* function [T02/174] [T03/178]. It interpolates smoothly between the various double-soft, mixed soft-collinear, double-collinear, and triply-collinear limits. It is a direct generalization of the single-emission antenna function I constructed several years ago. The formalism admits a very elegant generalization to higher loop orders [T02/183]. I have also been working with Dr. W. Giele (Fermilab) on developing a new approach to merging fixed-order and parton showering, based on these antenna functions.

H.4.2 Perturbative QCD at colliders (D. Kosower)

With Dr. Peter Uwer (formerly a postdoc in our Department, now at CERN) I completed the recalculation [T03/085] of the NLO corrections to the Altarelli–Parisi kernel, which governs the evolution of nonperturbative functions such as fragmentation functions and parton distributions. The result has been known for over twenty years, of course; what is novel is the method. It is an infrared one, computing the remaining divergence to be factorized directly, rather than the ultraviolet divergences of the corresponding operators. This means it can be done in parts, each of which can be checked independently against other calculations.

With Drs. C. Anastasiou (ETH), Z. Bern (UCLA), and L. Dixon (SLAC), I computed the two-loop splitting amplitude in an $\mathcal{N} = 4$ supersymmetric gauge theory [T03/128] [T04/012] as well as in

QCD [T04/051]. This function describes the behavior of two-loop amplitudes in limits where two external momenta become collinear. The $\mathcal{N} = 4$ splitting amplitude [T03/128] has the amazing property that the two-loop function is expressible in terms of the one-loop splitting amplitude. This led us to suspect that the same might be true of the full amplitude, not just in collinear limits. We were able to verify this explicitly for the four-point amplitude. The relation relies on very non-trivial cancellations between different integral functions. (Very recently, Bern, Dixon, and Smirnov have shown that it generalizes to higher loops.) It is presumably related to the anti-de Sitter/conformal field theory duality that has been the subject of much theoretical activity among string theorists in recent years. The relation could partially explain how the perturbative series could be simple enough to possess the expected duality.

H.4.3 QCD and twistor string theory (D. Kosower)

Witten's 2003 paper on twistor string theory and its connection to the $\mathcal{N} = 4$ gauge theory spurred several investigations. Drs. Bena and Bern, and I showed [T04/079] how to understand the different ('disconnected' and 'connected') pictures of amplitudes in the string theory, from a gauge-theory point of view. In addition, we also reformulated in a compact recursive manner, the new computational rules that had been presented by Cachazo, Svrček, and Witten. Drs. Bena (UCLA), Bern, Roiban (Princeton) and I gave [T04/125] a twistor-space prescription for handling infrared-divergent contributions, and also showed that an explicit evaluation of the Cachazo–Svrček–Witten 'holomorphic anomaly' indeed leads to a simple geometric picture for the twistor-space structure of loop amplitudes.

With Drs. Bern and Dixon, and initially V. Del Duca (Torino), I embarked on a new set of computations of one-loop amplitudes in the $\mathcal{N} = 4$ supersymmetric gauge theory. We computed all seven-point amplitudes not previously known [T04/131]; and later extended this to all next-to-MHV amplitudes (i.e., with three negative-helicity gluons) with an arbitrary number of external legs [T04/166]. These calculations revealed a simple twistor-space structure for the coefficients of integral functions, and will likely lead to new insights into the theory. With Drs. Bern and Dixon, I have been working to apply on-shell recurrence relations, originally proposed at tree level by Britto, Cachazo, Feng, and Witten, to the calculation of rational terms in one-loop amplitudes [T05/015] [T05/058] [T04/165].

H.5 Quantum fields and particles (J. Bros)

The methods of complex geometry and harmonic analysis are applied to some fundamental problems concerning fields and particles, namely

H.5.1 Fields and particles in Minkowski spacetime

In [T03/020], we show that in field theories satisfying two-particle asymptotic completeness, all the sets of "localized states" (i.e. field-excitations of the vacuum in bounded regions of spacetime) submitted to a finite energy projection in the two-particle spectral region yield *compact subsets* in the Hilbert space of states (part of the Haag-Swieca conjecture).

General thermal aspects of quantum field theory are studied in [T03/217].

H.5.2 Fields and particles in de Sitter spacetime

The paper [T02/228], studies the de Sitter analogue of the AdS/CFT correspondence treated previously in the framework of analytic N-point functions.

CHAPTER I

Non-equilibrium Dynamics and Disordered Systems

Contents

This chapter involves contributions of 10 permanent members: A. Billoire, G. Biroli (since 2002), C. De Dominicis, J.M. Drouffe, T. Garel, J. Houdayer (since 2003), O. Golinelli, J.M. Luck, K. Mallick and C. Monthus; and of two post-docs: B. Coluzzi and J. Houdayer. There have been two PhD students: G. de Smedt (end 2002) with advisers J.M. Luck and C. Godrèche (SPEC); A. Andreanov (since 2004) with advisers G. Biroli and J.P. Bouchaud (SPEC).

The field of non-equilibrium statistical mechanics is extremely broad, because the non-equilibrium character may have various origins : (i) a system can be driven in a non-equilibrium steady state by external boundary conditions or driving forces; (ii) a system can be out-of-equilibrium because it gets trapped into metastable states, or because there exists a dynamical phase transition, (iii) a system can remain forever non-stationary and present aging, because the dynamics takes place in a rough energy landscape. These various non-equilibrium situations are well represented in this chapter, with studies on driven diffusive systems, on glasses, on granular media, and on random walks in random media.

The field of disordered systems also contains a great variety of subjects because the presence of disorder induces different effects in various contexts : in spin glasses, the long-standing debate between the broken replica approach and the droplet scaling picture is still very lively; for polymers, the question is how disorder in the polymer sequence or in the random medium changes the pure critical properties; finally, in quantum models, the disorder usually induces drastic effects, such as the Anderson localization and strong disorder critical points.

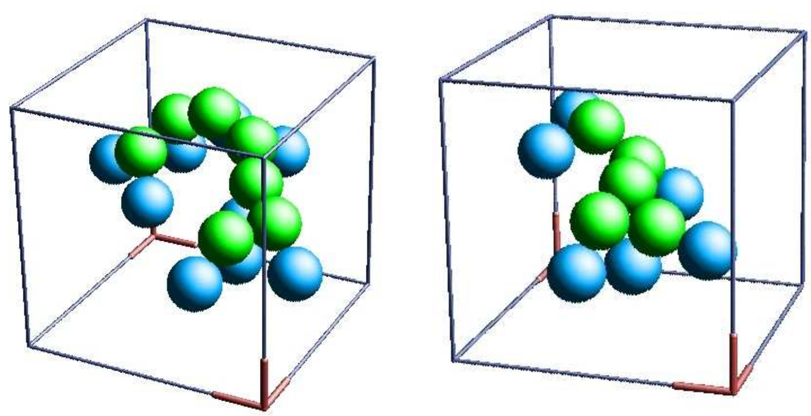


Figure I.1: Bridges are configurations of spheres in dense packings, in which the three-point stability conditions of two or more particles are linked; that is, two or more particles are mutually stabilised. They are thus structures which cannot be formed by the sequential placement of individual particles [T04/092]. Left: a seven-particle linear bridge with nine base particles. Right: a five particle complex bridge with six base particles.

I.1 Kinetic models

I.1.1 Bethe Ansatz for non-equilibrium models (O. Golinelli, K. Mallick)

The asymmetric simple exclusion process (ASEP) is a driven diffusive system of particles on a lattice interacting through hard-core exclusion, that serves as a basic model in various fields ranging from protein synthesis to traffic flow. In non-equilibrium statistical physics, the ASEP plays the role of a paradigm thanks to the variety of phenomenological behaviors it displays and to the number of exact results it has led to in the last decade. In fact, the ASEP is one of the very few models, far from equilibrium, for which exact solutions have been obtained. In particular, the ASEP is an integrable system, *i.e.*, the Markov matrix that encodes its stochastic dynamics can be diagonalized by Bethe Ansatz. In contrast with the Hamiltonians that appear in Quantum Mechanical integrable models, the Markov matrix of a stochastic model is non-Hermitian: its eigenvalues are thus distributed in the complex plane. In particular, the real part of the spectral gap of the Markov matrix (*i.e.*, the difference between the two eigenvalues with largest real parts) defines the relaxation time of the model that scales as L^z, L being the size of the system and z the dynamical exponent. We have obtained in [T03/196] a new derivation of the spectral gap of the totally asymmetric exclusion process (TASEP) on a half-filled ring of size L by using the Bethe Ansatz. We have shown that, in the large L limit, the Bethe equations reduce to a simple transcendental equation involving the polylogarithm, a well-known special function, and that the Bethe roots lie on classical curves, the Cassini ovals. By solving that equation, the gap and the dynamical exponent are readily obtained. An important advantage of our method is the possibility to extend it to a system with an arbitrary density of particles [T04/145].

I.1.2 Hidden symmetries in exclusion processes (O. Golinelli and K. Mallick)

We have also studied the global properties of the Markov matrix spectrum. Whereas the natural symmetries (translation, charge conjugation combined with reflection) predict only two fold degeneracies, we have found that in TASEP higher order multiplets also exist and that, when the system size increases, the degeneracies become generic. We have shown that these spectral properties are due to a hidden symmetry in the Bethe Ansatz equations. We have derived exact combinatorial formulae for the orders of degeneracy and the number of multiplets. Our results are confirmed by exact diagonalisations of small size systems. Such an unexpected structure of the TASEP spectrum suggests the existence of an underlying large invariance group [T04/132] [T04/167]. We are currently investigating the spectral degeneracies of the family of transfer matrices (constructed by algebraic Bethe Ansatz) that commutes with the TASEP Markov matrix.

I.1.3 Ising chain with Kawasaki dynamics (J.M. Luck)

The self diffusion of a tagged particle has been proposed as an efficient tool to investigate dynamical features, such as cage effects and dynamical heterogeneities, in glasses or dense granular media. We have studied the motion of a tagged spin in a ferromagnetic Ising chain evolving under symmetric or totally asymmetric Kawasaki dynamics at finite temperature. The infinite-temperature limit corresponds to the celebrated exclusion processes SEP and ASEP. In the situation of equilibrium at any finite temperature, the displacement is found to be Gaussianly distributed in the symmetric case (i.e., the SEP with ferromagnetic correlations), with a variance increasing as $A\,t^{1/2}$, and to have a nontrivial asymptotic profile in the asymmetric case (i.e., the ASEP with ferromagnetic correlations), with a variance growing as $B\,t^{2/3}$. The temperature dependence of the prefactors A and B of both laws of anomalous self diffusion is derived analytically, using an exact mapping onto the Edwards-Wilkinson and Kardar-Parisi-Zhang continuum theories. At low temperature (where the static correlation length ξ is large), in the non-equilibrium coarsening regime, the typical displacement of a tagged particle scales as a finite fraction of the mean domain size, i.e., as $(t/\xi^2)^{1/3}$ in the symmetric case and as $(t/\xi^2)^{1/2}$ in the asymmetric case [T03/064].

I.1.4 Metastability (J.M. Luck)

Glassy dynamics is often thought of as motion in a complex energy landscape, with valleys separated by barriers. The relevant valleys have been given several inequivalent definitions in different contexts. One of the main difficulties resides in the fact that truly metastable states are only observed either at the mean-field level or at zero temperature. The zero-temperature dynamics of simple models provides a natural benchmark to test general ideas on the statistics of metastable states. This line of investigation has been pursued on the case of the ferromagnetic Ising chain with Kawasaki dynamics. Any finite system gets trapped into a disordered absorbing configuration after a relatively short blocking time. The statistics of the blocking time has been both predicted and measured in numerical simulations, as well as various characteristics of the metastable configurations, including the statistics of the final energy, spin and energy correlations, and the distribution of domain sizes. Results of numerical simulations are compared with exact predictions concerning the a priori ensemble à la Edwards, consisting of all the blocked configurations with equal weights. Qualitative differences are found, e.g. in the domain sizes, which are found to be neither statistically independent nor exponentially distributed [T02/142]. These results have been put in perspective with earlier works on metastability and statistics of attractors in a review paper [T04/161].

I.1.5 Competitive cluster growth (J.M. Luck)

We have investigated a deterministic model of interacting clusters which compete for growth. Although the model arose in an astrophysical context, that of mass accretion by black holes coupled by the radiation field in a braneworld, its emergent features might be relevant to a wider range of problems. For a finite assembly of coupled clusters, the largest one always wins, so that all but this one die out in a finite time. This scenario of "survival of the biggest" still holds in the mean-field limit, where the model exhibits glassy dynamics with two well-separated time scales. In the case of short-range interactions between clusters, a finite fraction of the clusters survive forever and form a spatially non-trivial metastable pattern [T03/230] [T04/129] [T05/055].

I.2 Glasses and glass-formers

I.2.1 Lattice glass models (G. Biroli)

In order to make progress in the understanding of the glass transition problem we have introduced and studied statistical mechanics lattice models for the glass transition. The previous works on these type of models were either only numerical simulations or exact solution but of quenched disordered mean-field systems, which are clearly far from being realistic models because of the quenched disorder and the underlying completely connected lattice. We focus on two large classes of models.

Statically Constrained models . In collaboration with M. Mézard we introduce in [T02/207] coarse grained lattice models of usual (off-lattice) hard spheres systems. On each site of the lattice there can be zero or one particle but these occupations are restricted by a *static constraint* that takes into account the concept of geometrical frustration of three dimensional packings developed by Nelson et al.: a particle cannot have more than l occupied sites among its nearest neighbors (l is a model dependent parameter). Our Monte Carlo simulations in three dimensions show that they display a dynamical glass transition which is very similar to that observed in off-lattice models of glass-forming liquids. In [T02/207] and [T03/108] in collaboration with O.C. Martin, M. Mézard and O. Rivoire we derive analytically the phase diagram for these models on Bethe lattices by the cavity method, and discuss different equilibrium glassy phases.

Kinetically Constrained Models In [T03/089], [T04/016], [T04/033], [T04/153] in collaboration with D.S. Fisher and C. Toninelli we study Cooperative Kinetically Constrained Models. They are lattice models in which particles have only hard core interactions. However there is a *kinetic constraint* that particles cannot move if surrounded by too many others and this causes extremely slow dynamics at high density or low temperature. Previous numerical simulation had suggested the existence of a glass transition in three dimension. We show that on Bethe lattices a dynamical glass transition to a partially frozen phase indeed occurs and it is similar to the one of mean-field disordered systems. However, we prove for all the models introduced so far that in finite dimensions there exist rare mobile elements that destroy the transition. The physical behavior is nonetheless very interesting: approaching close packing or zero temperature the dynamics is intrinsically cooperative and the characteristic time scale diverges in a Super-Arrhenius way. We derive analytically the scaling law for the structural relaxation time that compares well with the results of numerical simulations we perform for two dimensional models. In [T04/127] in collaboration with M. Sellitto and C. Toninelli we analyze in more detail the dynamical transition of these models on Bethe lattices. We show that their off-equilibrium aging behavior is similar to the one predicted by the dynamical theory of mean-field disordered systems.

Finally, in a recent work with D.S. Fisher and C. Toninelli we define and study short range models (without quenched disorder) that are a generalization of the previous ones but that do have an ergodicity breaking transition in two dimensions due to the appearance of an infinite spanning cluster of jammed particles. These models provide the first example of short-range finite dimensional models (without disorder) displaying a glass-jamming transition. Their phenomenological behavior is very similar to the one of real glass-formers.

I.2.2 Dynamical heterogeneity and cooperativity (G. Biroli)

Understanding and measuring growing dynamical correlation in glass-formers is a topic that have received an enormous amount of interest recently. In [T04/007], in collaboration with J-P Bouchaud, using field theory for liquid dynamics we show that the Mode Coupling Theory (MCT) of the glass transition leads to a diverging dynamical length scale. We obtain the MCT dynamical scaling exponents ν and z that relate diverging space and time scales to $|T - T_c|$, as well as the scaling form of the critical correlation functions. Furthermore, we show that the upper critical dimension of the theory is $d_c = 6$.

In [T04/168], in collaboration with L. Berthier, J.-P. Bouchaud, C. Toninelli and M. Wyart we test numerically the predictions derived in [T04/007] for MCT and contrast them to the ones we derive for several other theoretical approaches to the glass transition, in particular elasto-plastic deformations, collectively rearranging regions, diffusing defects and kinetically constrained models. The molecular dynamics simulations of two model systems, a Lennard-Jones mixture and a soft-sphere mixture, display a good agreement with the MCT predictions on growing dynamic correlations. Elasto-plastic deformations can describe only the short-time behavior and the other approaches do not describe well the numerical results. Unfortunately, up to now only indirect experimental indications of a cooperative length scale associated to heterogeneous dynamics have been reported for glass-forming liquids. This is true also on a different front, that of spin-glasses, where length scale ideas have also been expressed in the recent years to account for equilibrium and non equilibrium phenomena such as aging, memory and rejuvenation effects. In [T05/017], in collaboration with J.-P. Bouchaud, we argue that for *slow* glassy systems, the low frequency non-linear (cubic) response to an external field (electric, magnetic, pressure, etc.) encodes directly dynamic correlations opening the way to a *direct experimental measurement* of the cooperative length in glass-formers and the non equilibrium coherence length in spin-glasses. D. L'Hote, F. Ladieu and E. Vincent of SPEC have started experiments along the lines of this study.

I.2.3 On the Kirkpatrick–Thirumalai–Wolynes scenario (G. Biroli)

In [T04/095] in collaboration with J.-P. Bouchaud we reformulate the interpretation of the mean-field glass transition scenario for finite dimensional systems, proposed by Wolynes and collaborators. This allows us to establish clearly a temperature dependent length above which the mean-field glass transition picture has to be modified. We argue in favor of the mosaic state introduced by Wolynes and collaborators, which leads to the Adam-Gibbs relation between the viscosity and configurational entropy of glass forming liquids. Physical consequences and possible numerical checks are discussed.

I.2.4 On defect models of glass-formers (G. Biroli)

In [T04/154] in collaboration with J.-P. Bouchaud and G. Tarjus we show that point-like defect model of glasses cannot explain at the same time dynamic and thermodynamic properties of glass-formers, as for example the excess specific heat close to the glass transition, contrary to recent claims in the literature. More general models and approaches in terms of extended defects are also discussed.

I.2.5 The Kovacs effect in model glasses (J.M. Drouffe)

In [T03/101], we discuss the 'memory effect' discovered in the 60's by Kovacs in temperature shift experiments on glassy polymers, where the volume (or energy) displays a non monotonous time behavior. This effect is generic and is observed on a variety of different glassy systems (including granular materials). The aim of this paper is to discuss whether some microscopic information can be extracted from a quantitative analysis of the 'Kovacs hump'. We study analytically two families of theoretical models: domain growth and traps, for which detailed predictions of the shape of the hump can be obtained. Qualitatively, the Kovacs effect reflects the heterogeneity of the system: its description requires to deal not only with averages but with a full probability distribution (of domain sizes or of relaxation times). We end by some suggestions for a quantitative analysis of experimental results.

