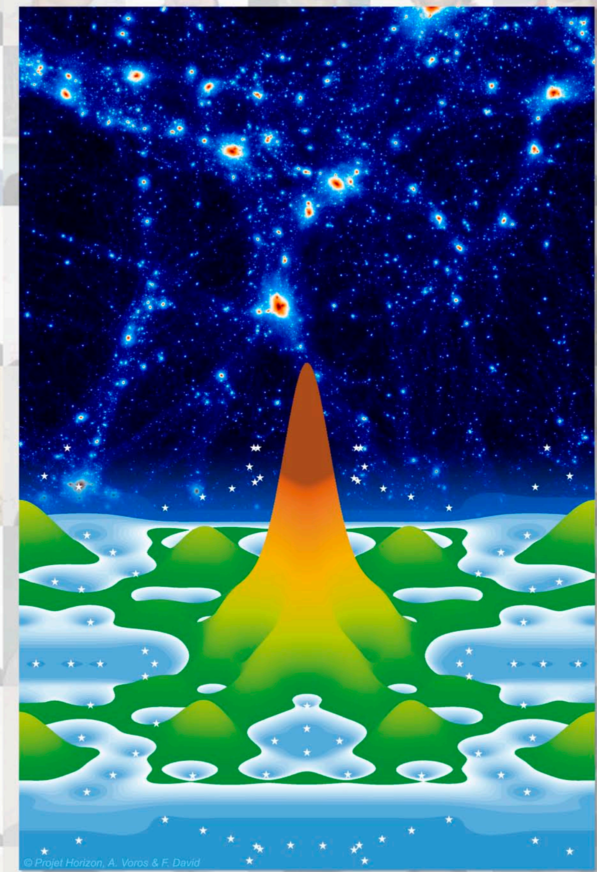
Service de Physique Théorique

Rapport d'activité juin 2005 - mai 2007



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

Centre national de la recherche scientifique
Département mathématiques, physique, planète et univers
CNRS/MPPU/URA2306

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Contents

CHAPTER A

Foreword

This report presents an overview of the activities of the Service de Physique Théorique (SPhT) from June 2005 to May 2007.

There have been dramatic changes in the landscape of French Scientific Research since our last scientific evaluation two years ago. The emergence of the ANR (Agence Nationale pour la Recherche), a funding agency modeled after the American NSF, the increase in financing power of the European Community through various mechanisms and the creation of large thematic networks (RTRA) is deeply modifying the way French research is financed, by funding directly scientific projects and teams rather than labs. This in turn may have, in the long run, a very strong impact on the scientific policy of laboratories. Indeed, part of the scientific policy of the lab will be decided indirectly by these funding agencies and may in extreme cases interfere with the long-time orientations determined by the Scientific Council of the lab. In the same time, the creation of an independent agency in charge of the scientific evaluation of all the French public research, the AERES ("agence d'évaluation de la recherche et de l'enseignement supérieur"), is hopefully going to have a positive impact by imposing more rigorous standards to all actors.

In the last two years, we have taken part to the creation of a federation of four labs of Theoretical Physics in the southern area of Paris (LPTMS Orsay, LPT Orsay, CPT Ecole Polytechnique and SPhT), which gathers together 66 researchers in Statistical Physics. This large structure, known as "Fédération Phystat-Sud", has been approved by the CNRS, and will allow joint actions such as the invitation of scientists and post-docs over several labs and the organization of small workshops. The Fédération Phystat-Sud in turn is participating in the RTRA "le Triangle de la Physique" ("réseau thématique de recherche avancée") which groups 1200 researchers (almost all experimentalists) in nanophysics, solid state physics, atomic physics and statistical physics. Our participation in this instance will allow us to finance the stay of visiting professors or high level post-docs.

It is in this very new context that the evaluation of the SPhT takes place.

During the period 2005-2007, we have hired four CEA physicists (three in mathematical physics and string theory, and one in cosmology and astroparticles due to come in September 2008) and we have been assigned one junior CNRS physicist in statistical physics and a senior one in string theory. We have also benefited from the detachment of a young physicist from the University of Orsay, who spends 2/3 of his research time in our lab. In addition, one senior CEA statistical physicist from SPEC (the Condensed Matter Laboratory next to us) has joined us.

Let us emphasize that the main criterion for hiring at the SPhT is the scientific excellence of the candidate. Both CEA and CNRS applicants go through a very rigorous process aimed at selecting the best internationally available candidates.

In the same time, one junior CEA physicist was awarded a Junior Faculty position at CERN, three CEA and one CNRS physicists have retired, and one CNRS physicist has moved to another lab. The total population of permanent physicists at SPhT as of May 31, 2007, comprises 32 CEA and 14 CNRS members.

As for the support staff, one secretary has retired and one of our computer administrators has left the lab, but both have been replaced. However, the person in charge of purchases and maintenance of the lab has retired and has not been replaced. We have thus split her work amongst several members of the support staff.

The manager of our library is also retiring and will be replaced by someone who will have the task of maintaining our library, our publications and also our web site. Since they have to take care of many external contracts and of a growing number of students, postdocs and visitors, our administrative staff is suffering from an increase of work load, and this problem will have to be addressed soon if the situation deteriorates any further.

The mandate of one of our two Deputy Directors came to an end in December 2006. In order to deal with all the new administrative tasks generated by the new organization of Research, we have decided to replace him by an Administrative Director. Anne Capdepon (who was the head of our local computer group) was appointed in this position as of January 1, 2007 and this move has proven to be of outstanding benefit for the lab.

As mentioned in the introduction, the SPhT has evolved from a lab entirely subsidized by the DSM (Direction des Sciences de la Matière) with a small contribution from CNRS, to one in which financing with external funds from various sources (ANR, EU, ESF, etc.) plays a major role. Thanks to a reasonable budget and these external funds, we have been able this year to host 18 post-docs, 16 students, and numerous long and short term visitors. This corrects the main shortcoming of the lab pointed out by the previous Evaluation Committee, namely the too small number of students and post-docs. This tremendous increase in the number of students, post-docs and international visitors is a unique chance for our lab, both in the inspiration and outstanding manpower they bring us. We are however starting to suffer from a lack of offices. As we don't want to curb this tendency, we have urged the DSM to allocate us new offices.

The huge increase in our training involvement reveals the strong dynamism of the younger generation of physicists in the lab.

Because of their passion for physics, many members of the SPhT want to continue with their research after their retirement. We all benefit from their experience and knowledge and welcome them to stay. We have at present thirteen retired physicists working either as Emeritus ("conseillers scientifiques") or as members of the "Association pour la Science". The official retirement age will change from the present age of 60 to the age of 65 by the end of 2009. Then there won't be any retirement until 2014, and we may face a difficult period starting in 2010 as far as hirings are concerned. It would be extremely prejudicial to the lab if hirings were to be stopped for five years, and we very much count on the help of the DSM and of the CNRS to help us in this issue.

With almost 50 permanent physicists, the Service de Physique Théorique de Saclay is a very large theoretical physics laboratory. Our common aim is a better understanding of the laws which govern our universe and its organization. This goal has obviously different understandings depending on the field considered. For mathematical physicists, this essentially means deciphering the ultimate mathematical structures that underlie physical phenomena, or building models which carry the essence of the physics while remaining solvable. For particle physicists or cosmologists, the ultimate goal is to understand the fundamental forces, their unification, or the origin of the Universe. For statistical or condensed matter physicists, the aim is to study states of matter that are still not understood (strongly correlated electron systems, glasses, biopolymers) or out of equilibrium phenomena.

All these very different themes utilize a common toolbox of methods, which comprise stochastic processes, path integrals, quantum field theories, conformal field theories, integrable systems, etc. It is this very diverse multidisciplinary character, unified by this common set of fundamental methods which makes up the beauty and strength of our laboratory

Most of the major subjects of modern theoretical physics are represented at the highest international level. Thanks to our scientific policy, we have been able in the last few years to establish world leading groups in string theory, perturbative QCD and small x physics, the physics beyond the standard model, condensed matter theory and the statistical physics of glassy and disordered systems. We have established our position as one of the world centers 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 the physicists who leave the laboratory and keep up the highest level of activity in these domains.

In the last period, we have tried to hire physicists in biological physics, perturbative QCD and astro-particles and cosmology. We have succeeded in hiring a cosmologist, but we have had difficulties with the two other fields. Perturbative QCD is very much in demand due to the imminent opening of the LHC and the number of young biophysicists interested in a position in France is too small at the moment. We will try however to pursue our hiring effort in these two fields, while remaining open to other domains, particularly those absent from the lab (such as cold atoms and their relations to condensed matter, or quantum information).

The wide range of subjects studied at SPhT results in there being always in the lab a local expert in almost any field. This is extremely useful and enriching, not only for young physicists, but also for the more confirmed ones, and it is one of the great benefits of such a large and diversified theory group. It concentrates a very large amount of scientific knowledge and expertise which, when combined with creativity, can lead to important and long-lasting results.

A beautiful example of this fact is illustrated by a very fruitful collaboration between theorists and experimentalists: In the theory of glasses, an old idea has been floating around, that the dynamics becomes sluggish as the glass transition approaches, because increasingly larger regions of the material have to move simultaneously to allow flow. New multipoint dynamical susceptibilities have been introduced by the theorists and have allowed to provide direct experimental evidence that the glass formation of molecular liquids and colloidal suspensions is indeed accompanied by growing dynamic correlation length scales. Similar ideas have been used in the study of granular materials and open the way to a systematic study of dynamic correlation functions.

Another example can be found in the interplay of string theory and integrable systems which has allowed to identify a certain long-range spin chain (a generalization of the Inozemtsev long range spin chain) as an approximation to a famous integrable short-ranged model of strongly correlated electrons, namely the Hubbard model.

High precision perturbative QCD calculations have become a specialty in the SPhT thanks to a world expert we have in this field. A new method for computing complete one-loop amplitudes in non supersymmetric gauge theories has been developed. This method merges the unitarity method with on-shell recursion relations and allows to compute next-to leading QCD corrections for various processes. This type of calculations will prove to be of utmost importance in the precision tests of the standard model at the LHC.

Path integrals can also find applications in biological systems! It has been shown that the folding of a protein between denatured and folded states can be formulated as a path integral, and the dominant folding paths can be viewed as the "semi-classical" trajectories joining the two states. These paths, which carry the dominant weight in the probability of folding, can be calculated by minimizing numerically some action.

Many other results have been obtained during the last two years in the lab. They are thoroughly described in this report.

The scientific life of the SPhT is weekly punctuated by five specialized seminars and one colloquium. Once a month, the monday afternoon Statistical Physics seminar is replaced by a thematic afternoon of seminars of the Fédération Phystat-Sud. In addition, five to six highly specialized courses for graduate students and researchers are given throughout the year. 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 prestigious international conferences, covering a large variety of subjects. The 2005 meeting "Quantum Field Theory Then and Now" did commemorate the 10th anniversary of the death of our friend and colleague Claude Itzykson and the 2006 meeting was devoted to "Strongly Correlated Electrons". The subject of the 2007 meeting (which took place in June) was "Integrability in Gauge and String Theory". These meetings attract the world leaders in their fields and are extremely beneficial to our lab, both from a scientific point of view and for its international visibility.

The high quality of the research of the SPhT has been rewarded by several prizes and distinctions. Giulio Biroli was awarded the first "Young Scientist Award in Statistical Physics" from the IUPAP, Christophe Grojean the "Jean-Thibaud prize" for theoretical particle physics , Cécile Monthus the "Gustave Ribaud prize" from the "Académie des Sciences" and Ivan Kostov the "Servant price" from the "Académie des Sciences".

In addition, a total of fifteen ACI and ANR projects have been approved and funded, and we have benefited from two Marie Curie International Reintegration Grants, one Marie Curie Outgoing International Fellowship, two Marie Curie Intra-European Fellowship and the lab is involved in four European Networks. Let us also mention that two young physicists, Géraldine Servant and Iosif Bena, have successfully passed the first round of the extremely competitive European Research Council Starting Grants competition.

In the last two years, we have had to suffer the loss of two prominent scientists: Paul Bonche, who was an outstanding Nuclear Physicist and Madan Lal Mehta, one of the pioneers of Random Matrix Theory. We all remember their outstanding scientific contributions which greatly participated in the prestige of the SPhT.