I.3 Granular media

I.3.1 Sphere packings (J.M. Luck)

Several works have aimed at modeling cooperative effects in the statics and dynamics of dense granular media. Concerning static aspects, we have investigated the statistics and the shape of bridges in granular packings, both from a phenomenological viewpoint and by means of extensive simulations. A bridge is a configuration of particles in which the stability conditions of two or more particles are linked, so that particles are mutually stabilized. Bridges therefore cannot be formed by the sequential placement of particles; they are, however, frequently formed by processes such as shaking and pouring, where cooperative effects arise naturally [T04/092].

Another phenomenological investigation has been dealing with the dynamics of the angle of repose. When a sandpile relaxes under vibration, it is known that its measured angle of repose is bistable in a range of values bounded by a material-dependent maximal angle of stability; thus, at the same angle of repose, a sandpile can be stationary or avalanching, depending on its history. We have proposed to model the dynamics of the angle of repose and of the density fluctuations, in the presence of external noise, by means of coupled stochastic equations. Among other things, this approach is able to describe sandpile collapse in terms of an activated process [T04/093]. [T05/027].

I.3.2 Dynamics of a column of grains (J.M. Luck)

We have introduced, and investigated at length, a stochastic model describing the dynamics of a column of grains near the so-called jamming limit, under the influence of a low vibrational intensity. Grains are anisotropic and possess a discrete orientational degree of freedom. Gravity induces long-range directional interactions down the column. Causality is therefore at work both in space and in time. The key control parameter of the model, ε, is a representation of granular shape. For irrational values of ε, corresponding to irregular grains, the model has a unique quasiperiodic ground state, and zero-temperature dynamics leads to a fast retrieval of this ground state by means of the ballistic growth of an ordered top layer. For rational values of ε, corresponding to regular grains, the model has extensively degenerate ground states and a positive configurational entropy. Zero-temperature dynamics is not able to retrieve any of the ground states; it rather drives the system to a non-trivial fluctuating steady state characterized by unbounded fluctuations [T02/164] [T03/062].

I.4 Random walks in random media

I.4.1 Sinai model (C. Monthus)

In [T02/133] in collaboration with P. Le Doussal, we study the time dependent potential energy $W(t) = U(x(0)) - U(x(t))$ of a Sinai walker. Using the real space renormalization group method (RSRG), we obtain the exact large time limit of the probability distribution of the scaling variable $w = W(t)/(T \ln t)$. Using the constrained path integral method, we moreover compute the joint distribution of energy and position at time t. In presence of a reflecting boundary at the starting point, our approach very simply yields the one time and aging two-time behavior of this joint probability.

In [T02/184], we study the anomalous diffusion phase $x \sim t^{\mu}$ with $0 < \mu < 1$ which exists in the Sinai diffusion at small bias. Our starting point is the Real Space Renormalization method in which the whole thermal packet is considered to be in the same renormalized valley at large time : this assumption is exact only in the limit $\mu \to 0$ and corresponds to the Golosov localization. For finite μ, we thus generalize the usual RSRG method to allow for the spreading of the thermal packet over many renormalized valleys.

I.4.2 Trap models (C. Monthus)

In [T03/030], we study in details the dynamics of the one dimensional symmetric trap model, via a real-space renormalization procedure which becomes exact in the limit of zero temperature. We first compute disorder averages of one-time observables, such as the diffusion front, the thermal width, the localization parameters and the two-particle correlation function. We then study aging and sub-aging effects : our approach reproduces very simply the two different aging exponents and yields explicit forms for scaling functions of the various two-time correlations. In [T03/083], we generalize the previous approach to the case where an external force is applied from the very beginning at $t = 0$, or only after a waiting time t_w, in the linear as well as in the non-linear response regime. In [T03/072], we derive a non-linear Fluctuation Theorem for the aging dynamics of disordered trap models in dimension d and we discuss its consequences.

I.5 Disordered spin models

I.5.1 Replicas (C. De Dominicis)

One of the most controversial problem in the theory of disordered systems concerns the statistical mechanics description of the so-called spin-glasses (i.e. random magnetic impurities in a non-magnetic metal). Two views coexist. One view follows from the exact solution of mean-field equations (the Sherrington–Kirkpatrick model) due to Parisi and recently mathematically proved by Talagrand. In infinite dimensions the system is very complex and reveals a large number of metastable states. The other view that lacks an appropriate Lagrangean starting point, provides an analysis of the low excitations of the system (droplets). The following publications deal with various aspects of this controversy. [T02/200] concerns the very difficult problem of searching for fixed points of the spin-glass in the presence of a magnetic field. [T03/249] solves exactly for the free-energy and fluctuations associated with the most used Lagrangean describing spin-glasses via the replica trick. [T04/157] points out to a weakness of the theory showing that the cost in free energy of the introduction of a twist on the boundary conditions bears the wrong sign and traces it back to the fact that in Parisi's approach all multiplicities are negative (a strange effect due to the use of the replica trick). It is then shown that if one uses an approach that simulates the dynamics (where all multiplicities are positive as they should) this weakness is removed. Further work is in preparation on this aspect of the theory that would allow then to go beyond the Parisi-Talagrand result. [T04/216] finally is a collaboration with numerical experts to try to discriminate between predictions of the two viewpoints (the mean-field like and the droplet like). With the inevitable difficulty that the theory is only able to propose, at best, general scaling answers when one goes well below the upper critical dimension (i.e. dimension 6) of the system.

I.5.2 Mean-field spin glasses (A. Billoire)

As well known, the probability distribution function of the order parameter of the Sherrington–Kirkpatrick mean-field model of spin glasses $P_N(q)$ has a nontrivial shape in the broken phase, with, in the infinite volume limit, two delta function peaks separated by a nontrivial background. On a finite volume, this two peaks are rounded. It is possible, using the so-called coupled replica scheme, to compute analytically the behavior of the tails of $P(q)$ as a function of the system size N, temperature T and field h . Testing the coupled replica scheme is quite important in view of the temperature chaos problem. In the spin glass phase, we show in [T02/072] that generically, for any model with continuous RSB, $1/N \log P_N(q) \approx -\mathcal{A}\,(|q| - q_{EA})^3$. We compute the first two terms of the expansion of $\mathcal{A}$ in powers of $T_c - T$ for the Sherrington–Kirkpatrick model. We also study the paramagnetic phase, where results are obtained in the replica symmetric scheme that do not involve an expansion in powers of $q - q_{EA}$ or $T_c - T$. We give finally precise semi-analytical estimates of $P(|q| = 1)$. The overall agreement between the various points of view is very satisfactory.

It is now believed that there is temperature chaos in the Sherrington–Kirkpatrick model, but it is abnormally small, namely it appears analytically only in ninth order in perturbation theory, and numerically only for very large systems, mostly beyond our present computational reach. In contrasts, the magnetic chaos is believed to be strong. In [T02/145], we have done a simulation in order to check that we do see the effects of magnetic chaos, and that it appears for increasing system sizes the way one believes chaos does : namely a new "chaotic" peak appears in the probability distribution function of the order parameter $P_N(q)$ for $q \approx 0$, thats eventually dominates the whole distribution as $N \to \infty$. We use an original variant of the popular Parallel Tempering algorithm in which several copies of the system, with different values of the magnetic field h, are simulated in parallel. The behavior of the probability distribution of the overlap between two replicas at different values of the magnetic field h_0 and h_1 gives clear evidence for the presence of magnetic field chaos already for moderate system sizes, in contrast to the case of temperature chaos.

As a side product of the previous work, we studied in [T03/014] the Sherrington–Kirkpatrick model as function of the magnetic field h, with fixed temperature $T = 0.6T_c$. We investigate the finite size scaling behavior of several quantities, such as the spin glass susceptibility, looking for numerical evidences of the transition on the De Almeida Thouless line. We find strong corrections to scaling which make difficult to locate the transition point. This shows, in a simple case, the extreme difficulties of spin glass simulations in nonzero magnetic field. Next, we study various sum rules (consequences of stochastic stability) involving overlaps between three and four replicas, which appear to be numerically well satisfied, and in a nontrivial way. Finally, we present data on $P(q)$ for a large lattice size ($N = 3200$) at low temperature $T = 0.4T_c$, where, for the first time, the shape predicted by the RSB solution of the model for nonzero magnetic field is visible.

The mean field p-spin ($p > 3$) model has turned out to have many similarities with structural glasses, which make it much more than just another model. In [T05/005], we investigate numerically the equilibrium dynamical behavior of the finite volume mean field 3-spin spin glass model: we study equilibrium dynamics, and compute equilibrium time scales as a function of the system size N (with N up to 192). We find that below the static 1RSB transition, the time scales τ increase like $\ln \tau \propto N$, as N grows, in marked contrast with the Sherrington–Kirkpatrick model, where $\ln \tau \propto N^{\approx 1/3}$. We also present an accurate study of the equilibrium static properties of the system.

I.5.3 2D Ising spin glasses (J. Houdayer)

Spin glasses are disordered magnetic systems. Theoretically, it is still unclear whether the mean field replica symmetry breaking solution is pertinent to finite dimensional spin glasses. We have investigated the somewhat simpler 2D version of this problem. In [T04/152], we have made a Monte Carlo simulation of 2D Gaussian Ising spin-glasses at very low temperature and large sizes (up to $T = 0.02J$ and $L = 75$) using a recently devised cluster algorithm. The main results are the following: The transition temperature is fully compatible with $T_c = 0$. The correlation length diverges as a power law ($\xi \sim t^{-\nu}$) in opposition to $\pm J$ spin-glass. Moreover this behavior is compatible with the droplet theory, since $1/\nu \simeq 0.295 \simeq -\theta$ where θ is the droplet exponent.

I.5.4 Random field Ising chain (C. Monthus)

The thermal fluctuations that exist at very low temperature in disordered systems are often attributed to the existence of some two-level excitations. In [T04/097] in collaboration with P. Le Doussal, we revisit this question via explicit studies of the following 1D models (i) a particle in 1D random potentials (ii) the random field Ising chain with continuous disorder distribution. In both cases, we define precisely the 'two-level' excitations and their statistical properties. For the random-field Ising chain, we obtain that the specific heat is dominated by small nonuniversal excitations, whereas the magnetic susceptibility and the Edwards-Anderson order parameter are dominated by universal large excitations.

I.5.5 Spin-glass chain in field (T. Garel and C. Monthus)

In [T04/144], we numerically revisit the spin-glass chain in an external field h to obtain detailed statistical information on the ground state configuration and on the low-energy two-level excitations that govern the low temperature properties. The ground state consists of long unfrustrated intervals separated by weak frustrated bonds: We accordingly compute the strength distribution of these frustrated bonds, as well as the length- and magnetization- distributions of the unfrustrated intervals. We characterize the nature and the statistical properties of the low-energy excitations.

I.6 Polymers and disorder

I.6.1 Mixture of random copolymers (J. Houdayer)

Mixing different kind of polymers to produce new materials is in general a difficult task. Due to early phase separation, homogeneous mixture can rarely be obtained. To prevent this, one can produce polymers containing different kind of monomers. In certain production processes, the arrangement of monomers along the polymer chains is random. Due to the the presence of a large number of chemical species, determining the thermodynamic phase diagram is a challenge. Different theories have been recently developed to describe these systems. But they are largely incompatible with one another. In a series of papers [T02/215] [T02/216] [T03/198], we have done extensive Monte Carlo simulations of such systems. We developed many new algorithmic approaches, such as efficient local moves for random copolymers and efficient sampling of the overall composition fluctuations. Without these algorithmic improvements the simulations would have been out of reach. Our main result is the following: for symmetrical mixtures with two kinds of monomer (A and B) at low disorder, the system is homogeneous at high temperature, at smaller temperature it undergoes a phase separation between (relatively) A-rich and B-rich phases and at even smaller temperature it remixes into a microemulsion phase. At higher disorder, it goes continuously from homogeneous to microemulsion. Quite surprisingly, the mean field theory predictions become less and less good as the polymer length is increased (the opposite is almost always true).

I.6.2 Directed polymers (T. Garel and C. Monthus)

In [T03/195], we analyze, via Imry-Ma scaling arguments, the strong disorder phases that exist in low dimensions at all temperatures for directed polymers and interfaces in random media. For the uncorrelated Gaussian disorder, we obtain that the optimal strategy for the polymer in dimension $1 + d$ with $0 < d < 2$ involves at the same time (i) a confinement in a favorable tube of radius $R_S \sim L^{\nu_S}$ with $\nu_S = 1/(4 - d) < 1/2$ (ii) a superdiffusive behavior $R \sim L^{\nu}$ with $\nu = (3 - d)/(4 - d) > 1/2$ for the wandering of the best favorable tube available. The corresponding free-energy then scales as $F \sim L^{\omega}$ with $\omega = 2\nu - 1$ and the left tail of the probability distribution involves a stretched exponential of exponent $\eta = (4 - d)/2$. These results generalize the well known exact exponents $\nu = 2/3$, $\omega = 1/3$ and $\eta = 3/2$ in $d = 1$. We then extend our approach to correlated disorder in transverse directions and/or to manifolds in dimension $D + d = d_t$ with $0 < D < 2$. The strategy of being both confined and superdiffusive is still optimal for decaying correlations, whereas it is not for growing correlations.

I.6.3 Wetting with disorder (T. Garel and C. Monthus)

In [T05/026], we numerically study the adsorption transition of a polymer chain on a disordered substrate in $1 + 1$ dimension. Following the Poland-Scheraga model of DNA denaturation, we use a Fixman-Freire scheme for the entropy of loops. This allows us to consider chain lengths of order $N \sim 10^5$ to 10^6, with 10^4 disorder realizations. Our study is based on the statistics of loops between two contacts with the substrate, from which we define Binder-like parameters: their crossings for various sizes N allow a precise determination of the critical temperature, and their finite size properties yields a crossover exponent $\phi \simeq 0.5$. We then analyze at criticality the distribution of loop length l in both regimes $l \sim O(N)$ and $1 \ll l \ll N$, as well as the finite-size properties of the contact density and energy.

I.6.4 Random DNA denaturation (T. Garel and C. Monthus)

The homogeneous Poland-Scheraga (PS) model of DNA denaturation displays a first order denaturation transition if the loop exponent c is larger than 2. This first order transition is nevertheless characterized by a divergent correlation length. In [T05/039], we have studied the binary disordered PS model in this regime, both for bound-bound (bb) and bound-unbound (bu) boundary conditions. Our main conclusion is that the transition remains first order in the disordered case: in the (bu) case, the disorder averaged energy and contact densities present crossings for different values of N without rescaling. In addition, we obtain that these disorder averaged observables do not satisfy finite size scaling, as a consequence of strong sample to sample fluctuations of the pseudo-critical temperature. Finally, we obtain that the disorder averaged critical loop distribution is still governed by $P(l) \sim 1/l^c$ in the regime $l \ll N$, as in the pure case.

I.7 Quantum disordered systems

I.7.1 Anderson localization (J.M. Luck)

The quantum-mechanical transmission through a disordered tunnel barrier has been studied by analytical means in the regime of most physical relevance: correlation range of the random potential $\ll$ penetration length $\ll$ barrier length. The typical transmission has been shown by analytical means to be a non-monotonic function of the disorder strength, increasing at weak disorder, reaching a maximum in the crossover from weak to strong disorder, and decreasing at strong disorder. This investigation provides the first quantitative analysis of the phenomenon of disorder-induced enhanced tunneling. This effect, put forward by Freilikher et al. in 1995, is paradoxical, because random impurity potentials usually lead to additional scattering, which hinders transport [T03/136]. We have also analyzed the nature of eigenstates in a weak self-affine disordered potential in one dimension, whose Gaussian fluctuations grow with distance with a positive Hurst exponent. Typical eigenstates are superlocalized on samples much larger than a well-defined crossover length, which diverges in the weak-disorder regime. For the discrete tight-binding model, the effective localization length decays logarithmically with the sample size, and the logarithm of the transmission is found to be marginally self-averaging. For the continuum Schrödinger equation, the superlocalization phenomenon has more drastic effects. The effective localization length decays as a power of the sample length, and the logarithm of the transmission is fully non-self-averaging in the superlocalized regime [T04/113].

I.7.2 Random Transverse-Field Ising Chain (C. Monthus)

The Random Transverse-Field Ising Chain is the simplest disordered model presenting a quantum phase transition at zero temperature. In [T03/126], we use the real space RG approach, to compute its finite-size scaling properties in two different ensembles for the disorder (i) the canonical ensemble, where the disorder variables are independent (ii) the microcanonical ensemble, where there exists a global constraint on the disorder variables. The observables under study are the surface magnetization, the correlation of the two surface magnetizations, the gap and the end-to-end spin-spin correlation $C(L)$ for a chain of length L. The dependence in L of averaged observables differ in the two ensembles. For instance, the correlation $C(L)$ decays algebraically as 1/L in the canonical ensemble, but sub-exponentially as $e^{-cL^{1/3}}$ in the microcanonical ensemble. The conclusion is that the measure of the rare events that dominate various averaged observables can be very sensitive to the microcanonical constraint.

I.8 Reviews and lecture notes

I.8.1 Strong disorder RG approach of random systems (C. Monthus)

There is a large variety of quantum and classical systems in which the quenched disorder plays a dominant rôle over quantum, thermal, or stochastic fluctuations : these systems display strong spatial heterogeneities, and many averaged observables are actually governed by rare regions. A unifying approach to treat the dynamical and/or static singularities of these systems has emerged recently, following the pioneering RG idea by Ma and Dasgupta and the detailed analysis by Fisher. In [T05/029], in collaboration with F. Igloi, we report these new developments : after a pedagogical presentation of the method, we describe applications of the RG method to various disordered models, either (i) quantum models, such as random spin chains, ladders and higher dimensional spin systems, or (ii) classical models, such as diffusion in a random potential, equilibrium at low temperature and coarsening dynamics of classical random spin chains, trap models, delocalization transition of a random polymer from an interface, driven lattice gases and reaction diffusion models in the presence of quenched disorder. This review is partly based on the Habilitation Thesis [T04/082].

I.8.2 A crash course on aging (G. Biroli)

[T04/213] are lecture notes of the school "Unifying concepts in glass Physics III" in which I describe some of the main theoretical ideas emerged to explain the aging dynamics. They are meant to be a very short introduction to aging dynamics, no previous knowledge is assumed. I go through simple examples that allow one to grasp the main results and predictions.