While writing this introduction, we just learned of the decease of Alexei Zamolodchikov. Aliocha was a major figure of the physics of integrable systems and conformal field theories. He spent the whole year 2006 at SPhT, and after a one and a half year stay in Moscow, he was to come back to our lab as a permanent member in the fall of 2008. We are all profoundly saddened by this deeply moving news.

To conclude this introductory section, 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 quality and help us improve it. Jean-Yves Ollitrault has coordinated the preparation of this report, together with Loic Bervas, Anne Capdepon and Laure Sauboy. I wish to thank them all for their extreme competence. The presentation of the ten scientific chapters has been prepared by Stéphane Nonnenmacher (Chap. B), Philippe Di Francesco (Chap. C), Hubert Saleur (Chap. D), Pierre Vanhove (Chap. E), Patrick Valageas (Chap. F), Philippe Brax (Chap. G), Edmond Iancu (Chap. H), Giulio Biroli (Chap. I) Grégoire Misguich (Chap. J) and myself (Chap. K). I would like also to thank all the members of the lab for their help in preparing this report.

The trademark of the research done at the SPhT, as it has been recognized by many of our colleagues and collaborators, is its rigor, its soundness and its deepness. There is definitely a "Saclay style" and it is our duty to preserve this tradition. I would like again to express my gratitude to all the members of the SPhT for maintaining these high standards of scientific quality.

Henri Orland

CHAPTER B

Dynamical systems, chaos and turbulence

Although the types of dynamical systems studied in SPhT are relatively diverse (1-dimensional vs. N-dimensional, classical vs. quantum, deterministic vs. stochastic), the methods of analysis share some common features. The central object used to characterize the long-time behaviour of the system is the *spectrum* of a corresponding dynamical linear operator.

The spectrum can be the main object of study, like in the case of the Riemann zeta function, a "mock dynamical system" according to the conjecture (due to Pólya and Hilbert) that the nontrivial Riemann zeros are the eigenvalues of some hypothetical "Riemann operator". On the opposite, in the study of the dynamo effect, the spectrum is used to characterize the presence of an instability. It can be considered globally (*e.g.* through spectral determinants), or individually (when dealing with individual high-energy eigenstates).

The corresponding dynamical operator is selfadjoint in the case of a bounded quantum system (or, hopefully, for the "Riemann operator"). On the opposite, nonselfadjoint operators occur in the study of a quantum scattering system: indeed, the associated *resonances* may be defined as the eigenvalues of a complex-dilated Hamiltonian, which is no more self-adjoint.

The study of the dynamo effect also leads to the spectral analysis of a nonselfadjoint operator, namely the induction operator, which depends on a parameter. The dynamo threshold occurs when one eigenvalue of this operator crosses the real axis. In that case, one does not need to know in detail the full spectrum, but only its component close to the real axis, and its dependence with respect to the parameter.

The study of stochastic bifurcations in the dynamics of noisy oscillators is performed by explicitly computing the *Lyapunov exponent* of the system, by averaging over the asymptotic angular distribution of the particle. This distribution can also be regarded as the dominant (Perron-Frobenius) eigendistribution of an associated angular evolution operator.

This chapter contains contributions of 4 permanent researchers (K. Mallick, S. Nonnenmacher, C. Normand, A. Voros). A PhD student, Emmanuel Schenck, joined the group in October 2006. Part of this research activity is supported by an ANR[1] Young researcher grant on quantum chaos.

[1] Agence nationale de la recherche

Contents

B.1 Analytic number theory and 1D anharmonic oscillators *(A. Voros)*

B.1.1 A new criterium for the Riemann Hypothesis

The (still open) *Riemann Hypothesis* (RH) states that all the nontrivial zeros of Riemann's zeta function $\zeta(s) = \sum_{k=1}^{\infty} k^{-s}$ have real part $\frac{1}{2}$. The study of a new criterion for RH, of a purely *asymptotic* nature, has been pursued in [t05/108]. Namely, a numerical sequence u_n (related to the Keiper (1995) and Li (1997) sequence) will, for $n \to +\infty$, either tend to 0 — if RH is true — or oscillate with an exponentially growing amplitude — if RH is false. As new results: the criterion now covers more general number-theoretical zeta or L-functions having functional equations similar to Riemann's; some related numerical observations by Maślanka (2004) are now proven.

B.1.2 From exact WKB analysis to singular quantum perturbation theory

An exact analysis of the time-independent 1D Schrödinger equation has been pursued [t05/204] for the case of *binomial* potentials $V(q) = q^M + gq^N$ (with $N > M > 0$ even). Problem: even in the basic example of the quartic anharmonic oscillator, $V(q) = q^2 + gq^4$, the general ($g > 0$) exact WKB quantization conditions become singular in the $g \to 0$ limit, even though trivial exact quantization conditions are known for $g = 0$ (harmonic oscillator). One challenging issue is to recover an explicit perturbative behavior when the coupling constant $g \to 0^+$ in this singular case.

The asymptotic behavior of certain *global* spectral functions (zeta function, spectral determinant) has been obtained for $g \to 0$ in a *complex sector* (usual perturbation theory rather focuses on *individual* eigenvalues/functions). As a consequence, the evolution of the main exact dynamical equation (a Wronskian identity) has been analyzed when $g \to 0$, and shown to yield the correct $g = 0$ limit, in spite of the jump in degree ($N \mapsto M$). Thus, perturbative regimes can be attained in an exact WKB framework. In the quartic case, calculations have also been turned more explicit using complete elliptic integrals.

B.2 Quantum chaos

B.2.1 Chaotic eigenfunctions *(S. Nonnenmacher, A. Voros)*

This is a shorthand for: *eigenfunctions of quantum systems whose classical dynamics are chaotic*. Such eigenfunctions are most remote from any integrable or perturbative approach: they resist all analytical approximation methods, and their individual structure remains quite mysterious. In particular, the nature of "scars", that is local enhancements of eigenfunctions near classical periodic orbits, is still unclear.

Yet, some information about these functions can be obtained in the semiclassical limit $\hbar \ll 1$; in the particular case of a free particle in a chaotic billiard or a negatively curved manifold, this limit is equivalent with the limit of small wavelength, or high energy. In a series of publications S. Nonnenmacher and N. Anantharaman were able to describe chaotic eigenstates in terms of a classical dynamical object, namely the Kolmogorov-Sinai (KS) entropy.

This entropy is a nonnegative number associated with any stationary statistical distribution (probability measure) on the phase space. It reflects the "statistical complexity" of the dynamics, in the sense of information theory, but also the concentration properties of the distribution : if the latter is concentrated on a single periodic trajectory, the entropy vanishes; on the opposite, the entropy is positive for a "widespread" distribution, like the homogeneous (Liouville) distribution, or for "fractal" stationary distributions.

The link with quantum eigenfunctions is the following: in the semiclassical limit, each eigenfunction corresponds to a certain statistical distribution on phase space, called a *semiclassical distribution*. The latter describes how the "stationary quantum particles" is distributed over the phase space, and is stationary through the classical dynamics. It is known that for any *ergodic* dynamical system, *almost all* eigenfunctions become homogeneously distributed. It has been conjectured that, in the case of geodesic flows on manifolds of negative curvature, *all* eigenfunctions have this property. Naively, the unstable classical motion induces a fast *dispersion* of wavepackets, fobidding them to stay localized. On the other hand, *quantum interferences* may allow delocalized wavepackets to recombine into a localized state.

The main result [t06/123][t07/042] shows a balance between these two phenomena: eigenstates must be at least *half-delocalized*, in the sense that their KS-entropy must be larger than half the entropy of the homogeneous distribution. In particular, this rules out the possibility of "strong scars", that is, eigenstates concentrated along a single periodic trajectory.

The proof (which relies on an *entropic uncertainty principle*) was first applied to a simpler toy model, namely the baker's map on the torus [t05/203]. For this model, the lower bound on the entropy is sharp: there exist half-localized eigenstates.

To obtain more subtle details on the structure of chaotic eigenfunctions, A. Voros elaborated a special graphical display code for 1D quantum wave functions [t05/133]. The latter include eigenfunctions of discrete-time systems (*quantum maps*), as well as boundary functions of billiard eigenmodes.

Specifically, one portrays a 1D quantum pure state by an enriched 2D phase plot of a *Husimi density*; the lower half of the plot is a seashore landscape (shown in 3D perspective), and the upper half a skyscape (see Fig. B.1). The "sea level" is set at the average density. Then the "land" features (above sea level) are those which imprint the classical regime (in particular, scars of periodic orbits show as prominent peaks), whereas the "underwater" features are definitely quantal: the lowest-lying points are isolated zeros, with density 1/(Planck's constant), and each zero labels a building block to a product (Bargmann) representation of the full quantum state. Every state is thus faithfully parametrized by its *constellation of zeros*, which are displayed as skyscape (*stellar* representation). Aside from its possible aesthetical or allegoric appeal, this approach depicts the patterns followed by quantum states in very explicit detail; in particular, chaotic eigenfunctions exhibit sharply distinctive features against integrable cases. The hope is that future cataloging of eigenstates by this technique may uncover new computable or universal features of chaotic eigenfunctions.

B.2.2 Quantum chaotic scattering *(S. Nonnenmacher, M. Rubin)*

A quantum scattering system does generally not involve eigenvalues/functions, but rather *resonances* (or "complex eigenvalues") associated with metastable states, which decay exponentially with time. The decay time is inversely proportional to the imaginary part of the resonance, while its real part provides the average energy of the state. The structure of resonance spectra has been investigated, in cases where the associated classical scattering system exhibits a fractal *trapped set*, on which the flow is unstable. The semiclassical density of resonances is conjectured to be governed by the fractal dimension of the trapped set, leading to a *fractal Weyl law*. This conjecture has been numerically checked on a toy model, the open baker's map [t05/111][t05/112][t06/124].

For this model, the phase space distribution of the corresponding metastable states has also been studied in [t06/124]. In the semiclassical limit, these states converge to certain statistical distributions on phase space, which are classically invariant up to a scalar factor (the *decay rate* of the distribution). A classification of this novel type of semiclassical distributions has been initiated, in particular for the case of a solvable toy model.

In a subsequent work [t06/100][t07/106], the analysis of resonant states has been extended to more realistic models (scattering by a potential). For such models, it was also shown that the quantum decay times are uniformly bounded from above, provided a certain classical dynamical object (the topological pressure) is negative (roughly speaking, provided the trapped set is sufficiently "thin"). This condition ensures that a wavepacket propagating near the trapped set disperses fast enough (due to classical instability), so that it cannot "recombine" itself by constructive interference.

B.3 Parametric instability of the helical dynamo *(Ch. Normand)*

In the context of recent dynamo experiments, an important question is to identify the relevant physical parameters which control the dynamo threshold, and eventually minimize it. In addition to the parameters usually considered, like the geometry of the mean flow or the magnetic boundary conditions, the turbulent fluctuations of the flow seem to have an important influence on the dynamo threshold. Some recent experimental results suggest that the large spatial scales of these fluctuations could play a decisive role.

Ref. [t06/213] studies the modification of the dynamo threshold of a stationary helical flow by the addition of a large scale, time periodic, helical fluctuation. It extends a previous asymptotic study [t02/136] to the case of a fluctuation of arbitrary intensity (controlled by the parameter ρ). Moreover, two types of helical flows are considered : either (i) solid body like in [t02/136], or (ii) continuous flow. In case (ii) the

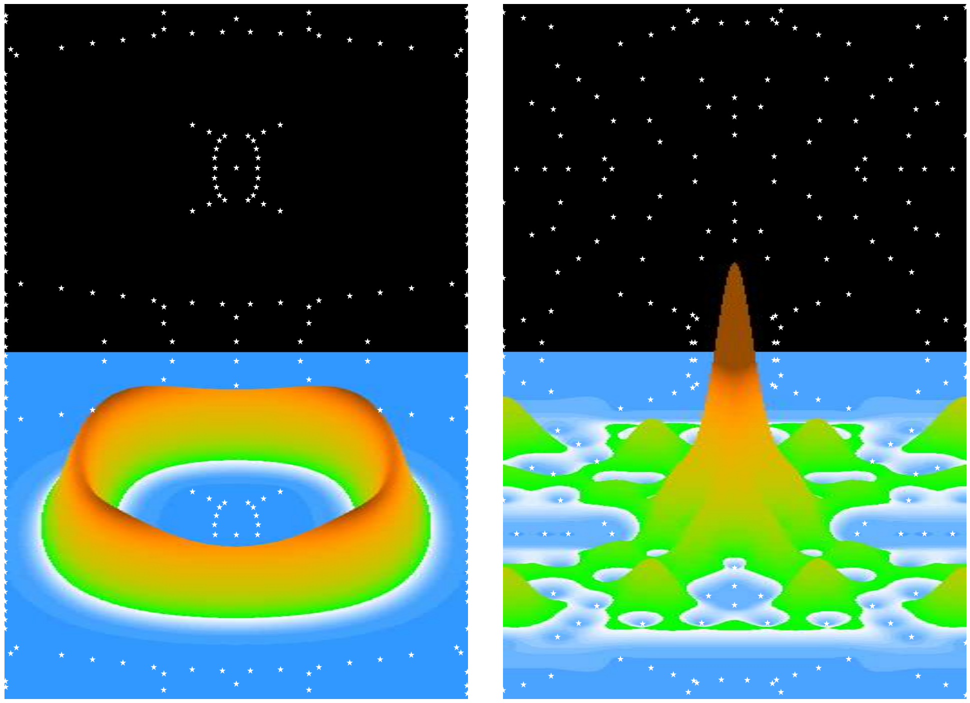

Figure B.1: Phase space representation of two billiard eigenfunctions, taking the Husimi representation of the boundary function. Left: eigenstate of an elliptic (integrable) billiard, localized on an *invariant curve*. Right: eigenstate of a stadium (chaotic) billiard, presenting a *scar* (peak) on a periodic orbit.

spatial behavior of the magnetic field is described using the Galerkin method introduced in [t04/049] for von Karman flows.

At large magnetic Reynolds number R_m, the dynamo efficiency of a helical flow is characterized by some resonant condition that can be achieved by choosing an appropriate geometry of the helical flow, such as changing its geometrical pitch. It has been numerically verified that the resonant condition holds at lower R_m corresponding to the dynamo threshold, for both a stationary and a fluctuating helical flow (with zero mean). Then, for a helical flow made of a mean part plus a fluctuating part, and for the asymptotic cases $\rho \ll 1$ (dominating mean), respectively $\rho \gg 1$ (dominating fluctuation), it is naturally the resonant condition of the mean part or the flow, resp. the fluctuating part of the flow, which governs the dynamo efficiency and then the dynamo threshold. Inbetween, for $\rho \sim 1$ and if the resonant condition of each flow part (mean and fluctuating) is satisfied, the threshold first increases with ρ, it then reaches a maximum, and then decays like $1/\rho$.

These results show that the optimization of a dynamo experiment depends not only on the mean part of the flow, but also on its large-scale nonstationary part. If the fluctuation is not optimized, then the threshold may increase drastically with (even small) ρ, ruling out any hope of producing dynamo action. In addition, even if the fluctuation is optimized (resonant condition satisfied by the fluctuation), our results suggest that there is generally some increase of the dynamo threshold with ρ when $\rho \leq 1$.

B.4 Stochastic dynamical systems *(K. Mallick)*

It is a well-known fact that a multiplicative noise acting on a dynamical system can generate unexpected phenomena such as stabilization, stochastic transitions, pattern formation or stochastic resonance.

B.4.1 Noise-induced bifurcations

As far as the stability of a random dynamical system is concerned, the exactly solvable example of a nonlinear first-order Langevin equation shows that the behaviour of the moments of the linearized equation can be misleading: higher moments seem to always be unstable, although it is known that the critical value of the control parameter is the same as that of the deterministic system. This apparent contradiction is due to the existence of *long tails* in the stationary probability distribution of the linearized equation, which are suppressed when the nonlinearities are taken into account.

In [t05/173], the authors study the noise-induced bifurcation of a nonlinear oscillator with random damping. This dynamical system, in which the noise acts on the velocity variable, provides another example of a bifurcation induced by a multiplicative noise. This model was introduced in the study of the generation of water waves by wind, where the turbulent fluctuations in the air flow are accounted for by the noise. It is also relevant in the study of dynamical systems involving an advective term with fluctuating velocity. The correct stability diagram of the system is obtained thanks to an analytical calculation of the Lyapunov exponent measuring the asymptotic growth rate of the energy.

Ref. [t06/183] is devoted to the study of the long-time behaviour for a nonlinear oscillator subject to a random multiplicative noise, the spectral density (power-spectrum) of which decays as a power law at high frequencies. When the dissipation is negligible, physical observables, such as the amplitude, the velocity and the energy of the oscillator, grow as power-laws with time. The associated scaling exponents are computed: their values depend on the asymptotic behaviour of the external potential and on the high frequencies of the noise. For this problem, the high frequencies of the noise spectrum thus play a crucial role: the faster the power spectrum decays at high frequencies, the slower the diffusion.

The physical interpretation is the following: the energy transfer from the external driving to the oscillator is optimal when the driving frequency is of the order of the natural frequency of the oscillator (*e.g.*, parametric resonance is maximal for driving at twice the natural frequency). Now, due to the nonlinearity, the frequency of the deterministic oscillator increases with the amplitude. Therefore, at large amplitudes, the energy transfer between the noise and the system involves higher and higher frequencies. If these frequencies have a small weight in the noise power spectrum, the amplification of the oscillator is less efficient.

The calculations bring this intuitive reasoning to a quantitative level, and can be generalized to include dissipative effects. In presence of dissipation, the system reaches a nonequilibrium steady state, in which the stationary PDF is not the canonical Gibbs-Boltzmann distribution, but a streched exponential.

B.4.2 On–Off Intermittency

A bifurcating system subject to multiplicative noise can exhibit on-off intermittency close to the instability threshold. Ref. [t05/162] discusses the dependence of this intermittency on the noise power spectrum. The study is based on the calculation of the Probability Density Function (PDF) of the unstable variable. Analytical results are derived for dichotomous Poisson noise and a cumulant expansion is used for harmonic noise.

For a system of first order in time and for a small value of the product of the noise amplitude with its correlation time, on-off intermittency is proved to occur if the noise spectrum at zero frequency is greater than twice the departure from onset. This prediction is in agreement with numerical simulations that use colored random processes or chaotic fluctuations as noises. In the same limit, the statistics of the durations of the laminar phases are also controlled by the departure from onset and the noise spectrum at zero frequency. Even at finite noise amplitude, it has been numerically verified that intermittency disappears when the low frequencies of the noise are filtered out.

For a system of second order in time, the behaviour of the unstable variable has been numerically studied: for small noise amplitudes, the PDF of the energy scales as a power law, with an exponent controlled by the noise spectrum at zero frequency and the departure from onset. Ref. [t06/182] studies related effects of the noise low frequencies on first passage times and on stochastic resonance. (see also [t05/184]). These results have been reviewed in [t06/224].

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CHAPTER C

Combinatorial statistical physics

Many problems in statistical physics start with enumerations of sets of configurations or states reachable by a given system. In this respect, many fundamental questions about statistical systems are of a combinatorial nature. The closeness of theoretical statistical physics and combinatorics has recently been highlighted by the 2006 Fields medals, two of which at least (Okounkov and Werner) may be described as mathematics inspired by combinatorial statistical physics. Another sign is the recent multiplication of workshops and conferences at the boundary between these two domains.

The methods and ideas of statistical physics allow for a completely different approach to standard combinatorial problems and helps shed new light on them. Indeed, some models turn out to have extremely rich structures, that subsequently get reflected into remarkable combinatorial properties that have no simple explanation, and that require instead to explore the machinery of integrable systems. Integrability appears as a sort of Leitmotiv in the various works collected below, and is the subject of a review article in the french version of Scientific American (Pour La Science) [t05/140].

One remarkably efficient statistical physics tool in this respect is the matrix integral, developed from the 70's after a remark by t'Hooft, which shed a completely different light on the earlier mathematical work of Tutte in graph theory. A strong group at SPhT explores and develops state of the art matrix integral techniques and formulations, which now also display intriguing relations to algebraic geometry. These have been extensively used to describe discrete models of quantum gravity, namely models of discrete matter (spins, particles) on fluctuating (random) lattices, as well as some more mathematical and abstract object known as the moduli space of curves.

Beyond matrix models, new combinatorial techniques have been developed partly at SPhT to study refined properties of random lattices, related to their intrinsic geometry, such as questions concerning geodesic distance between marked points on random surfaces. There again, integrability has made an unexpected appearance. The main techniques employed consist in cutting graphs into trees, endowed with the minimal information required to be able to reconstruct the initial graph. Henceforth, the statistics of random trees appear crucially in this analysis, and have been the object of independent work as well.

Finally, regular lattice statistical models have also been the subject of intense activity, around the so-called Razumov-Stroganov conjecture, that explores fascinating combinatorial properties of loop gases and/or spin chains in various geometries, namely their relation to so-called alternating sign matrices. Recent developments at SPhT, mainly based on the integrability of the statistical models involved, include actual proofs of parts of the conjecture, various generalizations to higher rank spin chains or different underlying algebras, and finally extensions in the direction of algebraic geometry, as part of the general theory of the multidegree of matrix varieties. So, that it be in the framework of random lattice models or regular lattice models, it seems that refined algebraic properties of matrices or matrix ensembles have a role to play. Beyond mere integrability, one can hope for a possible connection between all these problems, yet to be discovered.

This chapter contains contributions of 10 permanent researchers (M. Bergère, G. Biroli, J. Bouttier (since 2006), F. David, P. Di Francesco, B. Eynard, E. Guitter, J. L. Jacobsen, J.-M. Normand, V. Pasquier, some of which — Biroli, David, Jacobsen, Pasquier — have also contributed to other chapters), two post-docs (A. Prats-Ferrer and F. Zamponi, who is also involved in the activities described in Chap. I), and one PhD student (N. Orantin). The activity of the group is partially funded by several programs: the European network ENRAGE[1]; a Jules-Verne exchange program with Iceland; a national grant ACI[2] Masse de données and an ANR[3] project "Geometry and integrability in mathematical physics", led by Paul Zinn-Justin.

Contents

[1] Random Geometry and Random Matrices: From Quantum Gravity to Econophysics
[2] Actions concertées incitatives du Ministère de la recherche
[3] Agence nationale de la recherche

C.1 Random matrices: Theory and applications

C.1.1 Universal statistics of eigenvalues of large matrices *(B. Eynard)*

Random matrices were first introduced by Wigner in the 50s, as a model for the universal statistics of nuclear energy levels. The same statistics have been observed in many other domains, from electronics to biology, economics,... and there is an intense activity in trying to prove their universality, as well as to classify all possible universal regimes. Universality means that the eigenvalue statistics of large random matrices are independent of the specific probability measure used to compute them. This property is far from trivial, and is not mathematically proved in most cases. When the matrix becomes large, the eigenvalues concentrate into some domains with some finite non-universal density, while eigenvalue correlations are universal. Different universal regimes may occur, for instance in the bulk of the spectrum, near the edges, or when two edges come close to one another. These regimes are all described by conformal field theory.

In [t06/046], a new universal regime was studied, namely that where a new connected piece appears in the spectrum. Despite its universality, this regime it is not related to a minimal model of conformal field theory. In particular its shows some periodic seesaw behaviours.

C.1.2 On the top eigenvalue of heavy-tailed random matrices *(G. Biroli, J.-P. Bouchaud, M. Potters)*

In [t06/216] and [t07/031] we study several problems concerning Random Matrix Theory and the generalization of the Tracy-Widom distribution when the disorder has "fat tails". We identify the new class of limiting distributions determining the statistics of the largest eigenvalue $\lambda_{\max}$ of Wigner random matrices with *iid* entries of variance $1/N$, but with power-law tails $P(M_{ij}) \sim |M_{ij}|^{-1-\mu}$ with $\mu \leq 4$. We extend these results to sample covariance matrices, and show that extreme events may cause the largest eigenvalue to significantly exceed the Marčenko-Pastur edge. Apart for its theoretical interest, this turns out to be important for the analysis of statistical data, in particular in financial applications. We also underline the relevance of power-law tails for Directed Polymers and mean-field Spin Glasses, and we point out various open problems and conjectures on these matters. We find that in many instances the assumption of Gaussian disorder cannot be taken for granted.