CHAPTER J

Condensed Matter

Contents

In the last century, the physics of electrons in solids has been dominated by concepts like band theory or Landau's symmetry breaking view on phase transitions. However, over the last two decades, a number of remarkable phenomena due to collective behaviors of (strongly) interacting electrons have been observed. The fractional quantum hall effect and high-temperature superconductivity are the two most famous and spectacular examples but many other important experimental discoveries had a major impact: magnetoresistance in manganites, superconductivity, magnetism and metal-insulator transition in organic materials, superconductivity in cobaltates, zero-temperature continuous phase transitions in metals and magnets, breakdown of the Fermi-liquid behavior in cuprates and in heavy fermions compounds, exotic orders (charge, spin, orbital) in transition-metal oxides, interaction and quantum effects in low-dimensional geometries (artificially structured nanoscale materials: dots, wires, 2D electron gas), and the newly connected field of trapped (cold) atoms in optical lattices.

Interestingly, the present activity of the SPhT in condensed matter has connections to almost all the subjects above. About one quarter of the papers published by the group over the period 2002-2005 are based on realistic models, quantitatively relevant to specific compounds or experiments. The other contributions came from the study of simplified but fundamental quantum many-body models: lattice spin models (Heisenberg), Hubbard model (spin-1/2 fermions with on-site repulsion), Kondo models (itinerant electrons interacting with localized magnetic moments), hard-core dimer models (short-ranged "Cooper pairs" with a no-double-occupancy constraint), or continuum actions for one-dimensional quantum fluids (Luttinger liquids). These studies aim at understanding the basic mechanisms involved in new states of matter, new phase transitions, or, more generally, new phenomena that have been (or which could be) observed in real systems. In these cases, perturbative or conventional mean-field calculations are well known to be inappropriate. More elaborate theoretical tools or ideas need to be employed to tackle these problems: integrability, renormalization group, dynamical mean-field theory, numerical simulations like quantum Monte Carlo or exact diagonalizations.

To be more specific, we briefly illustrate these ideas through three topics (to name just a few) where significant developments were carried out: non-Fermi liquid behavior in metals close to a $T = 0$ transition and dynamical mean-field calculations for the Hubbard model and field theory approaches to transport in mesoscopic systems.

The first problem deals with zero-temperature continuous phase transitions between phases with and without magnetic long-range order in itinerant electron systems. Understanding those *Quantum Critical Points* (QCP) is a central issue in condensed matter and an important body of theoretical work was carried out at the SPhT to understand how conduction electrons are affected close to such a transition. QCP are present in several heavy-fermion compounds where the itinerant charge carriers interact with localized spins.[1] They generally give rise to non-Fermi liquid

[1] Metals with localized magnetic moments in $d-$ or $f-$ orbitals, usually from rare-earth atoms. Because of

properties.[2] QCP may also provide a route to explain the anomalous properties of the high-T_c cuprate superconductors in their normal (non-superconducting) phase. This is all the more important as the theory of superconductivity in these materials is unlikely to emerge without a prior understanding of their normal phase.

Another central question in condensed matter physics is the Mott transition (metal-insulator transition driven by electron-electron repulsion). It is also deeply related to high-T_c superconductors, which are Mott insulators with additional charge carriers (added by chemical doping). Dynamical mean-field theory (DMFT) and its extensions offer a powerful way to treat electron correlations, and has lead to significant progress in understanding of metal-insulator transitions due in particular to its capacity to treat both coherent and incoherent part of the electronic fluid. DMFT is also playing an increasing role in realistic calculations of the electronic properties of correlated materials. The "cluster" extensions of DMFT developed at SPhT greatly improve the treatment of spatial correlations and of more complex phases like d-wave superconductivity.

Important progress in the study of transport in quantum dots and quantum point contacts has been realized using methods of integrable quantum field theory. The development of this interdisciplinary research area brings together experts of mathematical physics and conformal field theory with solid state physicists [T03/209], and even gave rise to some collaborations with experimentalists in nearby SPEC [T03/210]. Among the most noticeable results obtained are exact calculations of shot noise and full counting statistics in strongly interactive regimes and out of equilibrium, such as in the edge states tunneling setup which gave rise to the discovery of $e/3$ fractionally charged Laughlin quasiparticles.

The works in condensed matter theory described below (45 references) involved 12 persons from the SPhT among which 8 are permanent researchers,[3] 3 are post-docs[4] and one Ph. D student.[5] 5 members of this group[6] have a large part of their research activity in another area (mathematical physics and classical disordered systems) and the condensed-matter activity largely benefited from the expertise in their field. We finally stress that 5 of the researchers were hired in the laboratory over the past 6 years.[7]

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interactions, quasi-particle masses are renormalized to large values compared to that of bare electrons, hence the name 'heavy fermions'.

[2] The breakdown of the Landau theory of Fermi liquids manifests itself through some anomalous temperature dependence of thermodynamic and transport quantities like the specific heat or the electric conductivity.

[3] G. Biroli, J. Jacobsen (from the LPTMS of Orsay University and in delegation at the SPhT for 2004-2005), G. Misguich, O. Parcollet, V. Pasquier, C. Pépin, H. Saleur and D. Serban.

[4] I. Paul (From Oct. 2003 to Oct. 2005), F. Alet (from Oct. 2004 to Oct. 2005) and E. Boulat (From Nov. 2004 to Oct. 2005)

[5] J. Rech. Advisers: C. Pépin and P. Coleman (Rutgers University)

[6] G. Biroli, J. Jacobsen, V. Pasquier, H. Saleur and D. Serban

[7] C. Pépin(1999), G. Misguich (2001), O. Parcollet (2002), G. Biroli (2002) and H. Saleur (2003)

J.1 High-T_c superconductors (C. Pépin)

We review here the field of high temperature cuprate superconductors with an emphasis on the nature of their electronic properties. The review concentrates on the results obtained by angle resolved photoemission, inelastic neutron scattering, and optical conductivity [T03/044].

J.2 Itinerant electrons and localized magnetism

J.2.1 Heavy fermions, theory and experiments (C. Pépin)

We study the heavy fermion compounds which can be driven to a zero-temperature phase transition or Quantum Critical Point (QCP) by tuning an external parameter. Typically this parameter is the external hydrostatic pressure, the magnetic field or the chemical doping. These compounds are constituted from a lattice of heavy magnetic atoms, like Cerium, Ytterbium, or Uranium which interact with the conduction electrons of a metal. The resulting Kondo effect on a lattice is still an open problem in quantum solid state physics. Particularly, close to a QCP, the Landau Fermi liquid theory, which describes the universal laws of conduction in a metal (like the temperature dependence of the conductivity close to the absolute zero) are violated. The resistivity follows a linear dependence in temperature, while the ratio of specific heat over the temperature does not saturate.

We have collaborated with the experimental group in Dresden working at the Max Planck Institut for Chemische Physik Fester Stoffe, on the compound Yb Rh_2 Si_{1-x} Ge_x. The pure compound ($x = 0$) is driven to criticality by chemical doping replacing Si with 5% Ge. An extensive experimental study of the specific heat coefficient C/T is performed in this paper. It is shown that at the QCP, below 300 m Kelvin, the specific heat diverges in a stronger way than $\log(T)$, like $C/T \sim T^{-2/3}$. This stronger than logarithmic divergence is a challenge for theories on these compounds [T03/203].

On the theory side, we have worked on a model to understand the compound Yb Rh_2 Si2 close to a QCP. In a first paper, we used a "poor man scaling" technique in the Kondo-Heisenberg model for which a bosonic representation of the spin is used. The Kondo bound-states are thus treated in this problem with Grassmann variables (that we call χ-fermions). A non-Fermi liquid phase where the formation of the Kondo singlets breaks down occurs for a certain range of parameters [T03/043] [T04/181].

In a second paper, starting again with the Kondo-Heisenberg model in a bosonic representation, we formulate an effective theory which captures the unusual properties of the compound Yb Rh_2 $(Si_{1-x}$ $Ge_x)_2$. The idea relies on the presence of a new fermionic excitation which becomes massless at the QCP. The presence of a flat dispersion at the hot line enables to capture the observed upturn in the specific heat as well as the linear resistivity [T04/204].

J.2.2 Pseudo-gaps in nested antiferromagnets (C. Pépin)

We analyze the fluctuation corrections to magnetic ordering in the case of a 3D antiferromagnet with flat Fermi surfaces, as physically realized in the case of Chromium, and find that they are insufficient to produce a quantum critical point. This implies that the critical point observed in Vanadium doped Chromium is due to a loss of nesting. We also derive the fermion self-energy in the paramagnetic phase and find that a pseudo-gap exists, though its magnitude is significantly reduced as compared to the spectral gap in the ordered state [T03/202].

J.2.3 Quantum critical behavior for itinerant ferromagnets (J. Rech, C. Pépin)

An important body of theoretical investigations has been recently performed in order to understand QCP of itinerant electrons systems. The theoretical foundation of commonly accepted model, the Hertz-Millis-Moriya (HMM) theory, remains nonetheless questionable. The problem is that in the HMM theory the fermions have been integrated out of the partition function in order to derive the effective theory. Due to the Fermi surface, the fermions are not always fast compared to the effective bosons, and cannot be simply integrated out. When the fermions are coupled back to the effective bosons, some singularities occur, due to residues of 1D physics in a 3D system.

The first paper [T02/171] is an attempt to derive a power counting technique for theories with non relativistic fermions. As an example we have power counted the quantum critical spin-fermion ferromagnet, in which fermions interact with ferromagnetic paramagnons.

The second paper [T03/201] is devoted to the study of the stability of this model. We argue that in $D \leq 3$, long-range spatial correlations associated with the Landau damping of the order parameter field generate a universal, negative, non-analytic $|q|^{(D+1)/2}$ contribution to the static magnetic susceptibility $\chi(0, q)$ which makes the HMM theory unstable. The actual transition is either toward incommensurate ordering, or first order.

J.2.4 Quantum correction to conductivity close to ferromagnetic quantum critical point (I. Paul, C. Pépin)

The temperature dependence of conductivity in disordered metals at sufficiently low temperature is due to subtle quantum interference effects. One class of such effects, known as "interaction corrections" in the literature, arise as a result of quantum interference between semi-classical electron paths scattered by the impurities and the static potential due to Friedel oscillations which are electron density modulations. Since these corrections involve interplay between disorder and interaction, they are particularly interesting to study when a metal is near a quantum critical point where the interaction becomes long-range. We studied the interaction correction to conductivity for a two-dimensional disordered paramagnetic metal close to a ferromagnetic quantum critical point. We find new exponent for the temperature dependence of conductivity near a quantum critical point [T05/075].

J.2.5 Kondo lattice and impurity models with bosonic spin representation (I. Paul, J. Rech)

The Kondo lattice is a model describing metallic rare earth compounds which often exhibit second order magnetic phase transitions, with a quantum critical point where the transition temperature is reduced to zero by varying an external control parameter such as pressure. An adequate mean field theory of such a quantum phase transition is currently lacking, and we studied the possibility of using bosonic representation of the localized spins for the mean field description. With this representation it is easier to describe the magnetically ordered state where the elementary excitations are bosonic. The real challenge is to capture the Kondo physics in the paramagnetic state where the elementary excitations are fermionic. With this motivation we constructed a large N theory of the underscreened Kondo model which correctly captures the finite elastic phase shift of the conduction electrons due to Kondo bound state formation. Additionally, in the context of bosonic large N description of the Kondo lattice, we studied the consequence of sum rules that arise due to conservation of electric charge and total spin, and derived an expression for the entropy [T04/214] [T05/074].

J.3 Mott transition and dynamical mean field theory (DMFT)

J.3.1 Mott transition and cluster DMFT (O. Parcollet, G. Biroli)

In strongly correlated materials, the interaction between electrons can induce a Mott transition between a metal and an insulator, observed as a function of doping or pressure in transition oxides metals, actinides and some quasi-2d organic materials. Moreover, this effect seems to play an important role in the high-temperature superconductors cuprates, which are doped Mott insulators. The Mott transition appears at intermediate coupling: electrons are neither delocalized in Bloch waves nor localized on the atoms, thus standard theoretical methods (e.g. band theory) fail. "Dynamical Mean field Theory" (DMFT) reduces a strongly correlated problem to a quantum impurity embedded into a self-consistently determined dynamical bath. It has lead to a successful description of the Mott transition, mainly because of its dynamical aspect that allows a simultaneous treatment of coherent and incoherent part of electronic fluid (respectively the quasiparticle peaks and the Hubbard bands). In [T02/056], the limit of a large number of orbitals in DMFT has been studied. In order to treat short range spatial fluctuations, cluster extensions of DMFT have been proposed to interpolate between the mean field limit (DMFT) and the full lattice solution. In [T02/206] different schemes have been tested in a solvable large$-N$ limit. Controversy over the convergence properties of large clusters have been clarified in [T04/057]. In [T03/105], classical limit of various schemes has been studied, together with their causality properties, solving in particular an old puzzle about the violation of causality in the "nested" cluster scheme.

In [T03/123], the Mott transition in the 2d Hubbard model has been investigated using Cluster DMFT and solving the self consistent quantum impurity problem with a finite temperature Quantum Monte Carlo. To overcome the "sign problem" limitation of this algorithm at low temperature (specially in frustrated models), a solution of the self-consistent problem with the Lanczos method has also been developed [T04/173]. In a frustrated model, we observe signatures of a finite temperature Mott critical point (absent in unfrustrated model with Cluster DMFT) in agreement with experimental studies of 2d organics materials and with DMFT. Close to the Mott transition, momentum dependence of the electron self-energy develops along the Fermi surface [T03/123], which is strongly renormalized, and the quasiparticle description breaks down in an anisotropic fashion [T04/173], reminiscent of the experimental data on cuprate superconductors. Regions where the quasiparticles are strongly (resp. weakly) scattered form irrespectively of whether the parent compound has antiferromagnetic long range order. Their location is not universal and is determined by the interplay of the renormalization of the scattering rate and the Fermi surface shape.

J.3.2 Construction of localized basis for DMFT (I. Paul)

Many-body Hamiltonians obtained from first principles generally include all possible interactions that are non-local in space. But in dynamical mean field theory the non-local interactions are ignored, and only the effects of the local interactions are taken into account. Since the notion of locality depends explicitly on the single-particle basis states considered, the truncation of the non-local interactions is a basis dependent approximation. A criterion has been proposed to construct an appropriate localized basis in which the truncation can be carried out. It has been argued that such a localized basis is suitable for the application of dynamical mean field theory for calculating material properties from first principles. An algorithm has been proposed which can be used for constructing the localized basis [T05/077].

J.4 Cold atoms in optical lattices and lattice boson models

J.4.1 Interaction-induced adiabatic cooling of fermions (O. Parcollet)

Due to recent spectacular experimental progresses, ultra-cold atoms gas can now be studied in strongly correlated regime, even though they are very dilute. Indeed an optical lattice can be used to create an "artificial solid", reducing the kinetic energy. The interaction between atoms can also be strongly enhanced with Feshbach resonances. Therefore, these systems may constitute realizations of traditional condensed matter models. The main advantage of cold atoms systems is the large experimental control (one can for instance change the value of the effective Coulomb repulsion by adjusting a magnetic field) while the main difficulty is the small number of experimental probes available at present.

In [T05/076], we study two-component cold fermions in an optical lattice, and discuss its modelisation with a Hubbard model. We propose an interaction-induced cooling mechanism, based on an increase of the "spin" entropy upon localization, an analogue of the Pomeranchuk effect in liquid Helium 3. We discuss its application to the experimental realization of the antiferromagnetic phase. We illustrate our arguments with Dynamical Mean-Field Theory calculations.

J.4.2 Superfluidity and confinement in one dimensional fermionic cold atoms (E. Boulat)

On top of strong correlations, ultra-cold atomic systems provide also an opportunity to investigate the effect of spin degeneracy since in general alkali fermionic atoms have (hyperfine) spins $F > 1/2$ in their lowest hyperfine manifold. Degeneracy in electronic problems, such as orbital degeneracy in d-electron materials, is known to be responsible for a wide variety of unusual physical phenomena. Thus, cold atom systems with spin $F > 1/2$ are likely to display novel physics properties with respect to the simpler $F = 1/2$ case.

In [T05/086], by means of a low energy approach, we study the interplay of strong correlations and degeneracy for a gas of ultra-cold (generic) spin $F = N - 1/2$ fermions trapped on a one dimensional optical lattice. We reveal the existence of a Z_N symmetry which plays a central role in the determination of the low-energy properties of these systems. This exact symmetry just corresponds to certain redefinitions of the atomic wave function's phases. Two different superfluid phases are found according to whether the Z_N symmetry is spontaneously broken or not: an unconfined BCS pairing phase and a confined molecular superfluid instability made of $2N$ fermions. The confined-unconfined phase transition is further studied and shown to belong to the Z_N parafermion universality class.

J.4.3 Bosons in optical lattices (F. Alet)

We study trapped bosons in optical lattices, focusing on the crossover from a gas of soft-core bosons to a Tonks-Girardeau hard-core gas in a one-dimensional optical lattice [T04/228]. Depending on the quantity being measured and on the required resolution, we find that the Tonks-Girardeau regime can already be observed at relatively small values of the interaction strength, as seen in the recent experiments (B. Paredes *et al.*, 2004).

J.4.4 Supersolids (F. Alet)

We studied with Quantum Monte Carlo simulations the phase diagram of a bosonic Hubbard model as a function of on-site and nearest-neighbor repulsions [T04/226]. We found that such systems can exhibit supersolid order, an exotic state of matter where *solid crystalline order and superfluidity coexist*. This study was motivated by recent experiments on solid ^{4}He (Kim & Chan, 2004) where indeed a small supersolid fraction has been identified.

J.5 Antiferromagnets

J.5.1 Bose-Einstein condensation of magnons (G. Misguich)

$TlCuCl_3$ is an antiferromagnetic insulator with a non-magnetic ground-state (spin singlet). The elementary excitations (magnons) have a gap that can be reduced by an external magnetic field. When the gap closes, the magnons *condense*. This is the onset of magnetic long-ranged order (perpendicular to the applied field). The work [T04/190], done with M. Oshikawa, used a realistic dispersion relation of the magnons (measured by neutron scattering experiments) in a self-consistent Hartree-Fock calculation. The results showed a quantitative agreement with experiments, thus resolving some issues concerning the role of fluctuations effects in this system.

J.5.2 Heat transport in one-dimensional gapped magnetic systems (E. Boulat)

The experimental heat conductivities of a number of two-leg spin ladder compounds are surprisingly large. We argue that this behavior can be traced back to the existence of approximate symmetries and corresponding weakly violated conservation laws. When investigating low-temperature transport theoretically one has therefore to include physical processes which break the symmetries of the effective low-energy theories. In clean systems, it is essential to consider contributions which break the continuous translation invariance but still respect the discrete lattice symmetry. While such terms give only exponentially small corrections to thermodynamic quantities, they are crucial to describe transport. We investigate how the formation of a gap influences transport and study the role of phonons in two models: as a simple toy model we will first investigate the dimerized xy-chain and then focus on the more complex case of a two-leg spin-1/2 ladder.