C.1.3 Angular integrals over Lie groups *(P. Di Francesco, B. Eynard, A. Pratts-Ferrer, J.-B. Zuber)*

The Harish-Chandra–Itzykson–Zuber integral is a classical result of an integral over the unitary group, which was famous because it was very useful for numerous applications in physics, and particularly in random matrix theory. The Harish-Chandra formula extends to other groups, like the orthogonal and symplectic groups. However, for many applications in physics, knowing the value of the integral is not sufficient, one would also like to compute all moments. For instance counting configurations of an Ising model on a random lattice with fixed spins on the boundary requires such moments of the Harish-Chandra formula. Integrals over Lie groups are difficult, because the integration measure is the Haar measure, which is not flat and rather difficult to handle. In [t06/131], all those moments were computed, by first finding an exact semi-classical formula, which turned the Haar measure integral into a sum of gaussian integrals with flat Lebesgue measures, and then computing those easy gaussian integrals. The result is then very simple and shows a very universal structure which is yet to be understood.

C.1.4 Block-orthogonal polynomials *(J.-M. Normand)*

Constrained orthogonal polynomials have been recently introduced by B. Giraud *et al* [t04/075] [t05/001] [t05/071] in the study of the Hohenberg-Kohn variational principle to provide basis functions satisfying particle number conservation for an expansion of the particle density. More generally, we define block orthogonal (BO) polynomials which are orthogonal, with respect to a first Euclidean inner product, to a given i-dimensional subspace $\mathcal{E}_i$ of polynomials associated with the constraints.

By definition, the standard block orthogonal (SBO) polynomials are defined by choosing $\mathcal{E}_i$ equal to the subspace of polynomials of degree less than i. They are real polynomials $P_{i;n}(x)$, $0 \leq i \leq n$ of degree n which are orthogonal with respect to a first Euclidean scalar product to polynomials of degree less than i. In addition, they are mutually orthogonal with respect to a second Euclidean scalar product. In a first paper I [t06/058], we investigate the properties of SBO polynomials, emphasizing similarities to and differences from the standard orthogonal polynomials. In a second paper II [t06/059], applying the general results thereby obtained, we determine and investigate these polynomials when the first scalar product corresponds to Hermite (resp. Laguerre) polynomials. These new sets of polynomials, we call Hermite (resp. Laguerre) SBO polynomials, provide a basis of functional spaces well-suited for some applications requiring to take into account special linear constraints which can be recast into an Euclidean orthogonality relation.

C.2 Combinatorics of random surfaces and integrability

C.2.1 Counting surfaces, algebraic geometry and integrable systems *(M. Bergère, B. Eynard, N. Orantin)*

Many areas of theoretical physics have to do with counting 2-dimensional surfaces. For instance in statistical physics, one is interested in counting the number of configuration (the entropy) of particles or spins living on a random lattice, and in particular one needs to be able to compute the entropy of the lattice itself. Then one would like to consider the continuum limit when the lattice spacing becomes small and the lattice tends towards a continuous surface. In both cases, one needs to enumerate 2-dimensional latices (which are discrete surfaces), and 2-dimensional surfaces, with possibly some given weight. In string theory the particles themselves are 1-dimensional objects, and as they move, they sweep a 2-dimensional surface. Quantum mechanics means that one should average over all possible histories of the particles, i.e. over all possible surfaces, and the problem of counting surfaces appears again. Strings also move in a larger space-time of dimension 10, which contains the usual macroscopic 3 space dimensions and 1 time dimension, plus 6 extra microscopic dimensions which form a Calabi-Yau space. The classification of possible string theories requires a classification and characterization of Calabi-Yau spaces, which is done by computing some numbers of maps over surfaces (Gromov-Witten invariants). This problem again amounts to measuring a "number of surfaces".

In 2-dimensional quantum gravity, the surface is the universe itself, and again quantum gravity means averaging over all possible histories of the universe, i.e. averaging over surfaces weighed by Einstein's action, i.e. their curvature and area. In algebraic geometry, one is interested in counting the number of Riemann surfaces of given genus and with marked points, called the volume of the moduli spaces of algebraic curves.

It has long been noticed and conjectured that many of those "numbers of surfaces" can be obtained by computing some matrix integrals.

[t06/016] consisted in counting random lattices with an Ising model (i.e. an integral with 2-hermitian matrices). [t06/017] consisted in counting non-oriented random lattices (i.e. an integral with one non-hermitian matrix). [t06/037] and [t07/055] consisted in counting configurations of an Ising model on a random lattice with boundaries with fixed spins on the boundary. [t07/065] consisted in counting volumes of moduli spaces of curves with fixed length boundaries. The striking observation is that all of those various numbers of surfaces share a common structure.

Upon integration by parts, matrix integrals satisfy a set of equations, called loop equations, ward identities, Virasoro or W-algebra constraints depending on the context. Loop equations consist in recursion relations on the size and genus of the surfaces. In the simplest case (random triangular lattice with no matter on it), those equations have been known by combinatorists for 50 years (Tutte's census of planar maps). Leading-order solutions of loop equations have been known case by case for some models for more than 20 years, and some of the first subleading corrections for some cases have been found in the past decade. However, it was recentely discovered in [t07/021], that they can all be written in a single framework, related to algebraic geometry and integrability. [t07/021] defined that framework, i.e. the notion of invariants of algebraic plane curve, and studied the main properties of those newly defined invariants. Some interesting properties include the symplectic invariance (algebraic curves related by a transformation conserving some symplectic form have the same invariants, whence the name of invariants), as well as integrability: those invariants satisfy a set of equations called Hirota bilinear equations, and they form a hierarchy of integrable non-linear equations, called multi-component KP hierarchy. Moreover, those invariants can be best computed by a diagrammatic method, associating some graphs to each invariant.

Applications of the methods defined in [t07/021] are numerous. For instance is was possible to recover in a new and rather easy way some results of Kontsevich, i.e. the fact that some volumes of moduli space represented by the famous Kontsevich matricial Airy function satisfy the KdV integrable hierarchy and depend only on odd KdV times. Another application was to compute the continuous limits (called double scaling limits of matrix integrals) of discrete surfaces, and recover some known results of conformal field theory. Another application was to prove in [t07/020] that matrix integrals do satisfy the famous "holomorphic anomaly equation" discovered in the study of Calabi-Yau spaces, and which were conjectured by Dijkgraaf and Vafa to coincide with matrix integrals. Another application in [t07/065] was to observe that the recursion equations discovered by M. Mirzakhani for measuring the volumes of moduli spaces are the same as in [t07/021], and therefore provide one new proof of the link between matrix models, KdV, Kontsevich integrals and volumes of moduli spaces.

C.2.2 Discrete models for causal gravity *(F. Zamponi)*

In [t07/091], we study a statistical model for 3-dimensional surfaces, whose structure is inspired by (2+1)-dimensional quantum gravity, in the framework of the so-called Causal Dynamical Triangulations. The idea is to generate partly random lattices (here a 3D network made of tetraedra), mixing up regular directions and random ones. By imposing an additional notion of order on the 2-dimensional "spatial" slices (corresponding to a 1+1+1 structure), we simplify the combinatorial problem of counting geometries just enough to enable us to calculate the transfer matrix between boundary states labelled by the area of the spatial slices. In this way we can identify a critical point and investigate the continuum limit around this point, in particular calculating the quantum Hamiltonian of the continuum theory. This is the first time in dimension larger than two that a Hamiltonian has been derived from such a model by mainly analytical means, and might open the way for a better understanding of scaling and renormalization issues in these models.

C.2.3 Combinatorics of random surfaces with matter *(J. Bouttier, P. Di Francesco, E. Guitter)*

Traditionally introduced as toy models for 2D quantum gravity, statistical models of matter defined on discrete random surfaces have been extensively explored using techniques of matrix models. These techniques are however not fully satisfactory for various reasons: first the mathematical status of the method is still under development; then in many cases the simplicity of the results contrasts with the high sophistication of the methods used, and suggests that simpler approaches should exist; finally matrix techniques are limited mainly to global properties of surfaces. For all these reasons, we were led to develop more direct combinatorial methods, namely via bijections between maps and (possibly decorated) trees. This approach allows for a straightforward and mathematically rigorous re-derivation of many map-enumeration results, and moreover gives access to refined properties involving the intrinsic geometry of the underlying surfaces. So far, these techniques have been used only for surfaces without matter. In [t07/054] we show how to extend the above formalism to enumerate maps with matter. The presence of matter is mimicked by restrictions on the allowed paths on the maps, in the form of road blocks, that affect geodesic distances between points (see Fig.C.1 for an illustration).

These maps are then enumerated via bijections with decorated trees and inclusion-exclusion principles. This way to introduce matter turns out to be very general. Applications include maps with hard (mutually avoiding) particles, the Ising model and spanning trees on a discrete random surface.

C.2.4 Integrability and geodesic distance in random surfaces *(P. Di Francesco, E. Guitter)*

The bijective approach to enumerating maps while keeping track of geodesic distances, say between two marked points on the map, is known to provide discrete algebraic recursion relations for generating functions, as functions of the discrete geodesic distance between the points. Quite surprisingly, these relations turn out to be integrable, namely there exist quantities defined in terms of the generating functions that are conserved, i.e. independent of the geodesic distance.

In [t05/113] we investigate the integrability of the discrete non-linear equation governing the dependence on geodesic distance of planar maps with inner vertices of even valences, expressed in terms of generating functions for random walks. We construct explicitly an infinite set of conserved quantities for this equation, also involving suitable combinations of random walk generating functions. The proof of their conservation relies on the connection between random walks and heaps of dimers. The values of the conserved quantities are identified with generating functions for maps with fixed numbers of external legs.

C.3 Random trees

C.3.1 From quantum gravity to multicritical random trees *(J. Bouttier, P. Di Francesco, E. Guitter)*

The models of discrete random surfaces in the form of weighted maps with arbitrary (even) valences give access to a host of possible multicritical behaviors, already investigated in the context of 2D quantum gravity, obtained by fine-tuning the vertex weights. By applying recent bijective techniques, we may code these maps by trees decorated with labels which keep track of the geodesic distances on the map. Multicritical models of maps translate therefore into multicritical models for labeled trees, and a natural question is to characterize their continuum limit. In [t06/021], we consider a simpler version thereof, without the labels. Starting from discrete models, we perform a continuum limit, leading to a statistical ensemble of weighted continuous trees generalizing the standard Aldous Continuous Random Tree, for which we compute various thermodynamic quantities, like the shape distribution, involving scaling functions such as generalized Airy functions. As for maps, the multicriticality in trees induces non-unitary properties for the quantities at hand. Indeed, at the discrete level, the fine-tuned weights have signs, and imply a complete reshuffling of the statistical ensemble, in which cancellations must occur. In spite of this difficulty, we have been able to provide an axiomatic continuous formulation for multicritical trees based on consistency relations between multi-point correlation functions.

C.3.2 Universality in randomly growing trees *(F. David, P. Di Francesco, E. Guitter, T. Jonsson)*

Random trees arise in many branches of science, ranging from the social sciences through biology, physics and computer science to pure mathematics. In physics, random trees often occur in the context of statistical mechanics or quantum field theory, and fall into one universality class, called *generic random trees*. Another large class of random trees arises in *growth*

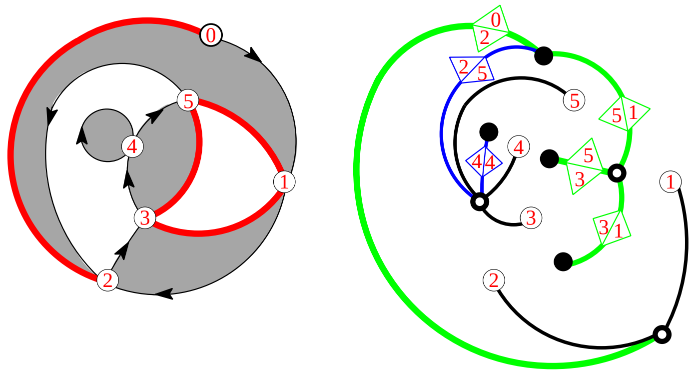

Figure C.1: *Left:* A typical planar Eulerian map with bicolored faces and oriented edges, some of them (in red) being blocked. These blockings affect geodesic distances (vertex labels) from a given origin (labeled 0). *Right:* Coding of this map by a decorated tree.

processes (for instance branched polymer growing in a solution), and in many important real world cases one can observe the structure of the growing tree but only guess the rules which govern the growth (social networks, the internet, citation networks etc.).