We show that thermal conductivity for the magnetic system only (without phonons) is very sensitive to the high energy details of the magnetic microscopic Hamiltonian. In contrast, when phonons are included and under the experimentally reasonable assumption that phonon modes are much softer than magnetic ones, we arrive at the conclusion that the magnetic contribution to thermal conductivity is fully controlled by the low energy features of the magnetic Hamiltonian. [T05/XX5]

J.5.3 Frustrated quantum antiferromagnets (G. Misguich)

The work [T03/181], done with C. Lhuillier (UPMC, Paris), is a review chapter in the book "Frustrated spin systems". It describes recent developments in the field of two-dimensional quantum antiferromagnets, with a special emphasis on systems without magnetic long-ranged order at $T = 0$ (quantum spin liquids).

The studies below are devoted to some specific spin-1/2 models with frustrated interactions:

- The specific heat of the Heisenberg spin-1/2 model on the kagome lattice shows a low-temperature peak. Despite of important theoretical efforts over the last years, its origin is not yet understood. In [T04/189] we analyzed this "anomaly" by means of high-temperature series expansion. Using a similar method, we analyzed [T03/022] the magnetic susceptibility data of the compound Li_2VOSiO_4 to estimate the magnitude of the magnetic couplings in this compound. Both works were done with B. Bernu (UPMC, Paris).
- The work [T04/200], a collaboration with the group of F. Mila (EPFL, Lausanne), was motivated by the unusual magnetic properties of the compound $Na_2V_3O_7$, that has a spin tube structure with frustrated interactions. We studied numerically (Density Matrix Renormalization Group simulations) an effective 1D model for this system.
- In [T04/085] we explored the connexion between i) the antiferromagnetic Ising model on the checkerboard lattice (square lattice with crossings every other plaquette) and ii) the 6-vertex model. In analogy with quantum dimer models, we introduced a quantum dynamics in the 6-vertex model and proposed a zero-temperature phase diagram for the resulting model. It shows three ordered phases and one continuous phase transition. One phase displays some unusual properties of spinon deconfinement.

J.5.4 Ising transition with a continuous symmetry (G. Misguich)

The Mermin-Wagner prevents the spontaneous breaking of a continuous symmetry at finite temperature in two dimensions. This however does not exclude a *discrete* broken symmetry in a model with a larger, continuous, symmetry. With the group of F. Mila, we studied (Monte-Carlo simulations) [T03/107] a classical $O(3)$ model in two dimensions (so called J_1-J_2 model) where the *frustration* leads to the emergence of *discrete* degrees of freedom and a phase transition belonging to the Ising universality class.

J.5.5 Quantum Monte Carlo simulations and Néel temperatures of quasi-1d and quasi-2d antiferromagnets (F. Alet)

Numerical simulations provide an excellent complementary tool to study strongly correlated systems whenever analytical methods fail or are too approximate. Among them, Quantum Monte Carlo (QMC) methods (when available) are often seen as the most powerful because they can treat very large systems *exactly* [T05/022]. We develop state-of-the-art QMC algorithms and apply them to realistic studies of magnetic systems. In particular, we have studied the dimensional crossover of quasi-1d and quasi-2d Heisenberg antiferromagnets [T03/256], leading to precise determinations of the Néel temperatures as a function of interchain (interplane) couplings. The results are directly applicable to experimental compounds. We also take part in the international project ALPS (*Algorithms and Libraries for Physics Simulations*), which is an open source effort aiming at providing high-end simulation codes for strongly correlated systems (see web page http://alps.comp-phys.org and publication [T04/227]). It provides black-box numerical codes to experimentalists, especially in the field of quantum magnetism.

J.6 Dimer models

J.6.1 Quantum dimer model for the kagome antiferromagnet (G. Misguich, D. Serban, V. Pasquier)

Heisenberg models offer accurate descriptions of many antiferromagnetic insulators but in several cases, quantum fluctuations drive the system to phases without any magnetic order, even at $T = 0$. Those phases, so called "spin-liquids", are not easily described directly in terms of the spin degrees of freedom but they can be qualitatively understood through simplified models where the basic degrees of freedom are *pairs* of spins coupled in a singlet state, also called valence-bond, or *dimer*. A quantum dimer model (QDM) describes the dynamics of these (short-ranged) singlet pairings. The hard-core coverings of the lattice by dimers are basis states of the Hilbert space and the"kinetic" terms of the Hamiltonian allow dimers to hop. Depending on the parameters, the ground-state may display some dimer crystalline order or may be a"dimer liquid" state (all the lattice symmetries remain unbroken).

The spin-1/2 antiferromagnetic Heisenberg model on the *kagome* lattice remains poorly understood. In [T03/021] we introduced a QDM which displays a similar phenomenology but which, due to specially tuned parameters, allows some exact analytical treatment. Unlike all the QDM studied so far, the kinetic terms (dimer hopping) have non-trivial *signs*. These signs appear when restricting the Heisenberg model to the subspace of valence-bond coverings. This QDM has a (somewhat hidden) local symmetry that allows to prove the absence of long-ranged dimer correlations and the presence of an *extensive residual entropy at zero temperature*, reminiscent of some properties of the spin-1/2 model observed in simulations. We showed (finite-size diagonalizations) that the QDM does *not confine* static monomers (= test charge) [T04/027].

J.6.2 Toy model for a topological quantum bit (G. Misguich, V. Pasquier)

n some of the dimer liquids mentioned above the ground-state has a degeneracy that depends on the *topology* of the lattice (disc, cylinder, etc.). While degeneracies usually come from some spontaneous symmetry breaking, the situation is more involved as the ground-states cannot be distinguished by *any* local observable. These properties, called *topological order* (X. G. Wen 1991), can be realized by a solvable toy QDM on the kagome lattice ([T02/058], SPhT report 2000-2002). We solved two extensions of the model in presence of perturbations (potential energy attracting the dimers along a line or introduction of monomers) [T04/188]. In both cases there is a critical value of the coupling above which the degeneracy (two-fold on a cylinder) of the ground-state is lifted. This model provides a solvable Hamiltonian for a topological quantum bit (controlled two-level system). We discuss how the phase transitions may be used to optimize the manipulation of the quantum bit.

J.6.3 Classical dimer models (F. Alet, J. Jacobsen, G. Misguich, V. Pasquier)

The study of quantum dimer models (QDM) have greatly benefited from the good understanding of some of their classical analogs. However, very little was known about classical dimer models in presence of short-ranged interactions beyond the hard-core repulsion, although such interactions are crucial in the QDM studied so far. In [T05/014] we studied numerically (Monte-Carlo and transfer-matrix calculations) a classical dimer model on the square lattice with nearest-neighbor dimer interaction (favoring dimer alignment). This model turned out to have two phases: a critical phase at high temperature described by a dilute Coulomb gas ("rough" in the height model terminology) and a dimer crystal at low temperature ("flat" in a height representation). The transition between the two phases is Kosterliz-Thouless like. We provided accurate estimates for the Coulomb gas coupling constant and critical exponents as a function of temperature (critical phase). The introduction of monomers (doping) and the implications on the finite-temperature phase diagram of the square-lattice QDM are also discussed.

J.7 Mesoscopic systems and quantum field theories for transport and tunneling

J.7.1 Spin dynamics of nanomagnet (O. Parcollet)

In spintronic, the electron's behavior is controlled with by spin instead of its charge. The recent discovery of spin injection effect, in which current modifies the magnetic configuration, has open the possibility of controlling magnetic properties with small currents and creating magnetic memories (MRAM). In these nanometric systems, at low temperature, interaction between quantum fluctuations and magnetism give rise to new effects. Understanding the mutual influence of magnetism and transport properties is both challenging from a fundamental point of view and crucial for applications.

In [T04/177], we studied the influence of the Coulomb blockade on the spin dynamic of a nanomagnet of spin $S_0 \sim 1000$ connected to magnetic leads via tunnel barriers. We showed that the standard phenomenological Landau-Lifshitz-Gilbert equation governing the spin dynamics must be replaced by a richer one. Indeed the interplay between Coulomb blockade and magnetism gives some additional structure to the current induced spin torque. In addition to the possibility of stabilizing uniform spin precession states, we find that the system is highly hysteretic: up to three different magnetic states can be simultaneously stable in one region of the parameter space (magnetic field and bias voltage).

J.7.2 Transport in nanosystems (H. Saleur)

It turns out that methods from integrable 1+1 quantum field theory can be generalized and applied to the exact calculation (even out of equilibrium) of transport properties in systems such as tunnel junctions between quantum Hall samples, small Josephson junctions, quantum dots etc. Strong interactions and non-perturbative effects are characteristic of these nanosystems, which, in addition to being rich of applications, are also laboratories for fundamental questions such as spin charge separation, charge fractionalization, asymptotic freedom, supersymmetry etc.

What makes exact calculations possible here is either the true one dimensionality of the systems, or the very localized interactions which allow, like in the Kondo case, coupling to s-waves only, and thus reduction to effective one dimensional theories such as the boundary sine-Gordon model and its multifields generalizations [T03/209].

J.7.3 Properties of Laughlin quasiparticles (H. Saleur)

One of the main questions studied over the last few years has been the dynamics of the "Laughlin quasiparticle", that is, generically, the fractionally charged excitations that appear in strongly correlated systems such as edge states in the fractional quantum Hall effect. Experimental study of tunneling between two $\nu = 1/3$ fractional quantum Hall samples had provided the first experimental evidence (based on analytical calculations by Kane and Fisher, and P. Fendley. A. Ludwig and H. Saleur, [T96/178], [T02/225]) for the existence of such excitations. Since then, exploring the properties of these excitations e.g. the way they interact, tunnel through barriers etc - has been a fascinating direction of research, both theoretically and experimentally.

Saleur's contributions (carried out in a series of works with B. Trauzettel, A. Koutouza, C. Glattli and P. Roche, [T03/037], [T03/210], [T03/235]) involve the calculation of scattering amplitudes at tunnel junctions (e.g. probability that one electron scatters into three Laughlin quasiparticles etc), and the calculation of the effect of a temperature or irrelevant operators on the shot noise and other properties. Aside from quantitative predictions, the main qualitative result of these studies is that, in the presence of strong interactions, non perturbative effects can and do occur, which are hard to understand semi-intuitively. For instance, finely tuned potentials can be almost transparent to Laughlin quasiparticles particles while opaque to bare electrons, an effect currently being investigated experimentally at the Weizmann Institute.

J.7.4 Quantum dissipation (H. Saleur)

Another question of great interest in this field is the effect of the environment and dissipation on tunneling processes in small circuits. In a work with I. Safi [T03/209], Saleur has shown that the coupling to the electromagnetic environment (ie, a resistance) in a circuit with small capacitance such as a small Josephson junction or a small tunnel junction produces Luttinger liquid physics, with its telltale signs of power laws and strong temperature dependence. This is currently being studied by D. Estève and C. Urbina at SPEC.

J.7.5 Luttinger liquids and superconductivity (H. Saleur)

Still another question has been the study of Josephson junctions of the type Supra — Luttinger liquid — Supra, which are currently being investigated by H. Bouchiat in the context of nanotubes. In a series of papers ([T02/221], [T02/224], [T03/087]) with J. S. Caux and F. Siano, H. Saleur has been able to calculate the Josephson current first in the special case where the Luttinger interaction parameter is $g = 1/2$, and then, for other values of g, after several years of technical difficulties. The problem has indeed strong relations with the double boundary sine-Gordon model, and explores very subtle aspects of the integrable description and the thermodynamic Bethe Ansatz.

J.7.6 Quantum Hall effect (V. Pasquier)

[T03/211] is related to some past work of V. Pasquier on the Hall effect where the noncommutative geometry arizes as an effect of projection in the Lowest Landau Level.

The authors investigate the non-commutative (NC) field theory approach to the vortex liquid system restricted to the Lowest Landau level (LLL) approximation. NC field theory effectively takes care of the phase space reduction of the LLL physics in a $\star$-product form and introduces a new gauge invariant form of a quartic potential of the order parameter in the Ginzburg-Landau (GL) free energy. This new quartic interaction coupling term has a non-trivial equivalence relation with that obtained by Brézin, Nelson and Thiaville in the usual GL framework. The consequence of the equivalence is discussed.

CHAPTER K

Biological Systems and Soft Condensed Matter

Contents

The Biological Systems and Soft Condensed Matter group comprises two permanent physicists (T. Garel and H. Orland) and one post-doc (G. Vernizzi). It has always been focused on the application of sophisticated statistical physics methods to these systems.

Over the years, the activity in biological systems and soft condensed matter has shifted from proteins, polymers and polyelectrolytes to problems where the interactions are simpler and better known.

Motivated by the development of single molecule experiments on DNA (stretching, twisting, unzipping) and by the increasing use of DNA chips, we have modeled various aspects of the DNA denaturation transition relevant to these experimental studies.

In a different spirit, in recent years, RNA has become a key player in the molecular biology of the cell, as it was shown that it could be a regulator or a catalyst, and not only an information carrier. A lot of biological information is encoded in the shape (or folding) of RNA. We have thus developed a new theory for RNA folding, where RNA folds are characterized by their topological genus. Both problems have in common the fact that the dominant interactions (except for short-range Coulomb interactions) are of the Watson-Crick pairing type, a fact which enormously simplify the models.

The above studied biopolymers are strongly charged and are immersed in ionic solutions in the cell. We have thus pursued our research on polyelectrolytes and electrolytes. We have developed some new approaches to charged fluids (electrolytes) in presence of charged surfaces, which mimic ions in the cells, in presence of membranes and DNA.

In section K.1, general reviews on protein folding are presented, with an emphasis on the homo- and hetero- polymeric aspects of these biopolymers.

In section K.2, we show how the most successful approach to the denaturation transition in DNA, namely the Poland-Scheraga model, can be generalized as a full theory for DNA hybridization, irrespective of the size and composition of the two strands. As such, it allows to better understand the extraordinary specificity of molecular recognition, and the effect of mismatches in DNA chips. Another kind of generalization allows to include the effect of a torque applied on the strands, and study the role of supercoiling in DNA denaturation.

In section K.3, using a topological classification of RNA structures (introduced previously in the lab), we show how to actually predict (by Monte Carlo calculations or by recursion relations) pseudo-knots, and also to exactly enumerate RNA structures as a function of their topological genii. This whole topic is an example of the cross-fertilization of various fields studied in the lab (matrix field-theories, combinatorial optimization, statistical and biological physics).

Finally, in section K.4 devoted to electrolytes, theories are presented to bridge the gap between the weak (Poisson-Boltzmann) and strong (exponential) coupling regime observed when the ionic strength and other charges are varied in biological systems.

K.1 Protein folding (T. Garel, H. Orland)

Different aspects of protein folding are illustrated by simplified polymer models. Stressing the diversity of side chains (residues) leads one to view folding as the freezing transition of a heteropolymer. Technically, the most common approach to diversity is randomness, which is usually implemented in two body interactions (charges, polar character,..). On the other hand, the (almost) universal character of the protein backbone suggests that folding may also be viewed as the crystallization transition of an homopolymeric chain, the main ingredients of which are the peptide bond and chirality (proline and glycine notwithstanding). The model of a chiral dipolar chain leads to a unified picture of secondary structures, and to a possible connection of protein structures with ferroelectric domain theory [T03/051] [T02/086] [T03/096].

K.2 DNA denaturation (T. Garel, H. Orland)

K.2.1 Generalized Poland-Scheraga model for DNA hybridization (T. Garel, H. Orland)

The Poland-Scheraga (PS) model for the helix-coil transition of DNA considers the statistical mechanics of the binding (or hybridization) of two complementary strands of DNA of equal length, with the restriction that only bases with the same index along the strands are allowed to bind. We extend this model by relaxing these constraints: We propose a generalization of the PS model which allows for the binding of two strands of unequal lengths N_1 and N_2 with unrelated sequences. We study in particular (i) the effect of mismatches on the hybridization of complementary strands (ii) the hybridization of non complementary strands (as resulting from point mutations) of unequal lengths N_1 and N_2. The use of a Fixman-Freire scheme scales down the computational complexity of our algorithm from $O(N_1^2 N_2^2)$ to $O(N_1 N_2)$.The simulation of complementary strands of a few kbps yields results almost identical to the PS model. For short strands of equal or unequal lengths, the binding displays a strong sensitivity to mutations. This model may be relevant to the experimental protocol in DNA microarrays, and more generally to the molecular recognition of DNA fragments. It also provides a physical implementation of sequence alignments. [T04/014]

K.2.2 Physical model for helix-coil transitions in supercoiled DNA (T. Garel, H. Orland)

The model of helix-coil transitions in DNA, describing the opening of the double-helix, plays an important role in structural and molecular biology. The physics of this model is well established only for unconstrained linear DNAs. The extension to supercoiled strands mostly relies on phenomenological laws. We derive here the physics of the helix-coil transition in supercoiled DNA from a simple model for the twist energy. We modify the linear model to account for a torque applied to the extremities of the molecule, and deduce the properties of supercoiled DNA through a Legendre transform. In this framework we derive the entropy of constrained loops and the properties of denaturation under fixed torque or fixed supercoiling. Finally, for the the homogeneous case, and weak supercoiling, we recover the phenomenological quadratic law relating the torsional energy to the fraction of unpaired bases [T04/136]

K.2.3 Electric response of DNA hairpins to magnetic fields (H. Orland)

Although they have a quite large gap (~ 0.5 eV), DNA and RNA fragments can be semi-conductors, in presence of a strong electric field. In this paper, we study the conductivity of single-stranded biopolymers (DNA or RNA) in presence of a strong magnetic field. The advantage of using single stranded molecules is that they may fold onto themselves to make hairpin-like structures that contain helical parts as well as open loops or bulges, through which there may be a magnetic flux. A helical part can be viewed as a twisted ladder. We show that the current amplitude can be modulated by the applied magnetic field. The details of the electric response strongly depend on the helical twist angles. The current exhibits periodicity for geometries where the flux through the plaquettes of the ladder can be cancelled pairwise (commensurate twist). Further twisting the geometry (by using gyrase) and changing its length causes complex aperiodic oscillations. Persistent currents are also studied: They reduce to simple harmonic oscillations if the system is commensurate, otherwise deviations occur due to the existence of closed paths leading to a washboard shape. [T04/126]

K.3 RNA folding (H. Orland, G. Vernizzi)

K.3.1 A Monte Carlo method for folding RNA

Many aspects of DNA and RNA biological functions depend on their peculiar 3D structure. The complete prediction of the actual structure (in particular pseudoknots) from their base sequence, is a challenging open problem. Recently Random Matrix Theory has been proposed as the key for a possible solution. By using a special graphical representation in which the secondary structures are described by planar diagrams, and RNA pseudoknots by nonplanar diagrams, we analyze the non-planar topologies of RNA structures. We propose a classification of RNA pseudoknots according to the minimal genus of the surface on which the RNA structure can be embedded (see Fig. K.1). This classification provides a simple and natural way to tackle the problem of RNA folding prediction in presence of pseudoknots. Based on that approach, we have developed a software based on a Monte Carlo algorithm for the prediction of pseudoknots in an RNA molecule. The role of the topological expansion term $1/N^2$, (where N is the size of the matrices) has been substituted by an effective "topological chemical potential" that in practice should correspond to the concentration of Mg^{++} ions in the solution where the RNA folds. The statistical model and the set up of the simulation are described in the papers [T04/061] [T04/205].