In [t06/186], we investigate the statistics of trees grown from some initial tree by attaching links to preexisting vertices, according to some stochastic rules, with local attachment probabilities. As long as one is interested only in global properties, these growth processes reduce to a model of evolution of populations which belongs to the class of so-called generalized Pólya urn problems, and have been extensively analyzed.

We consider the asymptotic mass distribution that measures the repartition of the mass of large trees between their different subtrees. We first study growing binary trees which are characterized by the ratio x between the probabilities that a new vertex attaches itself to an old vertex of valence 1 or of valence 2. This distribution is shown to be a broad distribution, and to depend in a non trivial way on the ratio x and on the initial condition (initial tree geometry). We derive explicit expressions for mass distribution scaling exponents that characterize its behavior when one subtree is much smaller than the others. We show in particular the existence of various regimes with different values of these mass distribution exponents. A particular case is exactly solvable and relates to the so-called reinforced random walk, in which a walker has a tendency to preferably return to places already visited. These results are generalized to the case of growing multinary trees as well.

C.4 Loop models, integrability and combinatorics

C.4.1 Razumov–Stroganov conjecture and beyond *(P. Di Francesco, V. Pasquier, P. Zinn-Justin)*

Based on a result of Baxter, Razumov and Stroganov (and also Nienhuis et al.) observed that the components of the ground state of the XXZ chain at a special value of the anisotropy ($\Delta = 1/2$) are positive integers enumerating certain classes of alternating sign matrices. This groundstate was also interpreted as yielding, in the context of the dense nonintersecting $O(n = 1)$ loop model, the probabilities of connectivity of boundary points on a semi-infinite cylinder of square lattice, according to a given “link pattern”. P. Di Francesco and P. Zinn Justin have recently proved a sum rule version of this conjecture by considering an inhomogeneous version of the loop model and using its integrability, in the form of intertwining properties of the transfer matrix, and identified the sum of unnormalized probabilities with the partition function of the inhomogeneous 6-vertex model on a square grid, with domain-wall boundary conditions (known as the Izergin-Korepin determinant).

In [t05/087], we used this result to propose a deformation depending on the general anisotropy parameter Δ (or general loop weight n). This vector is *not* the ground state of a transfer matrix, but its entries satisfy difference equations which make them form a polynomial representation of the Affine Temperley-Lieb Algebra. It also obeys remarkable vanishing properties and can be recovered as a q-deformation of certain Quantum Hall Effect wave functions. Finally, this vector displays positivity and integrality conditions that suggest combinatorial interpretations.

In [t05/130], these were alternatively interpreted as the polynomial solutions of the so-called quantum

Knizhnik-Zamolodchikov equation (qKZ), occurring in the framework of quantum groups. This allowed to generalize the earlier results to higher rank statistical models, based on the $U_q(sl(k))$ quantum group, and we have been able to prove generalized "Razumov-Stroganov" sum rules for the higher rank $sl(k)$ quantum spin chains at $q = -e^{i\pi/(k+1)}$. These involve new integer sequences that seem to generalize the numbers of alternating sign matrices (associated to $k = 2$).

Another generalization was given in [t05/121], by studying the polynomial representations of the affine Birman-Wenzl-Murakami algebra, that describes loops that over– or under–cross each other.

C.4.2 qKZ equation and algebraic geometry of orbital varieties *(P. Di Francesco, P. Zinn-Justin)*

In [t05/130], it was also observed that another value of $q = -1$ yielded surprisingly interesting combinatorics. At this point, the entries of the polynomial vector solution to qKZ reduce again to integers, like in the original Razumov-Stroganov case. For $k = 2$, we have found that these integers actually count the degrees of the components of the variety of upper triangular complex matrices with vanishing square. For general k, these yield the degrees of the components of the variety $M^k = 0$, M upper triangular complex. We have actually proved this fact, by interpreting the standard Hotta construction for computing degrees, and adapting it to the computation of multidegrees for these varieties, namely a decoration of the degree by weights affected to matrix elements, and yielding polynomials instead of just an integer.

This was further developed in [t05/181], where we considered the more general cases of qKZ equations based on root systems of classical Lie algebras, as a way of changing boundary conditions. We proved a number of generalizations of the sum rule, involving numbers of alternating sign matrices with various symmetries, as well as numbers of plane partitions with various symmetries. At $q = -1$, we have found that the components of the qKZ solution are always integers, counting the degrees of the components of the matrix variety M^2=0, with M in a Borel subalgebra of the corresponding Lie algebra. These are cases of so-called orbital varieties, defined for each Lie group.

C.4.3 Other boundary conditions *(P. Di Francesco,M. Kasatani, V. Pasquier, J.-B. Zuber)*

Instead of considering the loop model in cylinder geometry (periodic), Razumov and Stroganov have also considered it on a strip with open (reflecting) boundaries, leading to other conjectures, involving this time the vertically symmetric alternating sign matrices. The corresponding sum rule was recently proved by Di Francesco, and we have subsequently introduced the higher rank generalizations thereof [t05/135], leading to natural generalizations of the numbers of vertically symmetric alternating sign matrices.

Another modification of the boundary conditions consists in keeping the cylinder geometry, but introducing a puncture (at infinity), therefore keeping track of the relative positions of the loops with respect to this puncture. The corresponding sum rule was derived in [t06/020], using the qKZ techniques. In [t06/249] the q-generalization was worked out, including another weighting of loops encircling the puncture, displaying new combinatorial wonders.

C.4.4 Loop models and plane partitions *(P. Di Francesco, P. Zinn–Justin)*

As was noted by Pasquier and Di Francesco-Zinn–Justin, the entries of the qKZ solution for $sl(2)$ become in the homogeneous limit polynomials of the variable $n = -q - q^{-1}$, with non-negative integer coefficients. In [t06/084], we conjectured that the corresponding sum rule is the generating polynomial for n-weighted totally symmetric self-complementary plane partitions (TSSCPP). The latter are famous combinatorial objects, known to be in same number as the alternating sign matrices, but finding a bijection between both remains a challenge for combinatorialists. They are simply rhombus tiling of an hexagon via elementary rhombi made of adjacent unit equilateral triangle, when the hexagon is itself drawn on a triangular lattice, with a maximal number of symmetries (see Fig.C.2). Once reduced to a fundamental domain, these can be enumerated by considering non-intersecting lattice paths (NILP) formed by successions of two types of rhombi. The n-enumeration simply affects a weight n to one type of rhombus.

In [t06/144], an analogous conjecture was given for the open (reflecting) boundary case, relating this time the sum rule to n-enumerated plane partitions with less symmetries, namely cyclically symmetric transpose complementary plane partitions(CSTCPP). These are now rhombus tilings of an hexagon with simply rotational and reflection symmetries, the hexagon having a central triangular hole for odd size strips. In particular, it was noted that each entry of the open qKZ solution has a small n behavior involving a refined number of TSSCPP.

In [t07/053], by constructing explicitly solutions to qKZ via multiple contour integrals, we have been able to prove the conjecture of [t06/084], modulo a lemma proved by D. Zeilberger. The idea is to introduce a change of basis from link patterns to integer sequences, that code these multiple integrals. The change of basis is sufficiently explicit to allow to take care of sum rules.

C.5 Potts model and Combinatorics *(J. L. Jacobsen)*

In [t06/051] and [t06/210], we study combinatorial properties of the partition function of the Potts model

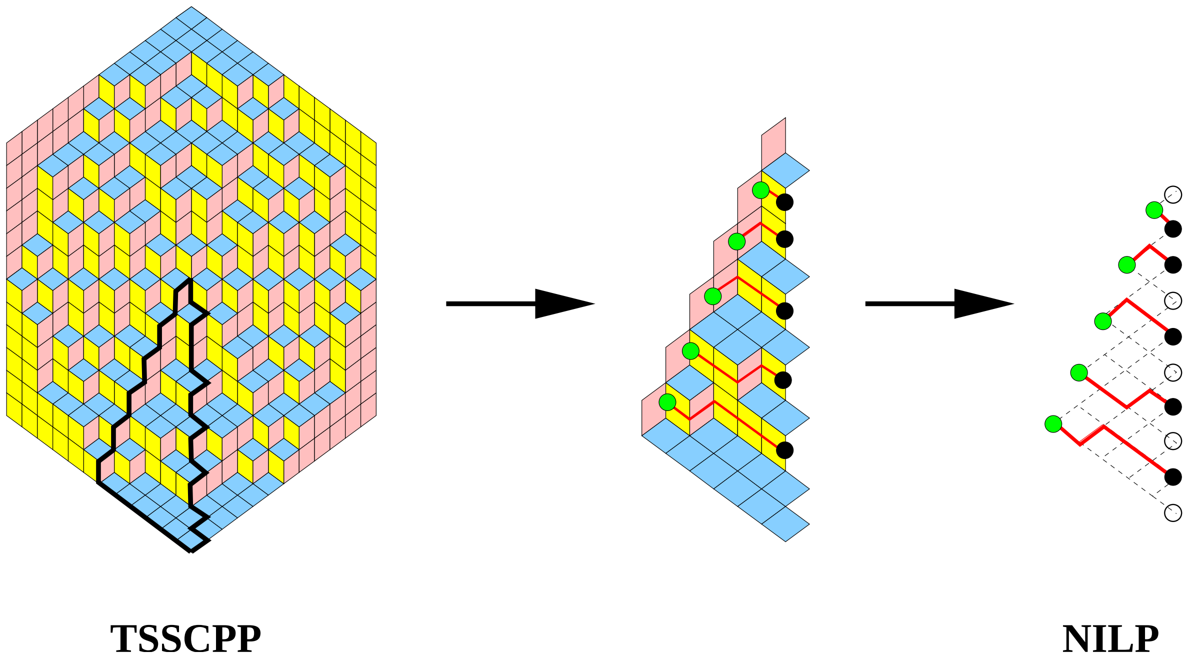

Figure C.2: A typical TSSCPP of size $2n = 12$. The area delimited by the black broken line is a fundamental domain for all symmetries of the partition (1/12th of the hexagon). This domain is expressed as a configuration of NILP, by following the sequences of yellow and pink rhombic tiles. The n-enumeration simply affects a weight n to the latter tile.

on a ring and on a torus, respectively (see also [t06/050]). We show that some operator multiplicities can be reinterpreted as amplitudes of eigenvalues of the transfer matrix, even in finite size. We derive these amplitudes from a rigorous combinatoric argument. In the toroidal case, our results make contact with number theory through generalized Ramanujan series.

In [t06/211], we study tilings of the plane with linear trimers. The transfer matrix of this problem has an interesting structure, with a number of sectors growing exponentially (instead of linearly) with the system size. The existence of a two-dimensional height representation, together with numerical evidence, lead us to the conclusion that trimers are described by two compact bosons in the continuum limit. In [t06/214], we tile the plane with T-shaped tetrominoes. Using arguments of bijective combinatorics, we find an exact correspondence with the Potts model. The number of states and the temperature of the latter can be varied by applying an electric field to the tetrominoes.

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CHAPTER D

Conformal field theory and random geometry

This chapter deals with research stretching somewhat between string theory and combinatorics. Although it would have been conceivable to insert some of the following sections in chapters C and E, this would have missed their truly interdisciplinary nature, and we have preferred not to do so.

As a result, the group whose work is now to be described has overlap with other groups, and consists of five permanents (M. Bauer, B. Duplantier, I. Kostov, V. Pasquier and H. Saleur), one post-doc (K. Kytölä, since Oct. 2006) plus two graduate students (Y. Ikhlef and C. Candu). The departure of D. Bernard for the ENS has been a major blow, partially compensated by the part-time delegation of J.L. Jacobsen from the LPTMS Orsay.

Relations between quantum field theory and random geometrical problems have an ancient history, dating back probably to Symanzik's random walk representation of the continuous ϕ^4 theory in the sixties. Many of the conformal field theories of interest today are, for technical reasons, often more conveniently studied using (discrete) loop representations as well.