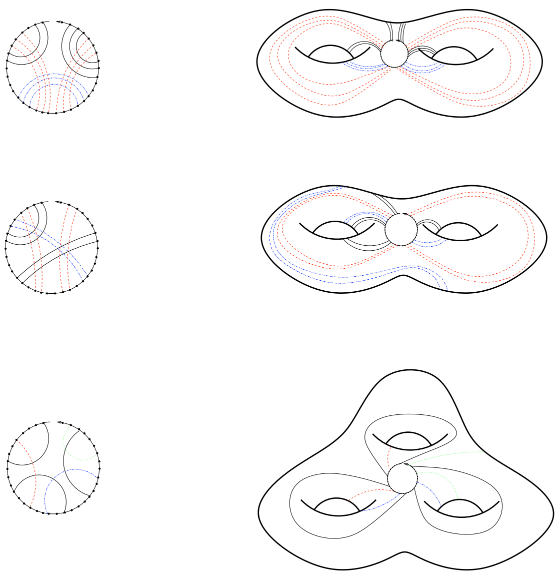

Figure K.1: Two pseudoknots of genus 2 and one of genus 3.

K.3.2 Exact enumeration of pseudoknots in a simplified model of RNA

We considered a simplified case of the Matrix Model in [T04/061], which can be applied to the folding of a flexible homopolymer at low temperature. The model has been solved analytically in [T04/135] and provides important informations about the distribution of the topology of pseudoknots for long sequences.

K.3.3 A steepest descent calculation of RNA pseudoknots

RNA is a single stranded biopolymer which has the property of folding onto itself (by making Watson-Crick pairings). A large fraction (about 90%) of these pairings are planar, and constitute the secondary structure of RNA. The remaining pairings are non-planar, and constitute the so-called pseudo-knots. In a previous work, using Matrix Field Theory, we had proposed that pseudo-knots might be classified by the topological genus of the surface on which they could be drawn without any crossing. In this paper, using a steepest-descent method on the Matrix Field theory, we have investigated the topological structure of pseudo-knots of genus 1. We show that pseudo-knots of genus 1 can have only 8 different topologies. Among these 8 topologies, some are very well-known in RNA, whereas some others are still to be found [T02/069].

K.3.4 An algorithm for RNA pseudoknots

The simplest way to compute RNA structures is through recursion relations. Such recursions had been obtained for planar structures in the late 80s. In this paper, we show how these recursion relations for (planar) secondary structures can be generalized into recursion relations for structures of genus 0 and 1. However, their algorithmic complexity scales like L^6, where L is the number of nucleotides. [T03/222].

K.4 Coulombic systems (H. Orland)

K.4.1 Variational charge renormalization in charged systems

When a highly charged surface (plane, cylinder, sphere) is immersed in a salt solution, the potential at large distances has a Debye-Hückel form, with a prefactor given by the charge density of the surface multiplied by a factor smaller than one. This factor, called charge renormalization, accounts for the fact that the surface charge is strongly screened at short distances, and attracts more counter-ions than co-ions. Within a field-theoretic formulation, the concept of surface-charge renormalization is recovered within a simple one-parameter variational procedure. For a single charge planar surface, the Poisson-Boltzmann surface potential is recovered both in the weak-charge and strong-charge regime. This technique is also applied to non-planar geometries where closed-form solutions of the non-linear Poisson-Boltzmann equation are not available. In the cylindrical case, the Manning charge renormalization result is obtained in the limit of vanishing salt concentration. However, for intermediate salt concentrations a slow crossover to the non-charge-renormalized regime (at high salt) is found with a quasi-power-law behavior which helps to understand conflicting experimental and theoretical results for the electrostatic persistence length of polyelectrolytes. In the spherical geometry charge renormalization is only found at intermediate salt concentrations. [T02/185]

K.4.2 Test-charge theory for the electric double layer

Interactions between charged objects in solution are determined by the distribution of ions around them. Understanding these distributions is thus of fundamental importance for theoretical treatment of water soluble (i.e. polar) macromolecules such as polyelectrolytes, charged membranes, and colloids. In recent years, much interest has been devoted to correlation effects in ionic solutions and to attempts to go beyond mean field theory in their treatment. In particular it has been realized that such effects can lead to attractive interactions between similarly charged objects, as was demonstrated in theoretical models simulations and experiments. We present a model for the ion distribution near a charged surface, based on the response of the ions to the presence of a single test particle. Near an infinite planar surface this model produces the exact density profile in the limits of weak and strong coupling. At intermediate coupling this approach leads to approximate density profiles that agree qualitatively with Monte-Carlo simulations. For large couplings, the model predicts a crossover from exponential to algebraic decay at large distances. The modified mean-field equation takes into account strong correlation effects, and in particular produces the "correlation hole" predicted around each counter-ion close to the plane in the strong coupling regime [T04/018].

CHAPTER L

Cross-disciplinary Works

Contents

L.1 Analytic number theory (A. Voros)

The analytical study of "secondary zeta functions" built over the Riemann zeros, started in an earlier article [T01/033], has been substantially developed and extended.

The *Riemann zeta function* $\zeta(\rho) = \sum_{k=1}^{\infty} k^{-\rho}$ is known to have countably many complex zeros besides its real ones; those are called *nontrivial* or Riemann zeros, and have the form $\rho_{\pm k} = \frac{1}{2} \pm \mathrm{i}\tau_k$ (with $\mathrm{Im}\,\tau_k < \frac{1}{2}$; the famous Riemann Hypothesis conjectures that all the τ_k are actually *real*). While the Riemann zeros continue to elude us individually, three kinds of zeta functions built over them (i.e., "secondary") now display many explicit properties:

- 1st kind: $Z_1(s,x) = \sum\limits_{\pm k} (x - \rho_{\pm k})^{-s}$;
- 2nd kind: $Z_2(s,x) = \sum\limits_{k} ({\tau_k}^2 + x)^{-s}$;
- 3rd kind (more singular): $\sum\limits_{k} (\tau_k + y)^{-2s}$.

Namely, a) all three are meromorphic functions in the whole complex s-plane, and their polar structures can be explicitly computed; b) for the first two, countably many values are computable in closed form, essentially in terms of the Riemann zeta function itself: those "special values" are mainly, with $j = 1$ or 2, $Z_j(n,x)$ for any relative integer n, and $-\partial_s Z_j(s=0,x)$ which upon exponentiation evaluate certain *zeta-regularized infinite products* over the Riemann zeros, such as $\prod_{\pm k} \rho_{\pm k} = 1/\sqrt{2}$ (under the same regularization as for functional determinants in field theory). The upshot is a large stock of explicit results, largely unreported before, about the Riemann zeros taken *collectively* [T03/078].

The formalism has then been extended to cover zeros of other zeta functions or number-theoretical generalizations of $\zeta(s)$, essentially those which have a functional equation similar to Riemann's: for instance, Dedekind zeta functions — zeta functions of algebraic number fields — and Dirichlet L-functions for real primitive Dirichlet characters [T03/159].

Another by-product of the earlier work [T01/033] is an *asymptotic* criterion for the Riemann Hypothesis (RH, or the conjecture that all the τ_k are *real*): namely, a specified numerical sequence u_n (related to the Keiper (1995) and Li (1997) coefficients) will, for $n \to +\infty$, either *go to* 0 if RH is true, or else *oscillate with an exponentially growing amplitude* if RH is false. This brings a new, very sharp and dichotomic, characterization of the Riemann Hypothesis [T04/140].

L.2 Brownian motion in mathematics, physics, and biology (B. Duplantier)

[T05/082] provides a survey of Brownian motion in physics and mathematics, past and present. It starts with the rich history of Brownian motion, with detailed emphasis on the fundamental contributions by Sutherland, Einstein, Smoluchowski and Langevin to its theory, and Perrin to its experimental verification. Some emphasis is put on the often overlooked earlier derivation by William Sutherland, from Australia, of the famous relation $D = RT/6\pi\mathcal{N}\eta a$, where R is the perfect gas constant, $\mathcal{N}$ Avogadro's number [$R/\mathcal{N} = k_B$, Boltzmann's constant], η the fluid viscosity, and a the radius of the suspended Brownian particle. The various subsequent derivations of increasing generality, due to Einstein, are presented in detail.

The spectacular relevance of Brownian motion to biophysics is illustrated by recent experiments, where the direct observation of Brownian fluctuations provides a non-invasive measurement of pico-Newton forces exerted on a single DNA macromolecule.

The fundamental importance of Brownian motion in mathematics is illustrated in two examples. The classical probabilistic representation of Newtonian potential theory via Brownian motion is explained in an elementary way. A final part provides a description of recent progresses in the fractal geometry of the planar Brownian curve, via the rich conformal invariance and multifractal concepts associated with it.

CHAPTER M

Diffusion of Knowledge

Contents

M.1 Academic monographs

[T02/112] *Intégrale de chemin en mécanique quantique : introduction*, by J. Zinn-Justin, *Collection Savoirs actuels* (EDP Sciences and CNRS Editions, 2003, 296 pages).

[T03/071] *Introduction to Classical Integrable Systems* by O. Babelon, D. Bernard (SPhT), M. Talon, *Cambridge Monographs on Mathematical Physics* (Cambridge University Press, 2003, 602 pages).

[T04/021] *Random Matrices* (3$^{\text{rd}}$ edition) by M.L. Mehta, *Pure and Applied Mathematics Series 142* (Elsevier, London, 2004, 688 pages).

M.2 Poincaré seminars

The Poincaré seminar, which takes place in Paris, is a series of pedagogical talks which aim at explaining a topic of current interest both from a theoretical and an experimental point of view, possibly complemented by a historical introduction. Directly inspired by the Bourbaki seminar in mathematics, it aims at a general audience of mathematicians and physicists and does not require any specialized knowledge.

Bertrand Duplantier is an editor of the "Séminaire Poincaré proceedings":

- [T02/100] *L'Énergie du Vide* (Séminaire Poincaré 2002-I) with contributions by R. Balian [T02/090] and B. Duplantier [T02/092].
- [T02/187] *La Renormalisation* (Séminaire Poincaré 2002-II) with a contribution by J. Zinn-Justin [T02/114].
- [T03/040] *La Condensation de Bose-Einstein* (Séminaire Poincaré 2003-I)
- [T03/173] *L'Entropie* (Séminaire Poincaré 2003-II) with a contribution by R. Balian [T03/193].

- [T04/219] *La Théorie des cordes, des particules au Cosmos* (Séminaire Poincaré 2004-I).
- [T04/217] *Effet Hall quantique* (Séminaire Poincaré 2004-II) with a contribution by V. Pasquier [T04/218]
- [T05/083] *Einstein, 1905-2005* (Séminaire Poincaré 2005-I) with contributions by B. Duplantier ([T05/082], see Chap. L) and J. Bros [T05/084].

M.3 History of sciences

Einstein's point of view on Statistical Mechanics (1910) (B. Duplantier)

[T05/081] is the translation from German to French of a previously unpublished lecture by A. Einstein ("Sur le principe de Boltzmann et quelques conséquences qui en découlent immédiatement"), delivered in 1910 at a meeting of the Zürich Physical Society, and recently discovered. It presents in a very vivid way Einstein's point of view on Statistical Mechanics at that time, based on the use of Boltzmann's formula for the entropy, and the role of fluctuations therein.
The latter is illustrated by a new demonstration of the famous physical formula for the diffusion coefficient D of a Brownian particle, as a function of temperature, perfect gas constant, Avogadro's number, fluid's viscosity, and radius of the suspended particle. Einstein considers the second moment of the position of a suspended particle in presence of a gravitational potential, and derives from the stationarity of its motion under the combined action of gravity and Brownian fluctuations, the expression of the Brownian diffusion coefficient D. I have added an extended comment to show the consistency of Einstein's approach for arbitrary potentials and general moments.

M.4 Biographical works

[T03/056] Teamed up with Professor Bernard Malgrange, A. Voros wrote the second part of a two-part analysis of Professor Frédéric Pham's lifelong work in axiomatic S-matrix theory, resurgence theory in complex analysis, and exact WKB methods, for a conference held in his honor at his retirement.

[T03/170], by A. Voros *et al.*, published in Physics Today, is an obituary notice for Professor Nandor L. Balazs, a regular and active collaborator of our Department throughout the eighties.

[T05/099], by J.-B. Zuber, published in the Saclay Journal, recalls the memory of our colleague Claude Itzykson, ten years after his death.

M.5 Tutorial papers and popular science

[T04/025] In the book *Demain, la physique* (Odile Jacob, Paris, 2004, 377 pages), ten famous French physicists, among which our colleague Roger Balian, present in simple words the current status of research in physics, the big questions that are still open.

[T02/156] In *Le Nucléaire expliqué par des physiciens* (EDP Sciences, Les Ulis, 2002, 320 pages), written under the direction of Paul Bonche, physicists explain the various aspects of nuclear energy in simple words.

[T04/148] "Les Mirages de la gravitation", by Francis Bernardeau, in *Pour la Science* 326, p.84, December 2004.

[T04/001] "Les distortions gravitationnelles pour cartographier l'Univers", by F. Bernardeau and Y. Mellier, in *Images de la physique, CNRS*, 2004.

[T03/046] "Wave propagation in a chiral fluid: an undergraduate study", by T. Garel, Eur. J. Phys. 24, 507-517 (2003) [physics/0304010] .

[T03/171] "A Newtonian pre-introduction to gravitational lenses" by T. Garel, Eur. J. Phys. 25, 771-780 (2004) [physics/0311038]

[T03/096] "DNA, RNA, and Protein Folding", by Henri Orland, in AAPPS (Association of Asia Pacific Physical Societies) Bulletin, April 2003.

[T05/067] "L'étrangeté du monde quantique", by Roger Balian, in *La Jaune et la Rouge* 604, April 2005.

[T02/186] "Prédire la structure 3d des protéines", by Henri Orland, in *Clefs CEA* 47, 2002-2003.

[T02/201] "Les avatars de la théorie pour une physique prédictive", by Jean Zinn-Justin, in *Clefs CEA* 47, 2002-2003.

[T03/068] "Plateaux d'aimantation pour des spins frustrés", by Grégoire Misguich and Thierry Jolicoeur, in *Phases Magazine, la lettre du DRECAM et du SPhT* 28, April 2003.

M.6 Science and society

[T02/065] In his monograph *Vivre savant sous le communisme* (*Collection Débats*, Belin, Paris, 2002, 301 pages), Georges Ripka investigates the life of scientists in Eastern Europe during the communist era.

[T05/065] "Les Multiples Visages de l'énergie", by R. Balian, is a contribution to the book *L'énergie de demain. Techniques — Environnement — Economie* (EDP Sciences, Les Ulis, 2005, 688 pages), which discusses the various sources of energy, and their interaction with climate.

[T04/184] "Les Savoirs fondamentaux au service de l'avenir scientifique et technique" (in *Les Cahiers du débat*, Fondation pour l'innovation politique, November 2004), by Roger Balian, Jean-Michel Bismut, Alain Connes, Jean-Pierre Demailly, Laurent Lafforgue, Pierre Lelong and Jean-Pierre Serre, discusses the issue of how to teach sciences in schools and universities, as well as the following article:

[T03/231] "Le point de vue de la SFP sur l'enseignement des sciences", by A. Morel, in *Bulletin de la Société française de physique* 142, January 2004.

[T03/002], written by R. Balian and J. Zinn-Justin as part of a "Rapport sur la science et la technologie" (RST) of the Academy of Sciences, investigates the relations between mathematics and physics.

[T04/123] "Un appel : sauvons le climat. Manifeste" ("Manifesto on Saving the Climate") by R. Balian *et al.*, in *La Jaune et la Rouge*, September 2004.

[T03/157] "A propos du Débat national sur les énergies", by R. Balian *et al.*, in *Bulletin de la Société française de physique* 141, October 2003.

Index

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T05/095 **BOONEKAMP M., ROYON C., PESCHANSKI R.,** *Diffractive Higgs Production at the LHC: Results and Open Questions,* in: Proceedings of the 10th International Conference on the Structure of Baryons (Baryons04), Ecole polytechnique, Palaiseau, France, October 25-29 2004, Nucl. Phys. A 755, 599-602 (2005), Guidal M., Kunne F., Pire B., Soyeur M., eds.