Conversely, many random geometrical problems of interest in particular in probability theory can be tackled using ideas of conformal field theory. This relationship has blossomed considerably in the last few years, giving birth to the field of mathematical physics often called "SLE" (from Schramm–Loewner Evolution). The group (M. Bauer, D. Bernard) in Saclay made considerable contributions to this field in the previous period, and wrote, in the last two years, an extensive review of the subject [t06/023] (Sec. D.4.1).

Another perspective (B. Duplantier) places random geometrical models on a random lattice and studies the conformal random geometry of their joint critical continuum limits. One thereby arrives at the study of critical curves or SLEs in quantum gravity, which allows to predict their planar critical or multifractal properties through the use of the well-known KPZ formula. This approach was summarized in comprehensive Lecture notes [t05/243] (Sec. D.4.2).

A great deal of activity from the group in this new period has been devoted to the study of sigma models with super-manifold target spaces. These models play a crucial role in the AdS/CFT correspondence, and their study is in fact part of the project "INT-AdS/CFT" funded by a grant from ANR[1], whose other components are described in Chapter E (D. Serban).

Considerable progress has been achieved on the pure conformal field theory side (Sec. D.1.1) in a series of collaborations by H. Saleur and V. Schomerus (who is now in Hamburg), by developing and using harmonic analysis on super-manifolds. The sigma models can also be studied using lattice regularizations, in particular of geometrical type. Using this approach and ideas of non semi-simple associative algebras theory, H. Saleur and N. Read (Yale) have been able to exhibit large symmetries somewhat analogous to Yangians, and map out the complete (boundary) structure of the superprojective models $CP^{n+m-1|n}_{\theta=\pi}$ (Sec. D.1.3). Y. Ikhlef, J. L. Jacobsen and H. Saleur (in collaborations with F. Essler (Oxford) and H. Frahm (Hannover)) have also made progress on the non-compact nature of these theories, and shown how continuous spectra of critical exponents could be extracted from the Bethe ansatz (Sec. D.1.2). Finally, interesting results for sigma models on superspheres have also been obtained (Sec. D.1.4).

The most powerful feature of the lattice regularizations is to provide insight on the conformal field theory from the simpler theory of lattice algebras like the Temperley Lieb, Brauer and other algebras. Apart from the progress on sigma models, the same idea has allowed V. Pasquier (Sec. D.2.1) to uncover a relationship between the ADE classification of modular invariants and representations of the affine Hecke algebra at roots of unity. It has also allowed J. L. Jacobsen and H. Saleur, after considerable work on the theory of boundary Temperley Lieb algebras (Sec. D.2.1), to propose a continuous family of conformal boundary conditions for loop models (Sec. D.3.1), which should have important geometrical applications. These "JS boundary conditions" have been recovered and elucidated further by I. Kostov using techniques of 2D gravity (Sec. D.3.2).

Geometrical models have also been studied for their own sake in a work by Y. Ikhlef, J. L. Jacobsen and H. Saleur (Sec. D.3.3) where non-intersection exponents for dense trails have been found to bear striking resemblance to those of pure Brownian motion.

Contents

[1] Agence nationale de la recherche

D.1 Sigma models on super-manifold targets

Two dimensional non-linear sigma models with super-manifold target spaces have emerged in a wide variety of systems, and their study has become increasingly relevant for some of the most challenging problems of modern physics.

In string theory, super-manifold target spaces received brief attention about ten years ago when they were argued to arise as mirrors of rigid Calabi-Yau (CY) manifolds. More important, is the role that super-group and super-coset targets play in superstring theory, where, in the Green-Schwarz or pure spinor type formulation, supersymmetries act geometrically as isometries of an underlying space-time (target space) supermanifold. Important examples arise in the context of the AdS/CFT dualities between supersymmetric gauge theories and closed strings. For instance, it has been known for a few years that string theory on $AdS_3 \times S^3$ could be quantized if it were possible to construct conformal quantum field theories with a PSL(2|2) target space.

In condensed matter, super-manifold target spaces arise mostly in the study of geometrical problems such as percolation and polymers, or in Efetov's supersymmetric approach to non-interacting disordered systems. The transition between plateaux in the integer quantum Hall effect is thus believed to be related to the sigma model U(1,1|2)/U(1|1) × U(1|1) at $\theta = \pi$, a conformal field theory which has not yet been understood, despite decades of work.

In addition to such concrete applications, there exists a number of structural reasons to be interested in particular in *conformal* σ-models with target space (internal) supersymmetry. On the one hand, being non-unitary, the relevant conformal field theory models exhibit rather unusual features such as the occurence of reducible but indecomposable representations and the existence of logarithmic singularities (on the world-sheet). On the other hand, the special properties of Lie supergroups allow for constructions which are not possible for ordinary groups. For instance, there exist several families of coset conformal field theories that are obtained by gauging a one-sided action of some subgroup rather than the usual adjoint. The same class of supergroup σ-models is also known to admit a new kind of marginal deformations that are not of current-current type. Finally, there seems to be a striking correspondence between the integrability of these models and their conformal invariance

D.1.1 Wess–Zumino–Novikov–Witten models on supergroups: CFT *(H. Saleur, V. Schomerus)*

The first direction of research concerns WZWN theories, which are conformal σ-models. Two essential properties facilitate an exact solution in this case. They are (i) the presence of an extended chiral symmetry based on an infinite dimensional current superalgebra and (ii) the inherent geometric interpretation. While (ii) is common to all σ-models, the symmetries of WZNW models are necessary to lift geometric insights to the full field theory. Both aspects single out supergroup WZNW theories among most of the logarithmic conformal field theories that have been considered in the past. While investigations of algebraic and mostly chiral aspects of supergroup WZNW models reach back more than ten years, it was not until recently that the use of geometric methods (developed first in the case of simpler non rational CFT - see [t05/139] for a review) considerably furthered our understanding of *non-chiral* issues. In [t05/152][t06/143], the full non-chiral spectrum for the $GL(1|1)$ and the $SU(2|1)$ WZNW models has been derived based on methods of harmonic analysis. The most important discovery in these articles is the relevance of so-called projective covers, and the resulting non-diagonalizability of the Laplacian which ultimately manifests itself in the logarithmic behaviour of correlation functions. These results were later extended to the case of $PSU(1,1|2)$ in [t06/049].

D.1.2 Wess–Zumino–Novikov–Witten models on supergroups: quantum spin chains *(F. Essler, H. Frahm, J.L. Jacobsen, Y. Ikhlef, H. Saleur)*

The second direction of research tackles WZNW theories on super groups from the point of view of their lattice regularizations and the Bethe ansatz. In parallel with [t06/143], Essler, Frahm and Saleur [t05/206] calculated the spectrum of the integrable vertex model built out of alternating fully symmetric representations and their conjugate for the algebra $sl(2/1)$. They found in particular clear evidence for a *continuous spectrum* of critical exponents [2], in agreement with the

[2] It is important to emphasize that this finding occurs for a lattice model with *finite* number of degrees of freedom per link.

construction of modular invariants in [t06/143]. This evidence gained further support from the analysis of a related model in [t05/193] and [t06/174] where details of the measure of integration over the continuous spectrum were also obtained, and found in agreement with the predictions in [t06/143].

D.1.3 $CP^{n+m-1|n}_{\theta=\pi}$ models *(N. Read, H. Saleur)*

The third direction of research concerns σ-models which, although conformal invariant and exhibiting local (super) group symmetry, are not WZNW theories. It is such a model that is expected to describe the critical properties at the transition between plateaux in the integer quantum Hall effect. In a series of papers, N. Read and H. Saleur made important steps towards the full solution of σ-models on superprojective spaces $CP^{n+m-1|n} = U(n+m|n)/[U(1) \times U(n|m-1|n)]$ at $\theta = \pi$, which are in particular related to the transition between plateaux in the *spin* quantum hall effect when $m = 1$. The general strategy of these works is to solve explicitely for the spectrum and symmetries of a lattice regularization of the field theory based on a Chalker-Coddington type network model. In an paper of 2001, the spectrum of critical exponents in the bulk was found to cover all rational numbers (modulo integers), showing that the theory is not rational, although it is quasi-rational. In [t06/136], the large degeneracies in this spectrum were explained in terms of a new type of algebra $\mathcal{A}_{n+m-1|n}$, which is not a Yangian (although it is reminiscent of one), can be given the structure of a braided Hopf algebra, and is (Morita) equivalent to the quantum group $U_q sl_2$ at a given root of unity. In [t06/154], the presence of this algebra was used to derive properties of the boundary conformal field theory for the superprojective sigma models. The structure of Virasoro representations was analyzed, exhibiting once again the relevance of projective covers. In addition, all fusion rules were derived.

D.1.4 Sigma models on super spheres *(C. Candu, J.L. Jacobsen, H. Saleur)*

The fourth direction of research concerns σ-models on superspheres, that is coset $OSP(n/2m)/OSP(n-1/2m)$. Jacobsen and Saleur showed in [t05/025] that the simplest such model - $OSP(1/2)/OSP(0/2)$ - finds remarkable applications in the statistics of spanning forests on two dimensional graphs, and provides what is probably the simplest asymptotically free quantum field theory. Candu and Saleur have also made considerable progress in the understanding of $OSP(2n+2/2n)/OSP(2n+1/2n)$ sigma models, which turn out to be exactly conformal; this will be described in the next report.

D.2 Conformal field theory and lattice algebras

Considerable insight on conformal field theories can be gained by studying the symmetries of their integrable lattice realizations; for instance, the structure of representations of the algebra satisfied by the local hamiltonian density (the Temperley–Lieb algebra in the simplest cases) is similar (this can, to some extent, be put on firmer categorical grounds) to the one of the chiral algebra (Virasoro in the simplest case) or left and right copies thereof, in the continuum limit. This idea has been pushed forward in two directions.

D.2.1 The ADE project *(V. Pasquier)*

Twenty years ago, to answer a question raised by of Cardy and following discussions with Bion-Nadal about subfactors, we proposed a series of models with a central charge $c < 1$ in correspondence with the ADE classification of Lie algebras. This was shortly after followed by a similar result based on modular invariance by Cappelli, Itzykson and Zuber. Since that time, many works have attempted to unravel the correspondance between ADE, quantum groups and CFT. Pasquier has done a step in this direction by showing that the irreducible representations of the affine Hecke algebras at root of unity transform like a tensor product of two Virasoro representations under the modular group, recovering in this way the modular invariance properties from the Dynkin diagrams [t06/249].

D.2.2 Boundary Temperley–Lieb algebras *(J.L. Jacobsen, H. Saleur)*

Jacobsen and Saleur have studied the representation theory of the one and two boundary Temperley Lieb algebras, obtaining in particular new formulas for the related Gram determinants [t07/041]. This has allowed them to put forward conjectures for the existence of a new continuous family of boundary conditions and related partition functions for boundary loop models.

D.3 Conformal field theory and geometrical models

D.3.1 Boundary loop models *(J.L. Jacobsen, H. Saleur)*

Dense loop models have been at the heart of most combinatorial and probabilistic developments related to conformal field theory in two dimensions. While the equivalent of Dirichlet and Neumann boundary conditions had long been extensively studied, Jacobsen and Saleur discovered in [t06/155] that a simple modification of the models — obtained by giving loops touching the boundary a different fugacity — was giving rise to a continuum of new boundary conditions, for which they gave critical exponents and annulus partition functions. This has some applications in the study of boundary aspects of logarithmic CFTs, and many potential applications in probability theory, since various new generating functions for percolation can, in principle, be now computed. Many of the results have been extended to the dilute case in [t07/041], with potential applications to self-avoiding walks.

[t07/034] is a long review article (82 pages) on the application of conformal theories to self-avoiding polymers and, more generally, to loop models. We present the results of the last two decades on the volume and surface properties of these models, for dilute, dense and compact conformations.

D.3.2 Non-rational theories of 2D quantum gravity *(I. Kostov)*

Theories of 2D quantum gravity with non-rational matter central charge $c < 1$ are interesting mostly because they have a geometrical description in terms of self and mutually avoiding clusters and thus can be used to study various geometrical critical phenomena random surfaces. A statistical system on a random lattice exhibits qualitatively the same critical phases as that on a regular lattice, but with different critical exponents.

The non-rational theories of gravity are still poorly understood, in spite of the attention they enjoy in the recent years. The 4-point correlation function in such theories is constructed using the ground ring action and some mild assumptions about its general structure. The computation is performed independently in the dual matrix theories, which represents a generalizations of the ADE string theories characterized by semi-infinite discrete target space [t06/086].

A typical example of such a non-rational theory is the $O(n)$ loop model coupled to gravity. The model has two non-trivial critical points, the dense and the dilute phases of the loop gas, described by two different matter conformal field theories. The physics along the thermal flow connecting the two critical points is studied in [t06/012]. Using the dual matrix-model description, explicit expressions were obtained for the partition functions of the gravitational $O(n)$ model on the disk and on the sphere along the thermal flow.

The correspondence between the critical phenomena on flat and random surfaces is particularly useful in presence of boundaries. Boundary 2D quantum gravity became a powerful tool for evaluating exact critical exponents, complementary to the Coulomb gas techniques and the Schramm-Loewner Evolution (see also Sec. D.4.2). A test on a random lattices of a powerful conjecture about the boundary $O(n)$ loop model, put forward recently by Jacobsen and Saleur, was performed in [t07/036]. The JS conjecture gives a complete classification of the boundary conditions of the $O(n)$ loop–gas model, which are labeled by a continuous parameter. The two-point boundary correlators of the L-leg operators with mixed Neumann-JS boundary condition, calculated explicitly in [t07/036], confirm the L-leg boundary exponents conjectured by JS.

D.3.3 The statistics of trails *(Y. Ikhlef, J. L. Jacobsen, H. Saleur)*

Based on the emergence of continuous spectra in [t06/155], Ikhlef, Jacobsen and Saleur have proposed that dense self loop models where sites can be visited twice (so called trails) possess many of the same properties of Brownian walks. A detailed numerical study [t06/173] has shown that, when the bulk look fugacity is equal to zero, this is almost true but not quite: non-intersection exponents are given by similar but different formulas from the by now well-known Brownian case. The study of packed trails is a problem in its infancy, and much remains to be done — we note in particular that they do not seem amenable to the SLE approach.

D.3.4 Relations between Potts and RSOS models *(J. L. Jacobsen)*

In [t05/246], we study the relationship between the Potts model and staggered RSOS models, a topic pioneered by Pasquier. We find in particular that on a torus, some linear combinations of restricted partition functions coincide in both models. In a related paper [t05/247], we draw the phase diagrams of several RSOS models in the complex-temperature plane. These phase diagrams differ significantly from those of the Potts model with a generic number of states.

D.3.5 Phase diagram of the chromatic polynomial on a torus *(J. L. Jacobsen)*

In [t07/026], we study the phase diagram of the chromatic polynomial of a triangular or square lattice, in the complex color plane. We find in particular that the number of phases depends both on the lattice, and on the topology (ring or torus). This paper concludes a series of four papers about the chromatic polynomial.

D.4 Stochastic Schramm–Loewner Evolution (SLE)

D.4.1 SLE and growth processes *(M. Bauer, D. Bernard)*

After a long period of active work in the field, M. Bauer and D. Bernard felt the need for writing a systematic review on the SLE and growth processes, from the point of view of physicists but also from the point of view of mathematicians [t06/023]. Trying to emphasize the depth of connexions betweeen the two approaches, we finally decided to write a Physics Report, including detailed probabilistic computations, but also illustrative numerical simulations and computations.

D.4.2 Conformal random geometry, SLE and quantum gravity *(B. Duplantier)*

The quantum-gravity approach to conformally invariant critical curves in two dimensions, e.g., Brownian curves, polymers, or contours of clusters in critical models, provides an (as yet) non-rigorous but exact alternative to the rigorous SLE probabilistic approach that led to the 2006 Fields Medal of W. Werner. The quantum-gravity perspective has been presented in comprehensive Lecture notes assembled at the occasion of the Les Houches 2005 Summer School on *Mathematical Statistical Physics* [t05/243].

D.4.3 Virasoro Module Structure of Local Martingales of SLE Variants *(Kalle Kytölä)*

Based on general ideas of Michel Bauer and Denis Bernard on relation of SLE and CFT, [t06/238] shows how local martingales ("quantities conserved in average under the SLE growth process") of general SLE variants form a representation of the Virasoro algebra. The result extends one in [t03/012] which says that for the simplest SLE variant, chordal SLE, polynomial local martingales form a Virasoro module. Moreover, the present work establishes the result in a straightforward fashion.

Compared to the case of chordal SLE, the structure of the representation is more complicated for general SLE variants. There is a submodule analogous to the module of polynomial local martingales for chordal SLE, but even this may fail to be contravariant of a highest weight module as one might naively expect. To shed light to the precise structure of this submodule, its contravariant "SLE state" is constructed for known variants $\mathrm{SLE}_\kappa(\underline{\rho})$ and multiple SLEs. These constructions are done in charged Fock spaces, i.e. in Coulomb gas formalism.

Even an incomplete understanding of the Virasoro module structure of local martingales has lead to partial results [Kytölä & Kemppainen: J.Phys.A: Math.Gen. vol.39 no.46] in favor of conjectures of reversibility of SLE trace and "Duplantier duality" between SLE_κ and $\mathrm{SLE}_{16/\kappa}$.

In addition, Feigin-Fuchs integral formulas are proposed as candidates for the conjecture of multiple SLE pure geometries [t05/101].

D.5 Conformal invariance in two-dimensional turbulence *(D. Bernard)*

The notion of conformal invariance appeared long ago in naval cartography where it is often more important to know the direction than the distance (otherwise one may not feel brave enough to quest for distant shores). Conformal invariance of a spatial pattern means that magnifying different parts by different degrees results in the pattern indistinguishable from the original as long as one does not change angles. In [t05/231], we extend the notion of conformal invariance to the whole new class of strongly fluctuating systems - turbulent inverse cascades. These are the cases of large-scale turbulence produced by a small-scale forcing. In fluid turbulence, such cascades are realized when the motions are effectively two-dimensional, which happens when they are excited at the scales exceeding the depth of a shallow layer of a fluid. We have studied boundaries between vortices of opposite rotation. In turbulence, they are fractal curves, and we have shown that their statistics is conformally invariant and similar to those found in two dimensional critical systems. This allowed us to establish numerous new quantitative results in turbulence. This indicates that conformal invariance may be expected for certain out-of-equilibrium strongly interacting systems.

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CHAPTER E

String theory and quantum gravity

String Theory along with other approaches to Quantum Gravity is one of the important directions of research at SPhT. The main activities in this area cover string theory in time-dependent backgrounds 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, higher-order perturbative computations in $\mathcal{N} = 8$ supergravity, construction of various black objects (black holes and rings) within string theory and microscopic analysis of their properties, the structure of the low energy limits of $\mathcal{N} = 1$ and $\mathcal{N} = 2$ compactifications of string theory, and the string pure spinor formalism.

The group has been strengthened with the recent hirings of Mariana Graña (October 2005) and Iosif Bena (September 2006). Since 2005, the group has had two post-doctoral researchers, Michael Chesterman and Kazuo Hosomichi; two graduate students, Jean-Emile Bourgine and Dimo Volin under the supervision of Didina Serban and Ivan Kostov; a long term visitor, supported by a research fellowship from Portugal, Filipe Moura, and a graduate student from the Technische Universität of Vienna, Sebastian Guttenberg. Each of them spent a year at SPhT. One master student, Clement Ruef, is doing an internship with Iosif Bena and will continue with a PhD thesis at SPhT. Four new post-doctoral researchers — Frank Saueressig (now at University of Utrecht), Stefano Giusto, Ashish Saxena, and Kristian D. Kennaway (now at the University of Toronto) — will also join the group in September 2007. After two years in the laboratory, Michael Chesterman will leave the SPhT in September 2007 for the University of North Carolina in the USA, and Kazuo Hosomichi for KIAS in Korea.

The group has strong links with many laboratories in Europe and the US, and supports an active visitor program. It also holds a regular weekly seminar, where a particular effort is made to include speakers that are of interest to the members of the laboratory working in areas not directly related to string theory. The members of the group have been involved in the organization of major international conferences, schools and workshops (Cargèse in June 2006, "les Rencontres Itzykson" in June 2007, Les Houches school in string theory in July 2007, the Paris Summer Institute on Black Holes, Black Rings and Modular Forms in August 2007) and take part in the organization of the Paris-area string seminars at the Institut Henri Poincaré in Paris. The research of different group members is supported by 2 ANR[1] grants, a Marie-Curie International

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Recent cosmological observations have prompted a renewed interest in the study of time-dependent backgrounds. In string theory, these can be studied using the exact solution of large-N matrix quantum mechanics perturbed by chiral sources. Low-dimensional string theories and their matrix models are also good laboratories for the current topics in string theory such as open/closed string duality, D-branes and vacuum instabilities. 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 involve the duality between gauge and string theories (AdS/CFT correspondence). 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. On the gauge-theory side, 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 unravelled a discrepancy starting with the third order in perturbation theory. The ongoing activity is dedicated to understanding this spin chain to all orders in perturbation theory.

Due in particular to AdS/CFT correspondence, understanding the quantization of the superstring in AdS backgrounds has become a key problem. It remains unsolved for a number of reasons, depending on the choice of string model. For the RNS string, there is a fundamental obstruction to quantization in Ramond-Ramond backgrounds, whereas for the Green-Schwarz and Berkovits pure spinor strings, we have non-trivial interacting field theories, which are not well understood. Whichever string model one chooses, an important first step is to straightforwardly quantize the corresponding superparticle in each case. The group continues to analyze and develop the pure spinor formulation of string (perturbation) theory, with a particular focus on its application to the quantization of string theory in AdS background and the computation of string theory amplitudes in ten and four dimensions. The link between M-theory perturbative computations and string S-matrix has allowed to derive some important non-renormalization theorems in string theory and given strong constraints on the structure of higher-loop amplitudes in maximally-supersymmetric supergravity theories. These conditions imply a much better ultra-violet behaviour of $\mathcal{N} = 8$ supergravity in four dimensions and if valid to all order in perturbations would imply its ultra-violet finiteness. In particular, these conditions imply that the first divergence will appear at nine loops. Based on superspace methods the first divergence was expected at three-loop order and the absence of such a divergence was confirmed by an explicit evaluation of the four graviton three-loop amplitude using on-shell unitarity methods.

The structure of string compactification to four dimensions is not yet completely under control, especially when fluxes inside the compactification manifold are turned on. Turning on fluxes changes the structure of the effective low-energy $\mathcal{N} = 1$ or $\mathcal{N} = 2$

supergravity theory in four dimensions, leading to interesting new features like supersymmetry breaking, moduli lifting, and non-trivial warping. All these new features have important consequences on the relation between string theory and the observed low-energy physics. Inclusion of fluxes shifted the attention from the usual Calabi–Yau Ricci flat geometries to those with SU(3) structure and to more general geometries characterized by new types of structures (generalized complex) interpolating and unifying complex and symplectic structures. Generic $\mathcal{N} = 1$ and $\mathcal{N} = 2$ supergravities arise from flux compactifications on these manifolds, and generalized complex geometry has been shown to capture the main geometrical features of supersymmetric theories. Generalized geometry has also been shown to be relevant for studying the properties of four dimensional gauge theories dual to some class of type IIB supergravity with SU(2)-structure. In addition, there are points in the moduli space of $\mathcal{N} = 1$ MSSM-type vacua where a geometrical description is not applicable but can be described by exactly solvable $\mathcal{N} = 2$ minimal models called Gepner models. Within these models one can consider D-branes and orientifolds which play an important role in the structure of the $\mathcal{N} = 1$ vacua along side with the fluxes, and a general construction of permutation orbifolds and their orientifolds has been given.

Flux vacua are also relevant in our understanding of the microscopic physics of black holes. It has been proposed recently that black holes should be viewed as statistical ensembles of smooth geometries with fluxes having unitary scattering. This would solve Hawking's information paradox, and may be experimentally testable in the future. The group has been working on understanding black holes, black strings and black rings in string theory, and further establishing this picture of black holes.