T05/098 **SOYEZ G.,** *Fluctuations effects in high-energy evolution of QCD,* submitted to Phys. Rev. D [hep-ph/0504129]

T05/101 **BAUER M., BERNARD D., KYTÖLÄ K.,** *Multiple Schramm-Loewner Evolutions and Statistical Mechanics Martingales,* to appear in J. Stat. Phys. [math-ph/0503024]

T05/102 **BARRAU A., SALATI P., SERVANT G., DONATO F., GRAIN J., MAURIN D., TAILLET R.,** *Kaluza-Klein dark matter and galactic antiprotons,* Phys. Rev. D 72, 063507 (2005) [astro-ph/0506389]

T05/103 **COULOMB S., BAUER M., BERNARD D., MARSOLIER M.C.,** *Gene essentiality and the topology of protein interaction networks,* to appear in Proc. R. Soc. B

T05/110 **BRAX P., MARTIN J.,** *Shift symmetry and inflation in supergravity,* Phys. Rev. D 72, 023518 (2005) [24 pp.] [hep-th/0504168]

ANNEXES :

BILAN QUANTITATIF DES PUBLICATIONS

On dénombre 747 publications pour la période juin 2002 – mai 2005, dont plus de la moitié dans des revues internationales avec comité de lecture. Les principales revues sont

Nom de la revue	Nombre de publications SPhT
Physical Review D (particles, fields, gravitation and cosmology)	57
Nuclear Physics B (particle physics, field theory and statistical systems, physical mathematics)	38
Nuclear Physics A (nuclear and hadronic physics)	35
Journal of Physics A (general and mathematical)	34
Physical Review Letters	32
Physics Letters B (nuclear physics and particle physics)	31
Journal of High Energy Physics	24
Physical Review B (condensed matter and materials physics)	21
Physical Review C (nuclear physics)	14
Physical Review E (statistical, nonlinear, and soft matter physics)	13
European Physical Journal B (condensed matter physics)	13
Journal of Statistical Mechanics, Theory and Experiment	12
Communications in Mathematical Physics	9
Journal of Statistical Physics	9
Monthly Notices of the Royal Astronomical Society	8
Physics Reports	7
Europhysics Letters	6
Nature	2

PRIX, MEDAILLES, DISTINCTIONS

• **Roger BALIAN** :	Commandeur de l'ordre des palmes académiques	2004
• **Denis BERNARD** :	Médaille d'argent CNRS	2004
• **Phuong Mai DINH** :	Prix Jeune Chercheur Daniel Guinier de la Société Française de Physique	2002
	Prix de thèse de l'Ecole polytechnique	2003
• **Bertrand DUPLANTIER** :	Chevalier de l'ordre des palmes académiques	2004
• **Francois GELIS** :	Médaille de bronze CNRS	2003
• **Christophe GROJEAN** :	Médaille de bronze CNRS	2002
• **Mannque RHO** :	"KBS Science Prize" (Korean Broadcasting System, Corée)	4 mars 2004

PROGRAMMES, PROJETS, CONTRATS

COLLABORATIONS INSTITUTIONNALISEES ET FINANCEMENTS EXTERIEURS

PHYSICIENS DU SPhT CONCERNES	SOURCE DE FINANCEMENT	NOM DU PROJET	NOM DU RESPONSABLE	DATES
David (coordinateur local), Di Francesco, Eynard, Guitter, Kostov	Marie Curie Research Training Network (FP5) Commission Européenne	EUROGRID, Dicrete Random Geometries: from Solid State Physics to Quantum Gravity	Desmond Johnston	1/4/2000-31/3/2004
Nonnenmacher	Marie Curie Research Training Network (FP5) Commission Européenne	Mathematical Aspects of Quantum Chaos	Jonathan Robbins	1/9/2000-31/8/2004
Bernard	Marie Curie Research Training Network (FP6) Commission Européeene	ENIGMA, European Network in Geometry, Mathematical Physics, and Applications	Gregorio Falqui (SISSA, Trieste)	01/01/2005-31/12/2008
David	Marie Curie Research Training Network (FP6) Commission Européeene	ENRAGE, Random Geometry and Random Matrices: From Quantum Gravity to Econophysics	Renate Loll (Utrecht)	01/01/2005-31/12/2008
Savoy	Marie Curie Research Training Network (FP6) Commission Européeene	The Quest For Unification: Theory Confronts Experiment	Ignatios Antoniadis (Ecole polytechnique, Palaiseau)	01/01/2005-31/12/2008
Vanhove	Marie Curie Research Training Network (FP6) Commission Européeene	ForcesUniverse (Constituents, Fundamental Forces and Symmetries of the Universe)	Dieter Lüst (Munich)	01/01/2005-31/12/2008
Saleur	Marie Curie International Reintegration Grant Commission Européenne			1/11/2004-31/10/2006
Vernizzi	Marie Curie Intra - European Fellowships Commission Européenne		Henri Orland	1/2/2004-31/1/2006

Billoire, Houdayer, Luck	Programme ESF (European Science Foundation)	Statistical Physics of Glassy and Non-Equilibrium Systems (SPHINX)	David Sherrington	1999-31/12/2004
Saleur	Programme ESF (European Science Foundation)	Interdisciplinary Statistical and Field Theory Approach to Nanophysics and Low-Dimensional Systems		depuis 2005
Grojean	ACI (Action concertée incitative) Jeunes chercheurs Ministère de la Recherche	ACI Grojean	Christophe Grojean	09/2002-08/2005
Pépin	ACI (Action concertée incitative) Jeunes chercheurs Ministère de la Recherche	ACI Pépin	Catherine Pépin	09/2003-08/2006
Orland	ACI IMPBIO (Action Concertée Incitative Informatique, Mathématique et Physique en Biologie Moléculaire) Ministère de la Recherche	Gene Phys	Edouard Yeramian	09/2004-08/2006
Guitter, Di Francesco	ACI Masses de Données Ministère de la Recherche	GEOCOMP (Compression de données de nature géométrique)	Gilles Schaeffer	09/2004-08/2007
Grojean	Programme CEFIPRA	Brane-world phenomenology	E. Dudas (Orsay)	06/2003-05/2006
Ollitrault	Programme CEFIPRA (centre franco-indien pour la recherche avancée)	Hot and dense Matter in Quantum Chromodynamics	J.-Y. Ollitrault	01/2005-12/2007
Grojean	Programme ECONET			09/2004-08/2006
Peschanski	Programme ECONET			09/2004-08/2006
Blaizot	Programme d'actions intégrées AMADEUS (France-Autriche)		J-P. Blaizot	01/2003-12/2004

SEMINAIRES DU SPhT

CEA/Saclay, SPhT-SPEC, Bâtiment 774, Salle Claude Itzykson

JOUR	THEME	ORGANISATEURS
Lundi 11h00	*Séminaire de physique mathématique*	S. Nonnenmacher, V. Pasquier
Lundi 14h15	*Séminaire de physique statistique*	G. Biroli
Mardi 11h00	*Séminaire général du SPhT*	B. Duplantier
Mercredi 14h15	*Séminaire de physique des particules et de cosmologie*	F. Gélis, C. Grojean
Jeudi 11h00	*Séminaire de théorie de la matière condensée sur le plateau*	O. Parcollet
Vendredi 11h00	*Séminaire de matrices, cordes et géométries aléatoires*	D. Bernard, I. Kostov

LES RENCONTRES CLAUDE ITZYKSON, PROGRAMMES

7ème rencontre Claude ITZYKSON : Gènes et physique
19-21 juin 2002
Organisateurs : M. BAUER, D. BERNARD et H. ORLAND (SPhT, Saclay)

- Ralf Bundschuh
  Sequence alignment and statistical physics
- Jean Thierry-Mieg
  Gene quantization
- Misha Gromov
  Geometry of Sequence and Configuration Spaces
- François Képès
  Topological and causal structure of the yeast transcriptional regulatory network
- Stanislas Leibler
  Space, Time and Genetic Networks
- Boris Shraiman
  Bio-physics and Bio-informatics of Transcription Control
- Eytan Domany
  Cluster Analysis of DNA Microarray Data
- Dan Notterman
  Transcriptional gene expression profiles of colon cancer: gene identification and pattern recognition
- François Radvanyi
  Transcriptome and tumor progression
- Paul Higgs
  Molecular Phylogenetics, RNA Sequences and Mitochondrial Genomes

- Raphaël Itzykson
  Assessing the functionnal relevance of transcriptome analysis: building a model for T cell leukemia
- Edward Trifonov
  Early life coping with polymer statistics
- Roland Netz
  DNA complexes, DNA collapse, and field effects
- David Mukamel
  Modelling DNA denaturation
- Didier Chatenay
  Folding and unfolding of single RNA molecule
- Françoise Livolant
  Conformation, interactions and supramolecular ordering of isolated nucleosome core particles
- David Bensimon
  The activity of a single helicase: recQ
- Jean-Louis Sikorav
  DNA renaturation

8ème rencontre Claude ITZYKSON : Quel(s) modèle(s) pour l'Univers primordial ?
18-20 juin 2003

Organisateurs : F. BERNARDEAU, Ph. BRAX, C. GROJEAN et S. LAVIGNAC (SPhT, Saclay)

- G. Veneziano
  Perturbations in non-conventional cosmological scenarios
- V. Rubakov
  Long-distance modification of gravity: is it possible?
- P. Salati
  Quintessence, scalar fields and the neutralino relic abundance
- J. March-Russell
  Meta-stable String Vacua and Membrane nucleation and metastable string vacua
- V. Mukhanov
  CMB-slow or how to estimate cosmological parameters by hand (PowerPoint, InternetExplorer)
- L. Kofman
  Topics of string theory in cosmology
- S. Sarkar
  Cosmic ray signature of superheavy relics
- S. Carroll
  Dark energy and the preposterous universe
- E.W. Kolb
  Inflation and the CMB
- Masiero
  SUSY and quintessence: hopes and worries
- H.P. Nilles
  A quintessential axion
- K. Olive
  Dark matter from minimal supergravity models
- L. Roszkowski
  Supersymmetric WIMP as dark matter
- R. Emparan
  Black hole astrophysics in AdS braneworlds
- G. Felder
  Radiating tachyon matter
- L. Pilo
  Massive gravity on a brane

- G. Servant
  Radion active universe
- G. Bertone
  Indirect detection of dark matter in the Galactic halo
- M. Bastero-Gil
  Large scale sctructure from the MSSM Higgs
- F. Ferrer
  Annihilation radiation from neutralinos in dwarf galaxies
- S. Winitzki
  Creation of particles in a tunneling universe
- Gregori
  Experimental cosmological constant from string theory
- M. Borunda
  Aspects of string gas cosmology at finite temperature
- J. Cline
  Implications of minimal-duration inflation
- T. Damour
  Runaway dilaton and varying constants
- Buonanno
  Gravitational waves and the early Universe
- G. Sigl
  Ultra-high energy cosmic rays: physics and astrophysics at extreme energies
- R. Brandenberger
  Challenges for brane gas cosmology
- P. Binetruy
  Time-dependence in string theory
- F. Quevedo
  Branonium

9ème rencontre Claude ITZYKSON : Les nouvelles frontières de QCD
9-11 juin 2004
Organisateurs : F. GELIS, E. IANCU, D. KOSOWER (SPhT, Saclay)

- F. Wilczek
  Hadron Systematics, Diquarks, and (Maybe) Pentaquarks
- N. Glover
  Progress in NNLO scattering cross sections
- S. Catani
  Soft-gluon resummation in QCD cross sections
- S. Moch
  Frontiers in perturbative QCD : splitting functions at three loops
- S. Frixione
  Higher-order QCD corrections and Monte Carlos: recent progress
- T. Gehrmann
  Techniques for Precision Jet Calculations
- G. Salam
  CAESAR : Computer automated resummations
- S. Forte
  A consistent theory of perturbative evolution at small x
- R. Pisarski
  Gross-Witten Point and the Deconfining Phase Transition
- A.H. Mueller
  Unitarization and saturation in QCD at small x

- L. McLerran
  What are the Theoretical Foundations of the Color Glass Condensate ?
- D. Rischke
  A General Effective Theory for Dense Quark Matter
- T. Rebhan
  Weak coupling techniques for the strongly interacting QGP
- Z. Fodor
  Hot and dense QCD on the lattice
- D. Triantafyllopoulos
  From Classical to Quantum Saturation in the Nuclear Gluon Distribution
- S. Munier
  New insights in high energy QCD from general tools of statistical physics
- Yu. Dokshitzer
  Some Interesting Quantum Mechanical Fluctuations in High Energy Hadron Scattering
- G. Dissertori
  The strong coupling constant : An experimentalist's review

AUTRES MANIFESTATIONS SCIENTIFIQUES AU SPhT

- **Conférence en l'honneur des 60 ans de Carlos SAVOY**
  10 décembre 2002
  Organisateurs : Ph. BRAX, C. GROJEAN, S. LAVIGNAC, I. MASINA, L. PILO (SPhT, Saclay)

- **Journée en l'honneur de Daniel IAGOLNITZER**, à l'occasion de son départ en retraite
  25 février 2003
  Organisateur : J. BROS

- **Conférence en l'honneur des 60 ans de Jean ZINN-JUSTIN :** Balade dans les champs
  26-27 juin 2003
  Organisateurs : A. BILLOIRE, R. GUIDA, J.-B. ZUBER (SPhT, Saclay)

- **Symposium en l'honneur des 70 ans de Jacques BROS :** Rigourous quantum field theory
  19-21 juillet 2004
  Organisateurs : D. BUCHHOLZ (Université de Goettingen), D. IAGOLNITZER (SPhT, Saclay), U. MOSCHELLA (Université de Côme)

ORGANISATION DE CONGRES ET ATELIERS

- **BALIAN**
  Membre de l'"International scientific committee" de la conférence "Frontiers of Quantum and Mesoscopic Thermodynamics", Prague, Czech Republic, 26-29 July 2004
  et de la conférence Quantum Theory: reconsideration of foundations-3, International Conference: June 6-11, 2005, International Center for Mathematical Modeling in Physics, Engineering and Cognitive Science, Växjö University, Sweden

- **BONCHE**
  Président du comité d'organisation Symposium : "Nuclear Physics around the Coulomb Barrier, The Vivitron and beyond", IReS Strasbourg, 20-22 septembre 2004

- **BROS**
  Conférence "in the honour of Daniel Iagolnitzer", at the occasion of his retirement, CEA/SPhT, Saclay, 25 février 2003
  (T03/019: "Présentation des travaux de Daniel Iagolnitzer et du programme de la journée")

- **DAVID**
  Organisation de la 4ème rencontre du réseau Européen Eurogrid, (avec P. di Francesco et B. Eynard) Les Houches, mars 2004

- **DI FRANCESCO**
  Organisation d'une conférence aux Houches en 2004 (David, Di Francesco, Eynard): 4th annual EUROGRID meeting : Random Geometry: theory and applications, Les Houches, 22-26 mars 2004

- **GROJEAN**
  Organisateur de la session consacrée à la nouvelle physique, "Physics at TeV colliders workshop", Les Houches, 2-20 mai 2005 :
  Organisateur de la session théorie des "journées jeunes chercheurs" de la société française de physique, Ile de Berder, France,18 novembre - 3 décembre 2004 :
  Célébration scientifique à l'occasion du soixantième anniversaire de C. Savoy, Service de Physique Théorique, CEA-Saclay. 10 décembre 2002

- **GUIDA**
  Organisation avec Zuber et Billoire des 60 ans de Zinn Justin au SPhT, 22-27 juin 2003

- **LAVIGNAC**
  Membre du comité d'organisation de l'école de Gif depuis 2001.
  Membre du comité local d'organisation de l'école de Gif 2003, Saclay, 15-19 septembre 2003.
  Membre du comité d'organisation de la conférence Neutrino 2004, Paris, 13-19 juin 2004
  Principal organisateur de la conférence Seesaw'25, Paris, 10-11 juin 2004
  Directeur scientifique de l'Ecole d'Eté de Physique Théorique des Houches, la session d'août 2005

- **ORLAND**
  Organisation de Conférence: Soft Matter, Biology and Statistical Physics, les Houches, 7-9 avril 2004

- **SCHOMERUS**
  3 month thematic programme at the ESI on String theory in curved backgrounds and boundary conformal field theory, organizers: H. Grosse, A. Recknagel, V. Schomerus April - June 2004. This included 2 workshops of 2 weeks each on "Mathematical and physical aspects of branes in Calabi-Yau spaces", April 29 - May 11, "String theory on non-compact and time-dependent backgrounds", June 7 – 18

- **SERBAN**
  Workshop : IHES "Non-unitary and logarithmic conformal field theory", Ecole des Houches, juin 2002
  "Applications of random matrices in physics", 6-25 juin 2004

- **SERVANT**
  Organisation du workshops "Argonne Theory Institute on Supersymmetry, Higgs and Extra dimensions" 24-28 mai 2004

- **VANHOVE**
  Co-organisateur de Strings 2005, au Collège de France, Juin 2004.
  Organisation du workshop "Workshop on Pure Spinors Formalism in String Theory" avec N. Nekrasov à l'IHES, 15-17 janvier 2005

- **VOROS**
  Membre du Comité d'organisation de l'École thématique du CNRS "Resonances and periodic orbits: spectrum and zeta functions in quantum and classical chaos" (27/06-05/07/2005) prévue dans le cadre du trimestre "Time at Work" à l'Institut Henri Poincaré (Paris, 2005).

FORMATION

HABILITATIONS A DIRIGER DES RECHERCHES

- Philippe BRAX — *"Supersymétrie et dimensions supplémentaires"* , Université Paris XI, Soutenue le 19 décembre 2003.
- Emmanuel GUITTER — *"Physique statistique de modèles contraints sur réseaux réguliers et aléatoires : des pliages aux méandres"*, Université Paris VI, Soutenue le 10 mai 2004.
- Cécile MONTHUS — *"Méthodes de renormalisation dans l'espace réel de type Ma-Dasgupta pour divers systèmes désordonnés"*, Université Paris VI, Soutenue le 1er juin 2004.
- Philippe DI FRANCESCO — *"Modèles contraints de mécanique statistique sur réseaux fixes et aléatoires : objets durs et pliages"*, Université Paris VII, Soutenue le 25 juin 2004.

THESES SOUTENUES AU SPhT

- Phuong Mai DINH — *"Etude des effets collectifs dans les collisions d'ions lourds ultrarelativistes"*, sous la direction de Jean-Yves OLLITRAULT. Soutenue le 26 juin 2002.
- Guillaume DE SMEDT — *"Systèmes hors d'équilibre : persistance et métastabilité"*, sous la direction de Jean-Marc LUCK. Soutenue le 11 septembre 2002.
- Thomas DUGUET — *"Problème à N corps nucléaire et force effective dans les méthodes de champ moyen auto-cohérent"*, sous la direction de Paul BONCHE. Soutenue le 30 septembre 2002.
- Urko REINOSA — *"Renormalisation d'un schéma d'approximation autocohérent en théorie des champs à température finie"*, sous la direction de Jean-Paul BLAIZOT. Soutenue le 10 juillet 2003.
- Serguei ALEXANDROV — *"Mécanique quantique matricielle et théorie des cordes à deux dimensions dans des fonds non-triviaux"*, sous la direction d'Ivan KOSTOV. Soutenue le 23 septembre 2003.
- Paolo RIBECA — *"Precise evaluation of universal quantities in second-order phase transitions"*, sous la direction de Jean ZINN-JUSTIN et de Riccardo GUIDA. Soutenue le 25 septembre 2003.

THESES EN PREPARATION AU SPhT

Liste des étudiants préparant une thèse au SPhT au 1er juin 2005 :

- Jérémie BOUTTIER — *"Physique statistique des surfaces aléatoires et combinatoires bijective des cartes planaires"* sous la direction de Philippe DI FRANCESCO et Emmanuel GUITTER.
  Soutenue le 10 juin 2005.

- Gerhard GÖTZ — *"String theory in non-compact backgrounds"*, sous la direction de Volker SCHOMERUS.
  Soutenance prévue à l'automne 2005.

- Nicolas CHATILLON — *"Brisure de symétrie et mondes branaires courbés"*, sous la direction de Philippe BRAX.
  Soutenance prévue le 30 septembre 2005.

- Stéphane COULOMB — *"Evolution des graphes aléatoires"*, sous la direction de Michel BAUER.
  Soutenance prévue en octobre 2005

- Cyrille MARQUET — *"QCD à haute énergie : Invariance conforme et phénomenologique"*, sous la direction de Robi PESCHANSKI.
  Soutenance prévue en septembre 2006.

- Tristan BRUNIER — *"Recherche de signatures d'une physique non-standard dans les relevés cosmologiques"*, sous la direction de Francis BERNARDEAU.
  Soutenance prévue en septembre 2006.

- Alexey ANDREANOV — *"Transition vitreuse et dynamique lente"*, sous la direction de Giulio BIROLI.
  Soutenance prévue à l'automne 2007.

- Pierre HOSTEINS — *"Masses des neutrinos et physique au-delà du modèle standard",*
  Soutenance prévue en septembre 2007

- Yann MICHEL — *"Déformation des structures en théorie des cordes"*, sous la direction de Pierre VANHOVE.
  Soutenance prévue en septembre 2007.

- Nicolas ORANTIN — *"Théorie et applications des matrices aléatoires en physique"*, sous la direction de Bertrand EYNARD.
  Soutenance prévue en septembre 2007.

- Jérôme RECH — *"Phénomènes quantiques macroscopiques dans les systèmes d'électrons fortement corrélés"*, sous la direction de Catherine PEPIN.
  Soutenance prévue en septembre 2007.

POSTDOCTORATS ENCADRES

NOM	ENCADRANT	INSTITUTION D'ORIGINE	FINANCEMENT	DATES
AKEMANN Gernot	DAVID F.	Institut Max Planck, Heidelberg	Bourse Heinsenberg/ Eurogrid via Egide	01/09/2001-31/07/2004
ALET Fabien	MISGUICH G.	ETH, Zurich	CEA	04/10/2004-30/09-2005
BORGHINI Nicolas	OLLITRAULT J-Y	ULB, Belgique	CEA	01/09/2002-31/08/2004
BOULAT Edouard	SALEUR H.	Rutgers University, NJ	CEA via IRG Marie-Curie	15/11/2004-01/09/2005
COLUZZI Barbara	BILLOIRE A.	Université de Rome La Sapienza, Italie	Marie-Curie	15/01/2002-14/01/2004
FONSECA Pedro	SALEUR H.	Rutgers University, USA	CEA	01/10/2003-01/06/2004
FORDE Darran	KOSOWER D.	Durham University, UK	CEA	01/10/2004-30/09/2006
GUTKIN Boris	VOROS A.	Weizmann Institut, Israël	CEA	14/12/2001-15/11/2003
ITAKURA Kazunori	IANCU E.	RIKEN, Brookhaven, USA	JSPS (Japan Society for the Promotion of Science)	01/06/2003-31/05/2005
MASINA Isabella	SAVOY C.	Université de Padoue, Italie	CEA	08/01/2001-08/01/2003
PAUL Indranil	PARCOLLET O.	Rutgers University, NJ	CEA	03/11/2003-02/11/2005
PONSOT Bénédicte	KOSTOV I.	Max-Planck-Intitut, Gölm	CEA	10/09/2002-09/09/2003
RIAZUELO Alain	BERNARDEAU F.	Institut de Gölm, Genève	CEA	05/11/2001-04/10/2003
SCHUBERT Roman	VOROS A.	Max-Planck-Institut, Dresden	Paris-Sud, Orsay	01/01/2001-31/08/2002
SOYEZ Grégory	PESCHANSKI R.	Université de Liège, Belgique	FNRS (Belgique)	01/10/2004-26/09/2006
TRIANTAFYLLOPOULOS Dionysis	IANCU E.	Columbia University, New-York	CEA	29/09/2003-28/09/2005
VERNIZZI Graziano	ORLAND H.	Spinoza Institute, Utrecht	Marie-Curie	06/02/2004-31/08/2005

AUTRES STAGES UNIVERSITAIRES

ENCADRANT	NOM DU STAGIAIRE	NIVEAU DE STAGE	DUREE	SUJET
BERNARD	DESPLECHIN-LEJEUNE Ambroise	1ère année de magistère de mathématique (Paris XI Orsay)	06-07/2005	
BIROLI	LUKIC Jovanka	Doctorat à Rome, Université la Sapienza	6 mois	Le modèle d'Ising en champ aléatoire
EYNARD	PRATS FERRER Aleix	Doctorat en Espagne	10-12/2004	Initiation aux matrices aléatoires
EYNARD	ORANTIN Nicolas	DEA	04-08/2004	Initiation aux matrices aléatoires
GROJEAN	FERRI Antonin	Master 2ème année	17/01-15/05/2005	Transition de phase et nucléation de bulles
GROJEAN	DELAUNAY Cédric	Master 2ème année	04-07/2005	Transition de phase électrofaible, nucléation de bulles et production d'ondes gravitationnelles
MISGUICH & PASQUIER	DAO Tung-Lam	stagiaire de l'X (stage d'option)	04-06/2004	Phys. Stat. / Matière condensée (modèles de dimères quantiques)
MALLICK	ORANTIN Nicolas	Ecole Centrale	04-08/2003	Effets d'un processus de Poisson dichotomique sur une transition de Hopf stochastique
MALLICK	EL ALAOUI Faris Moulay	Ecole Centrale	04-08/2003	Exposants de Lyapunov associés à un oscillateur avec bruit additif et multiplificatif
MALLICK	RANDOM Julien	Université de Cambridge	3 mois	Introduction aux méthodes fonctionnelles appliquées aux systèmes dynamiques aléatoires
MALLICK	PEYNEAU Pierre-Emmanuel	Ecole Polytechnique	04-06/2004	Influence d'un bruit non-Markovien sur une transition de phase stochastique
NONNENMACHER	PICOT Thomas	Maîtrise	05-07/2004	Bruit quantique et transformation de Fourier
NONNENMACHER	RUBIN Mathieu	Maîtrise	03-07/2005	Diffusion chaotique pour des applications quantiques
PARCOLLET avec GORGES A./CPHT	WERNER Félix	DEA de Physique quantique (2004)	3 mois	Antiferromagnétisme dans un système de fermions ultra-froids dans un réseau optique / Article soumis à publication : cond-mat/0504003
ZUBER	NGUYEN A.M.	DEA de mathématiques (ENS Lyon)		Matrices à signes alternés, modèle de la glace et boucles denses sur réseau

ENSEIGNEMENT

Cours du SPhT

Les cours ont lieu au SPhT, en salle Claude Itzykson, tous les vendredis de 14 h 30 à 16 h.
Ceux marqués d'une * sont agréés par l'Ecole Doctorale de physique de la région parisienne (ED107).

- **Angel URANGA** (Universidad Autonoma, Madrid) *28 - 30 octobre 2002*
  Brane models

- **Nicolaï RESHETIKHIN** (Université de Californie) *Octobre - novembre 2002*
  Statistics of Young diagrams and related problems

- **Xavier WAINTAL*** (SPEC, CEA/Saclay) *22 novembre - 13 décembre 2002*
  Théorie de scattering en Physique mésoscopique

- **Gernot AKEMANN** (SPhT, CEA/Saclay) *28 février - 21 mars 2003*
  Introduction aux modèles de matrices

- **Antonio MASIERO*** (Université de Padoue) *A partir du 25 avril 2003*
  The flavour and CP problems as windows for new physics beyond the Standard Model

- **Jean-Louis SIKORAV*** (CEA/Saclay/DSV) *26 septembre - 28 novembre 2003*
  Biologie moléculaire

- **Hubert SALEUR*** (SPhT, CEA/Saclay) *9 janvier - 13 février 2004*
  Introduction aux théories conformes

- **Bernard DERRIDA*** (ENS Paris) *5 mars - 9 avril 2004*
  Physique statistique hors d'équilibre

- **Christos CHARMOUSIS** (Université Paris-Sud 11/Orsay) *30 avril - 4 juin 2004*
  Aspects of General Relativity in higher dimensions

- **David KOSOWER*** (SPhT, CEA/Saclay) *19 novembre - 10 décembre 2004*
  N=4 supersymmetric gauge theory, twistor space and dualities

- **Bertrand EYNARD*** (SPhT, CEA/Saclay) *7 janvier - 28 janvier 2005*
  Intégrabilité, modèles de matrices et géométrie algébrique

- **Fabien ALET*** (SPhT, CEA/Saclay) *4 février - 18 février 2005*
  Introduction aux méthodes de Monte-Carlo Quantique en matière condensée

- **Marios PETROPOULOS*** (Ecole polytechnique, Palaiseau) *11 mars - 15 avril 2005*
  Cordes et environnements gravitationnels

- **Denis BERNARD*** (SPhT, CEA/Saclay) *13 mai - 17 juin 2005*
  Processus de croissance bidimensionnels pour (et par) des amateurs

Enseignement en Licence

- **ZUBER** *2004-2005*
  Université Paris 6 niveau L2, "Méthodes mathématiques pour la Physique",
  77 h : cours magistraux, TD et TP.

- **BRUNIER** *2003-2005*
  TP d'optique en première année du Magistère de Physique Fondamentale à l'Université Paris-Sud 11/Orsay : 90 h.

- **CHATILLON**
  - Projet Professionnel (méthodologie) en DEUG à l'université Paris-Sud 11/Orsay, 36 h
  - TD de magnétostatique en DEUG à l'Université Paris-Sud 11/Orsay, 8 h

- **COULOMB** *2003-2005*
  TP de physique en DEUG à l'Université Paris-Sud 11/Orsay (2*64h)

- **HOSTEINS**
  1er semestre : TP à des DEUG S1SV : 34 h et TD "Projet Pro" : 12 h
  2e semestre : TD (phy stat) : 10 h et TP à des DEUG S4SMC : 12 h

- **RECH** *Septembre 2003 à Janvier 2004*
  Cours/TP de Physique à l'Université Paris-Sud 11/Orsay (S1SM) Incertitudes de mesure, Optique, Mécanique : 48 h.
  Mai-Juin 2004 et Mai 2005
  Cours/TP de Physique à l'Université Paris-Sud 11/Orsay (S2SM) Electromagnétisme et induction : 80 h.

Enseignement dans les Grandes Ecoles

- **BERNARD**
  Ecole Polytechnique (Professeur chargé de cours)
  2002-2004
  Mécanique quantique (1ère année & 2ème année)
  2004-2005
  Relativité restreinte (1ère année)
  Mécanique quantique (2ème année)

- **BIROLI** *2004-2005*
  Tutorat à l'ESPCI, Paris.
  Cours:"Thermodynamique statistique", Prof.Jean-Philippe Bouchaud, 18 h.

- **DUPLANTIER** *2003-2005*
  Ecole Polytechnique de Palaiseau (Professeur chargé de cours),
  Physique des membranes et polymères biologiques (3ème année)
  Mécanique quantique et physique statistique (2ème année) *2003*

- **MALLICK**
  Ecole Polytechnique, Cours de rentrée de Majeure Mathématique
  Supraconducteurs mésoscopiques, 5 h. *Septembre 2002*
  Tutorats à l'ESPCI (25 h) : mathématiques pour physiciens (1ère année) *Oct.-Déc. 2002*
  Ecole Polytechnique, Cours de rentrée de Majeure Mathématique
  Modèles de mécanique statistique hors d'équilibre, 6 h. *Septembre 2003*
  Tutorat à l'ESPCI (40 h) : Mathématiques pour physiciens,1ère & 2ème années *Oct. 03-fév. 2004*
  Tutorat à l'ESPCI (15 h) : Mathématiques pour physiciens, 2ème année *Déc. 2004-fév. 2005*

- **OLLITRAULT** *2002-2003*
  Tutorat à L'ESPCI, Paris, Méthodes mathématiques, ESPCI (1ère année).
  2003-2005
  Ecole Polytechnique (Professeur chargé de Cours)
  Petites classes de physique quantique et statistique.

- **ORANTIN** *2004-2005*
  Travaux Pratiques de Physique (Spectroscopie) à l'école Centrale de Paris, deux sessions de 30 h.

Enseignements en master

Cours

- **BERNARDEAU** *2003-2005*
  DEA de physique théorique, ENS Paris, Cours d'option de Cosmologie, 18 h.

- **DAVID** *sept-déc 2003 & 2004*
  DEA de Physique Théorique, ENS Paris,
  Introduction à la théorie statistique des champs ~40 h.

- **OLLITRAULT** *2003-2005*
  Magistère interuniversitaire de physique (2ème année), ENS Paris.
  Introduction à la théorie quantique des champs, 30 h.

TD

- **GELIS** *2003-2005*
  DEA de physique théorique, ENS Paris, QCD et model Electrofaible, 20 h.

- **PARCOLLET** *2004-2005*
  DEA de physique quantique, 15 h.
  Théorie quantique de champs.

TP

- **CHATILLON**
  TP de physique nucléaire en magistère et maîtrise de physique fondamentale
  à l'Université Paris-Sud 11/Orsay, 35 h.

- **COULOMB** *2002-2003*
  TP de physique statistique en Maîtrise à l'Université Paris-Sud 11/Orsay, 64 h.

Cours en Ecoles d'été

- **BERNARD** *Juin 2004*
  Cargese summer school, "string theory: from gauge interactions to cosmology" 3 x 1.5 h
  Mai 2004
  "EUCLID european TMR network school", Montpellier 3X2 h.

- **BERNARDEAU** *16-20 septembre 2002*
  Cours sur la formation des grandes structures à la 34ème Ecole d'été de Physique des Particules, (Ecole de Gif), Strasbourg, (3 x 1 h 30)
  Cours sur les lentilles gravitationnelles à l'école de Cargèse, *8-20 septembre 2003*
  "Frontiers of the Universe", (2 x 2 h)
  Cours sur la croissance des instabilités gravitationnelles à l'école *4-9 octobre 2004*
  de cosmologie de Luminy "Mécanismes non linéaires en cosmologie" : (3 x 1 h 30)

- **BIROLI**
  Cours sur "Aging and off-equilibrium dynamics" à Bangalore (Inde) *Juin 2004*
  dans le cadre de l'école "Unifying concepts in glass physics III" : 4 h,
  Les Lecture notes seront publiées en JSTAT [T04/213,cond-mat/0504681].

  Cours "Kinetically Constrained Models for structural glasses" : *Novembre 2004*
  "motivations, physical behaviors and comparison with experiments and simulations" dans le cadre du "Slow Dynamics Tutorial" à la Brandeis University, Boston USA : 4 h.

  1st Latin-American School and Conference on "Statistical Physics and Interdisciplinary *Fév. 2005*
  Applications", Cours sur "Statics of Glassy Systems." : 4 h.

- **DE DOMINICIS**
  Porto Alegre (UFRS), Brésil : 20 h *Mai 2003*

- **DI FRANCESCO** *Janvier-Avril 2003*
  Matrix Models and Combinatorics, semester "Geometry and Statistics of Random Growth", Institut Henri Poincaré, Paris : 20 h.
  6-25 juin 2004
  Matrix Models, 2D quantum gravity and graph combinatorics}, (9 hrs), summer school "Applications of random matrices in Physics", Ecole de physique des Houches, Lecture notes: [T04/078].

- **DUPLANTIER**
  Cours au Centro di Ricerca Matematica "Ennio De Giorgi", *5-9 juillet 2003*
  Ecole normale supérieure de Pise, trois cours de deux heures chacun sur l'invariance conforme multifractale et la gravité quantique.
  Hahn Memorial Lectures 2003, Department of Mathematics, Yale University *Septembre 2003*
  deux cours d'une heure et demie sur "Quantum Gravity & SLE"
  Marc Kac Seminar on Probablity and Physics, main speaker of the year 2005 , Mars-Avril *2005*
  Utrechtn, deux cours d'une heure, une fois par mois pendant trois mois, sur "Conformal Random Geometry and Quantum Gravity".

- **EYNARD** *Juin 2004*
  Ecole d'été : Les Houches. Cours 1h "asymptotics of orthogonal polynomials, integrability and algebraic geometry",

- **GELIS** *Octobre 2004*
  Cours donné dans le cadre de l'école doctorale franco-allemande "Quantum Fields and Strongly Interacting Matter: From Vacuum to Extreme Density and Temperature Conditions"
  sujet: Applications of the Color Glass Condensate (Université de Bielefeld, Allemagne) 3 séances 1h30
  Cours donné au SPhN (CEA/DAPNIA), sujet: Introduction à la théorie du QGP et du *CGC* *Avril 2005*
  3 h.

- **IANCU**
  Cours de 6 heures sur "QCD at high energies" *17 au 20 novembre 2003*
  Laboratoire DESY (Hambourg, Allemagne) dans le cadre du programme d'études avancées destiné notamment aux jeunes physiciens (théoriciens et expérimentateurs). Les transparents de ce cours sont disponibles électroniquement sur le site internet suivant: http://www.desy.de/$\sim$acatrain/
  Cours de 4 heures sur "Gluon Saturation in QCD at High Energies" *Mars 2004*
  à l'Université de Rio de Janeiro (Brésil). Le cours a été suivi par des étudiants en thèse et des chercheurs.

- **KOSOWER** *24-29 avril 2005*
  Mini-cours (5 séances,) Université de Regensburg, Allemagne Weekly Program Summer Term 2005, "Quantenchromodynamik und String-Theorien auf einem Twistor-Raum".

- **LAVIGNAC** *15-19 septembre 2003*
  Cours à l'école de Gif 2003 "Saveurs, familles, violation de CP" (Saclay,)
  Sujet: Les masses des fermions : 2 cours de 1H30.

- **MALLICK**
  Cours d'Ecole Doctorale au semestre "Géométrie et Croissance aléatoire" à l'Institut Henri Poincaré
  Modèles de croissance et Processus d'exclusion asymétrique : 6 h.

- **NONNENMACHER** *Novembre 2002*
  "Résonances de Ruelle-Pollicott" au laboratoire Tandar, Buenos Aires, Argentine : 1 cours de 6h

- **OLLITRAULT** *11 - 17 mai 2005*
  Quark-Gluon Plasma and Heavy Ion Collisions: Past, Present, Future, INFN, Turin (Italie)
  "Hydrodynamics and flow" (2 cours).
  "Phenomenology of ultrarelativistic heavy ion collisions" (2 cours). *14- 15 novembre 2002*
  INFN, Bologne (Italie).

- **ORLAND** *16-20 décembre 2002*
  The First Taiwan Winter School on Modern Biophysics:, Taipei, Taiwan : 4 cours
  2 au 14 février 2004
  APCTP Focus Program on Biopolymers and Membranes, Pohang, Coree : 3 cours

- **PEPIN** *15 – 23 juin 2003*
  Institut NORDITA (Copenhague, Danemark), Summer School on Strongly Correlated Electrons "Quantum critical points".

- **RIPKA** *Janvier 2003*
  Cours au ECT* de Trento intitulé : "Dual superconductor models of color confinement."
  Ce cours a été publié par Springer Verlag en 2004, dans la série Lecture notes in physics, No. 639 [T03/050].

- **SAVOY** *14-19 septembre 2004*
  Ecole d'Eté de Gif sur Yvette, Introduction à la Supersymetrie : 3 h.

- **SCHOMERUS** *14–25 juillet 2003*

  Lectures on “PIMS lectures on Liouville theory”, 4 lectures ; Summer School on Strings, Gravity & Cosmology ; PIMS at University of British Columbia, Vancouver, Canada.

  15-23 mars 2004

  Lectures on “Non-compact string backgrounds”, 4 lectures; Trieste Spring School on Superstring Theory and Related Topics, ICPT Trieste – Italy.

  Juin 2004

  Lectures on “Introduction to Liouville theory”, 3 lectures ; ESi Programme on String theory in curved backgrounds and boundary conformal field theory ; Erwin-Schroedinger Institute, Vienna, Austria.

  3-13 août 2004

  Lectures on “Strings and branes in AdS_3”, 4 lectures; Frontiers of mathematical physics, Summer school on Strings, Gravity & Cosmology, PIMS at the University of British Columbia, Vancouver, Canada.

- **VALAGEAS** *4-9 octobre 2004*

  Un cours en école d'été : VII Ecole de cosmologie du CIRM Luminy, Marseille, "Mécanismes non-linéaires". Cours intitulé : "Croissance des structures à grande échelle de l'univers : le régime non-linéaire" : 4 h 30.

- **ZUBER** *9-13 mai 2005*

  Cours donné à l'école de printemps du réseau Euclid, SISSA, Trieste.
  "An introduction to random matrices" : 5 h.

ADMINISTRATION DE LA RECHERCHE

CONSEILS SCIENTIFIQUES ET COMMISSIONS DE SPECIALISTES,COMITES DIVERS

NOM et prénom	Organisme/laboratoire	Fonction/titre	Dates début et fin de mandat
BALIAN Roger	Académie des sciences	Membre Groupe de travail pour l'élaboration d'un rapport sur les interactions des mathématiques avec le reste des sciences Groupe de travail sur la physique de demain Délégué de la section de physique Commission des plis cachetés Comité restreint Comité de rédaction de la "lettre de l'Académie" Participation au comité de néologie et terminologie et au comité de l'environnement	Depuis 1995 2001-2005 2002-2004 2002-2003 Depuis 2003
BALIAN Roger	Académie des sciences	Comité de l'Académie sur la Charte de l'environnement	2004
BALIAN Roger	Académie des sciences	"Travaux pratiques" de la Charte de l'environnement organisés par le gouvernement.	2004
BALIAN Roger	Académie des sciences	Débat national sur l'énergie	2003
BALIAN Roger	CEA/DSM/Laboratoire Léon Brillouin	Conseil d'administration	Depuis 1998
BALIAN Roger	CEA	Conseil scientifique	Depuis 1995
BALIAN Roger	CEA/DAM	Conseil scientifique	Depuis 2001
BALIAN Roger	GANIL, SPIRAL 2	Scientific advisory committee	2003 – 2005
BALIAN Roger	AREVA	Conseil scientifique et éthique	Depuis 2000
BERNARD Denis (CNRS)	Comité National de la recherche scientifique, section 02	Membre élu	2004-2008
BERNARD Denis (CNRS)	Institut Henri Poincaré (IHP)	Membre du Conseil d'administration	Décembre 2004
BERNARD Denis (CNRS)	Commission de spécialistes 29^{e} section, Université Paris sud	Membre	2004-2008
BERNARD Denis (CNRS)	Laboratoire de physique théorique de l'Université Paris sud 11/Orsay	Membre du Comité d'évaluation	Janvier 2005
BERNARDEAU Francis	Comité National de la recherche scientifique, section 02	Membre nommé	2001-2004
BERNARDEAU Francis	Comité National de la recherche scientifique, section 47	Membre nommé	2002-2005
BERNARDEAU Francis	DAPNIA/SAp	Membre du Conseil scientifique et technique (CSTS)	Depuis 11/2002
BERNARDEAU Francis	Programme interdisciplinaire "Astroparticules" du CNRS	Membre nommé du Conseil scientifique	Depuis 01/2004
BERNARDEAU Francis	Programme national de cosmologie de l'Institut national des sciences de l'Univers (INSU) du CNRS	Directeur	Depuis 07/2002
BERNARDEAU Francis	Laboratoire de physique théorique (LPT) de l'Université Paris-Sud11/Orsay	Membre du Comité d'évaluation	01/2005
BIROLI Giulio	Commission de spécialistes de l'Ecole normale supérieure de Lyon, physique	Membre	2004-2008

BLAIZOT Jean-Paul (CNRS)	European Centre for Theoretical Studies in Nuclear Physics and Related Areas (ECT*), Trente, Italie,	Directeur	Depuis 09/2004
BLAIZOT Jean-Paul (CNRS)	Institut "Riken-BNL-Research-Center" à Brookhaven, USA	Membre du Comité d'évaluation	Depuis 2000
BLAIZOT Jean-Paul (CNRS)	IKP, Jülich	Membre du Conseil	Depuis 2003
BONCHE Paul	DSM/DAPNIA/GANIL	Membre du Conseil scientifique	2001-2004
BONCHE Paul	École internationale Joliot-Curie	Membre du Conseil scientifique	
BONCHE Paul	Laboratoire Subatech, Ecole des Mines de Nantes	Membre du Conseil scientifique	Depuis 2003
BONCHE Paul	DSM /DAPNIA/GANIL, projet SPIRAL 2	Membre du Conseil scientifique	Depuis 2003
BONCHE Paul	DSM/DAPNIA	Membre du CSTS	Depuis 2002
DAVID François	Institut Henri Poincaré (Paris)	Président du Comité de programmation	Depuis 2005
GOLINELLI Olivier	CEA/DSM	Secrétaire du Conseil scientifique du calcul centralisé (CSCC)	
GROJEAN Christophe	Comité National de la recherche scientifique, section 02	Membre élu	2004-2008
GROJEAN Christophe	Comité National de la recherche scientifique, commission interdisciplinaire 47 (astroparticules)	Membre élu	2004-2008
GROJEAN Christophe	Laboratoire Univers et théorie (LUTH), Observatoire de Meudon	Membre du Comité d'évaluation	2004
GROJEAN Christophe	Bureau national de métrologie, Systèmes de référence temps-espace (BNM-SYRTE), Observatoire de Paris.	Membre du Comité d'évaluation	2005
LAVIGNAC Stéphane (CNRS)	CEA /DAPNIA/SPP	Membre du Comité scientifique et technique (CSTS)	Depuis 06/2003
LAVIGNAC Stéphane	Commission de spécialistes 29e section, Université Paris-sud 11/orsay	Membre suppléant	2001-2003
LUCK Jean-Marc	Comite national de la recherche scientifique, section 02	Membre élu	2004-2008
OLLITRAULT Jean-Yves (CNRS)	Commission de spécialistes 29e section, Université de Nantes	Membre titulaire	2004-2008
OLLITRAULT Jean-Yves (CNRS)	Laboratoire Subatech, Ecole des Mines de Nantes	Membre du Conseil scientifique	Depuis 2004
OLLITRAULT Jean-Yves (CNRS)	Ecole internationale Joliot-Curie	Membre du Conseil scientifique	Depuis 2001
ORLAND Henri	Comité National de la recherche scientifique, section 02	Membre élu	2001-2004

ORLAND Henri	Laboratoire de dynamique des fluides complexes (LDFC), Université Louis Pasteur, Strasbourg	Membre du Comité d'évaluation	Décembre 2003
ZUBER Jean-Bernard	Laboratoire de physique théorique de Strasbourg	Président du Comité d'évaluation	Janvier 2004

EDITION DE REVUES SCIENTIFIQUES

NOM	REVUE SCIENTIFIQUE	FONCTION
BALIAN	Journal of Physics A	Membre du Advisory Panel
BAUER	CEA Saclay, le journal	Membre du comité de rédaction
DI FRANCESCO	European Journal of Physics B	Editeur associé (depuis 2005)
	Journal of Statistical Mechanics : theory and experiment (JSTAT)	Editeur
DUPLANTIER	Nuclear Physics B Geometric and Functional Analysis Journal of Statistical Physics Séminaires Poincaré	Editeur Editeur Editeur Editeur
	La Gazette des mathématiciens (Société mathématique de France)	Editeur
BLAIZOT	Physics Letters B	Editeur
EYNARD	Journal of Statistical Mechanics : theory and experiment (JSTAT)	Editeur
GOLINELLI	Phases Magazine, la lettre du SPhT et du DRECAM	Co-Editeur
LUCK	Journal of Physics A	Membre du Advisory Panel
MALLICK	La Gazette des mathématiciens (Société mathématique de France)	Editeur
NONNENMACHER	Nonlinearity	Membre du comité éditorial
ORLAND	European Journal of Physics B	Editeur associé (jusqu'en 2004)
	Physics Reports	Editeur associé
PASQUIER	Annales Henri Poincaré	Editeur associé
RHO	Int. J. Mod. Phys. E	Editeur
SALEUR	Nuclear Physics B Journal of Physics A Journal of Knot Theory and its Ramifications (JKTR)	Editeur Editeur jusqu'en 2002 Editeur
SCHOMERUS	Journal of High-Energy Physics (JHEP)	Editeur depuis 2001
	Reviews in Mathematical Physics	Editeur depuis 2005
SERBAN	Journal of Statistical Mechanics : theory and experiment (JSTAT)	Editeur
VOROS	Journal of Physics A	Membre du comité éditorial
ZUBER	Annales Henri Poincaré	Editeur

ORGANISATION ET FONCTIONNEMENT INTERNE

ORGANISATION

Le SPhT est une unité rattachée à la Direction des sciences de la matière (DSM) du Commissariat à l'énergie atomique (CEA), et une Unité de recherche associée (URA2306) au CNRS. Depuis le 01/09/2004, le Chef de service est Henri Orland, qui succède a Jean-Paul Blaizot. Il est assisté de deux adjoints, Michel Bauer (depuis le 01/01/2003, en remplacement de Jean-Marie Normand) et Jean-Yves Ollitrault (depuis le 01/10/2004, en remplacement de Alain Billoire).

Pour rendre plus commode la gestion de ce gros laboratoire, notamment en ce qui concerne les visiteurs et post-docs, il est divisé en trois groupes de tailles approximativement égales : 1) Modèles et structures : physique mathématique ; 2) Physique des particules et astrophysique ; 3) Physique statistique et physique de la matière condensée.

CONSEIL SCIENTIFIQUE EXTERIEUR

L'activité scientifique du SPhT est régulièrement évaluée par un Conseil scientifique extérieur composé de personnalités scientifiques de renom, sur la base du présent rapport d'activité et d'une visite de notre laboratoire, prévue les 12 et 13 décembre 2005. Ce Conseil se compose de

- Riccardo Barbieri (Scuola Normale Superiore, Pise, Italie)
- Eugueni Bogolmolny (LPTMS, Orsay)
- Alan Bray (Manchester, UK)
- Robert Dijkgraaf (KdV Institute, Amsterdam, NL)
- Henk Hilhorst (LPT, Orsay), président
- Mehran Kardar (MIT, USA)
- Antti Kupiainen (Helsinki, Finlande)
- Michelangelo Mangano (CERN, Suisse)
- Al Mueller (Columbia, USA)
- Subir Sachdev (Harvard)
- Joe Silk (Oxford, UK)

CONSEIL SCIENTIFIQUE INTERNE

Le Chef de service est étroitement assisté, dans ses décisions scientifiques (recrutements, orientations scientifiques), par un conseil scientifique. Celui-ci est composé de quatre membres élus pour deux ans parmi les physiciens permanents du laboratoire, du Chef de service et de ses deux adjoints, et se réunit environ tous les deux mois. Les membres élus sont, depuis décembre 2003, Denis Bernard, Philippe Brax (secrétaire du Conseil), Cécile Monthus et Robert Peschanski.

CONSEIL DE LABORATOIRE

La vie du laboratoire est animée par un Conseil de laboratoire composé de neuf membres élus pour deux ans (quatre physiciens permanents, deux personnels de support, un conseiller scientifique, un doctorant et un post-doctorant), du Chef de service et de ses deux adjoints. Il se réunit en moyenne trois fois par an. Les membres élus sont (depuis décembre 2003) Fabien Alet, Anne-Marie Arnold, Patrick Berthelot, Jacques Bros, Nicolas Châtillon, Bertrand Eynard, Olivier Parcollet, Hubert Saleur et Patrick Valageas (secrétaire). Les séances du Conseil scientifique et du Conseil de laboratoire font l'objet de comptes-rendus écrits qui sont mis sur la page web de l'intranet du laboratoire.

SUPPORT ADMINISTRATIF

Le secrétariat administratif est assuré par trois personnes pour un effectif moyen de 80 personnes dans le laboratoire. La charge de travail du personnel administratif continue de croître : l'alourdissement des tâches est dû principalement à la multiplication des types de financement et des invitations, et à la mise en place du logiciel de gestion XLAB du CNRS.

Outre le secrétariat courant d'un laboratoire dont le responsable a rang de chef de département, Sylvie Zaffanella assure principalement la gestion du personnel (CEA, CNRS et doctorants), de toutes les missions et des commandes CEA et CNRS. La gestion financière du SPhT est assurée par le groupe administratif du DRECAM en ce qui concerne le CEA, et par le Service financier et comptable du CNRS pour la partie CNRS. Cette activité devrait être reprise par Sylvie Zaffanella suite à la mise en place du logiciel XLAB.

Anne-Marie Arnold a pour tâches principales la gestion des dossiers des visiteurs de longues durées, français et étrangers et relevant de statuts divers (Post-doc, CTE, EGIDE). A cela s'ajoute, entre autres, une tâche de support logistique pour l'organisation annuelle des "Journées Claude Itzykson".

Laure Sauboy assure essentiellement la gestion des dossiers des visiteurs de courte durée (de plus en plus nombreux) et des contrats européens Marie-Curie. Ponctuellement Laure s'occupe de collecter les candidatures pour les postes ouverts au recrutement, et de l'organisation de différentes manifestations qui ont lieu au SPhT.

LE GROUPE DE DOCUMENTATION SPhT-SPEC

Notre bibliothèque "de proximité" (privée) comprend maintenant plus de 10 000 ouvrages et souscrit à plus de 120 abonnements à des revues scientifiques. Elle est commune au Service de Physique Théorique et au Service de Physique de l'Etat Condensé.

Nous maintenons la qualité de cet outil de travail indispensable aux chercheurs. Le choix des acquisitions est effectuée par les chercheurs qui sélectionnent les nouveaux ouvrages qui viennent enrichir le fonds (processus actuellement coordonné par Hubert Saleur).

La tenue des locaux, du matériel et des ouvrages est assurée par Bruno Savelli. Il est malheureusement resté seul après la demande de mutation de Philippe Fontaine. Aussi la réorganisation spatiale de la bibliothèque s'effectue plus lentement que prévu.

Loïc Bervas, secrétaire scientifique, assure l'enregistrement et le classement des publications scientifiques du SPhT et du SPEC. L'enregistrement a été grandement automatisé, ce qui procure un niveau élevé de qualité. En particulier, la transmission des données pour la base centrale des publications du CEA se fait de façon quasiment transparente.

Outre les tâches dévolues par la Direction du SPhT (gestion de l'annuaire, etc.), Loïc Bervas gère également l'enregistrement et l'affichage des séminaires et cours du Service. Outre la frappe d'articles, il réalise à la demande de chercheurs des figures et des numérisations de documents.

Marc Gingold effectue la mise au point et à jour des procédures d'enregistrement et de diffusion (publications, séminaires, ouvrages de la bibliothèque, conférences organisées par le Service, candidatures aux postes de post-doc). Il assure également la maintenance du site Web. Celui-ci sera prochainement renouvelé et adapté à un nouveau serveur; à cette fin un recrutement a été demandé, pour pérenniser l'ensemble de l'organisation informatique de la Documentation SPhT-SPEC.

Marc Gingold participe au réseau des bibliothèques du CEA; il est correspondant qualité et archives pour le SPhT.

L'INFORMATIQUE AU SPhT : le groupe informatique DRECAM/SPhT

La gestion du système informatique est commune au SPhT et au DRECAM (département de recherche sur l'état condensé, les atomes, et les molécules). Ce groupe informatique fait partie d'une Ulti (Unité Locale des Technologies de l'Information) DSM, qui cohabite à côté d'une Ulti de Centre : une réflexion est en cours sur l'éventuel rapprochement des deux Ulti suite au passage du centre de Saclay sous "bannière" DSM. Il est composé de 8 personnes, et sous la responsabilité de Jean-Louis Gréco. Laurent de Seze, qui était informaticien dans ce groupe depuis de nombreuses années est parti en retraite le 1er octobre 2005 ; il est remplacé dans sa tâche de responsable Windows par Stéphane Delaporte.

Localement, le groupe Unix est composé de 4 personnes : Anne Capdepon-Gros (Drecam), responsable de l'équipe, Christian Perez (SPhT, embauché en octobre 2003, après une période de 3 ans d'alternance) ingénieur responsable des Linux, Patrick Berthelot (SPhT, mutation en août 2002) responsable des Windows et du réseau Wi-Fi, et Olivier Croquin (Drecam, embauché en mars 2004) responsable Solaris. Ce groupe est aidé localement par Claudine Verneyre (SPhT), qui effectue d'une part le dépannage de "proximité" et gère d'autre part l'attribution des postes de travail et le suivi des commandes informatiques.

Compte tenu des besoins du SPhT, les postes de travail sont pour moitié des terminaux X et pour l'autre moitié des PC (Linux ou Windows) et des Mac. Depuis quelque temps, le nombre de postes de travail portables augmente, ce qui change les habitudes de travail. Nous remplaçons les serveurs de calcul Sun par des serveurs de calcul Linux ; le rapport qualité/prix étant bien meilleur, 6 machines ont récemment été achetées. Le SPhT dispose, en commun avec le Service de physique de l'état condensé (DRECAM/SPEC), de 40 noeuds de calcul (biprocesseurs, AMD Athlon-MP 2800 avec 2 Go de Ram) dans le cluster départemental.

Une commission informatique, composée de quatre physiciens du SPhT (actuellement : Michel Bauer, François David, Grégoire Misguich (secrétaire) et Olivier Parcollet) et de l'ensemble du groupe informatique, se réunit régulièrement, pour décider de sa politique informatique. Les comptes-rendus écrits de cette commission se trouvent sur l'intranet du laboratoire.

Trois gros projets ont été mis en place par le groupe :

- la fédération de 4 serveurs de messagerie et la mise en place du premier et seul webmail du CEA, en juin 2004, en collaboration avec le Laboratoire des sciences du climat et de l'environnement (LSCE), également rattaché à la DSM. Ce webmail répond à une demande des chercheurs qui n'est pas encore prise en compte par la Direction des systèmes d'information (DSI) du CEA.
- la fédération de tous les serveurs Internet de la DSM
- un réseau WI-FI pour les agents CEA, actuellement seul réseau sans fil autorisé au CEA.

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