Contents

E.1 Compactifications with fluxes *(M. Graña & R. Minasian)*

String configurations with additional physical structures called "fluxes" exhibit a number of interesting features such as supersymmetry breaking, moduli lifting, and non-trivial warping. All of these features are important in connecting string theory to the physics of the observed world. Non-trivial fluxes also appear in string backgrounds with field theory duals, and they therefore play an important role in the present understanding of a phenomenon known as holography. The subject of compactifications with fluxes is attracting more and more attention. The review paper [t06/220] is an overview of the subject, from the basic ideas to the recent developments.

String theory backgrounds without fluxes were known for a long time to involve manifolds which have two integrable algebraic structures (one complex and one symplectic), known as Calabi-Yau manifolds. Generalized complex geometry [t06/140] gives a single unifying description of these two, a priori different, algebraic structures. According to generalized complex geometry, complex and symplectic structures are special types of "generalized complex" structures. Furthermore, there are new hybrid complex-symplectic structures which also fit the description of generalized complex structures.

In the paper [t06/166] we study the four-dimensional effective theory resulting from compactifications with fluxes. Such four-dimensional theory has $\mathcal{N} = 2$ supersymmetry if the manifold has two (not necessarily integrable) generalized complex structures. In such case, the effective action is constrained by supersymmetry. The kinetic terms for the metric and B-field fluctuations are determined by a function called the Kahler potential and the masses for such fluctuations are determined by an ($\mathcal{N} = 2$) superpotential. We showed on one hand that the Kahler potential has exactly the same functional form as in Calabi-Yau compactifications, in spite of the non-integrability of the underlying algebraic structures. On the other hand, we computed the superpotential, finding additional terms to the previously well-known one for Calabi-Yau compactifications, which appear precisely when one of the algebraic structures is not integrable.

The reduction of type II supergravity on SU(3) structure manifolds was revisited in [t06/147] with special attention towards the structure of the moduli space of the resulting four-dimensional gauged $\mathcal{N} = 2$ supergravity. The reduction proceeds by expanding the invariant 2- and 3-forms of the SU(3) structure as well as the gauge potentials of the type II theory in the same set of forms, the analogues of harmonic forms in the case of Calabi-Yau reductions. By focussing on the metric sector, we arrived at a list of constraints these expansion forms should satisfy to yield a base point independent reduction. Identifying these constraints is a first step towards a first-principles reduction of type II on SU(3) structure manifolds.

D-branes in flux backgrounds were in the focus of [t05/202]. In generalized complex geometry, D-branes can be seen as maximally-isotropic spaces and are thus in one-to-one correspondence with pure spinors. When considered on the sum of the tangent and cotangent bundles to the ambient space, all the branes are of the same dimension and the transverse scalars enter on par with the gauge fields; the split between the longitudinal and transverse directions is done in accordance with the type of the pure spinor corresponding to the given D-brane. In the paper, the relations of this picture to the T-duality transformations and stability of D-branes were studied. A discussion of tachyon condensation in the context of generalized complex geometry was given, linking the description of D-branes as generalized complex submanifolds to their K-theoretic classification.

In the paper [t06/094] we performed an exhaustive search for flux vacua on ten-dimensional manifolds which are a product of a four-dimensional noncompact space, and a compact six-dimensional group manifold, defined by a six-dimensional solvable algebra. We found new vacua, but far fewer than expected (only on three out of fifty possible six-dimensional manifolds). In each case, we found the integrable algebraic structure describing the manifold. The paper gave the the first examples of Minkowski vacua in supergravity which are not connected by any duality to Calabi-Yau compactifications. This paper is a step towards the understanding of the "string-theory landscape", as it is the first exhaustive search for vacua on a given class of six-dimensional manifolds.

E.2 Gravity duals to deformed SYM theories *(R. Minasian)*

While the use of generalized complex geometry in string theory has been mostly motivated by compactifications to four dimensions, the formalism is equally effective when applied to non-compact backgrounds which can be used to study gauge theories AdS/CFT correspondence. When working with the backgrounds that do not have high symmetry it provides the only tool for the systematic study. Such a study started in [t06/068], where the supersymmetry conditions were analyzed for a class of SU(2) structure backgrounds of Type IIB supergravity which are dual to four-dimensional superconformal gauge theories with mass deformations or beta-deformations. It was shown that these geometries are characterized by a closed nowhere-vanishing vector field, which encodes the information about the superpotential, and a modified fundamental form which is also closed.

E.3 Brackets, sigma models and integrability of generalized complex structures *(S. Guttenberg)*

A lot of geometric brackets like the vector Lie bracket, the Schouten bracket, the Dorfman bracket of generalized geometry and — up to a total derivative — the Fröhlicher-Nijenhuis bracket can be understood as so-called derived brackets from certain algebraic brackets by the de-Rham differential.

In the paper [t06/095] it is shown how the derived brackets as well as the corresponding algebraic brackets naturally arise in sigma-models via the super Poisson- or super antibracket. The relation is shown for (sums of) multivector valued forms in arbitrary worldvolume dimension. This generalizes in some sense a recent observation by Alekseev and Strobl about the appearance of the Dorfman (or Courant) bracket in the current algebra of a two dimensional sigma model and its extension of Bonelli and Zabzine to the bracket of sums of vector fields and p-forms in a p-brane sigma-model. On the way to a precise formulation of this relation, an explicit coordinate expression for the derived bracket is obtained. The generalized Nijenhuis tensor of generalized complex geometry is shown to coincide up to a de-Rham closed term with the derived bracket of the structure with itself, and a new coordinate expression for this tensor is presented. The insight is finally applied to two-dimensional sigma models in a background with generalized complex structure, once in the Hamiltonian formalism using the super Poisson bracket and once in the antifield formalism using the super antibracket. The known but so far nonmanifest relation between the integrability of the target space generalized complex structure to worldsheet supersymmetry on the one side and to the master equation of a topological sigma model on the other side becomes manifest with the results of the paper.

E.4 Quantum Corrections to $\mathcal{N} = 2$ supergravity vacua *(P. Vanhove)*

Compactification of type IIA/B string theory on a Calabi–Yau manifold X leads to $\mathcal{N} = 2$ supergravity in four dimensions. The spectrum of $\mathcal{N} = 2$ supergravity theories is composed by vectormultiplets and hypermultiplets related to the moduli of the compactification manifold. 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 two theories are related to each others by the classical T-duality or c-map mapping type IIA on a X into type IIB on the mirror manifold $\tilde{X}$ exchanges the moduli space of vectormultiplet and hypermultiplet. The structure of the vectormultiplet has been extensively studied, and the special coupling given by F-term of the $\mathcal{N} = 2$ superspace theory are computed by topological amplitude in string theory. This subject is now part of the classical knowledge in string theory. On the other side, the structure of the hypermultiplet couplings is poorly understood. Under of the c-map, some properties of the vectormultiplet couplings are inherited by the hypermultiplets. But the moduli space for the hypermultiplets is a Quaternionic-Kähler manifold which makes and analysis of this properties more complicated than in the case of the vectormultiplet which are just given by a special Kähler manifold. On the other hand the metric is expected to satisfy important non-renormalization theorems given in [t03/088]. A microscopic analysis of the hypermultiplet couplings by computing string amplitudes was initiated in [t03/088] using the RNS formalism. But supersymmetry is not explicit in this formalism making the analysis rather difficult. In the article [t05/094] we have analyzed the structure of the F-term in the hybrid string formalism which gives a version of type IIA/B superstring on Calabi–Yau where supersymmetry is explicit. The hybrid formalism, constructed by Nathan Berkovits, is a four dimensional pure spinor string theory, where the pure spinor is given by the dynamics of a chiral boson which needs to be regulated in specific way compatible with supersymmetry. One of the major obstacle in the use of the hybrid formalism is the computation of the correlators of this chiral boson. A prescription that reproduces the usual F-terms computations has been given in [t05/094]. A pedagogical review of the hybrid formalism is given [t07/006].

E.5 Structure of higher-loop amplitude in $\mathcal{N} = 8$ supergravity *(P. Vanhove)*

In [t05/123], [t06/127] and [t06/156] we analyzed the structure of higher-loop interactions in $\mathcal{N} = 8$ supergravity. Using the relation between the M-theory and string theory, one connect the S-matrix elements of $\mathcal{N} = 8$ supergravity in $D = 11$ dimensions to perturbative string S-matrix by extrapolation between the strong coupling regime $R_{11} = g_s l_s \to \infty$ to weak coupling $R_{11} \to 0$. In this context we could determine a class of supersymmetry protected quantities (gravitational F-terms) and show that they satisfy a new class of non-renormalization theorems. These non-renormalisation theorems state that a coupling of the form $D^{2k}R^4$ does not receive string loop correction after genus k. These theorems have been proved explicitly up to genus 6 by Berkovits using his non-minimal pure spinor formalism. Turning the condition around these non-renormalization theorems state that a L-loop four-graviton amplitude in $\mathcal{N} = 8$ supergravity start contributing from the order $D^{2L}R^4$. This implies in particular that the ultra-violet behaviour of such amplitude in dimensions D is much milder than naively expected and is given by $\delta_L = (D-4)L - 6$ which is the same as for $\mathcal{N} = 4$ super-Yang–Mills amplitudes. If this behaviour is valid of all orders in perturbations that would imply that $\mathcal{N} = 8$ supergravity is finite in four dimensions. If this behaviour holds to all orders in perturbation then $\mathcal{N} = 8$ supergravity will be an ultra-violet finite theory of quantum gravity. More conservatively, from the knowledge that this good ultra-violet behaviour stands up to genus 6 amplitude in string theory one expects the first divergence of appear 9 loops in four dimensions [t06/156]. Although these arguments are indirect, they received a strong confirmation by the remarkable construction of the four gravitons amplitude at 3-loop in $\mathcal{N} = 8$ supergravity done by David Kosower and his collaborators in [t07/010].

E.6 Multiloop amplitude in $\mathcal{N} = 8$ supergravity *(D. Kosower)*

In [t07/010] the three-loop four-point amplitude of $\mathcal{N} = 8$ supergravity using the unitarity method was constructed. The amplitude is found to be ultraviolet finite in four dimensions. due to novel cancellations, not predicted by traditional superspace power-counting arguments. The degree of ultra-violet divergences in D dimensions is shown to be no worse than that of $\mathcal{N} = 4$ super-Yang-Mills theory – a finite theory in four dimensions. Similar cancellations can be identified at all loop orders in certain unitarity cuts, suggesting that $\mathcal{N} = 8$ supergravity may be a perturbatively finite theory of quantum gravity.

E.7 Higher-Derivative Corrected Black Holes *(F. Moura)*

During 2005 and 2006, my research activity was focused on black holes in the context of string theory, together with Ricardo Schiappa from CERN. This resulted in the research paper [t05/151] and the talks [t05/150]. We studied the effects of string higher-derivative corrections to black holes. We developed the perturbation theory for spherically symmetric, static string-corrected black hole solutions, with a dilatonic curvature–squared term in the action, for tensor type metric perturbations. We then focused on the Callan-Myers-Perry solution in d dimensions, describing stringy corrections to the Schwarzschild geometry. The potential obtained allowed us to prove the perturbative stability of that solution in any dimension. We then studied gravitational scattering at low frequencies; we computed the string corrections to the absorption cross section. Despite the corrections, we found that this cross section is still proportional to the area of the black hole event–horizon. We suggested an expression for this cross section which could be valid to all orders in the string tension.

E.8 Pure spinor theory quantization *(M. Chesterman)*

The pure spinor superstring, invented by Berkovits in 2000, distinguishes itself from other string models because full space-time super-Poincare symmetry is manifest. Physical states are given by the cohomology of a certain BRST charge, with the unusual feature that the ghost fields obey quadratic pure spinor constraints. In general, it is non-trivial to extract physical states, and the corresponding superfields from the cohomology, particularly at higher ghost number and for massive string states. In [t07/027], the relation between the Berkovits superparticle BRST charge and the exterior derivative is clarified, and this is used to find a procedure to derive expressions for physical superfields at any ghost number. An extension of this approach to the string, should be useful for computing the full string spectrum in the pure spinor formalism.

This should as well be useful for understanding the quantization of the Berkovits pure spinor string on AdS (curved space-time) backgrounds. This problem remains unsolved for a number of reasons, depending on the choice of string model. For the RNS string, there is a fundamental obstruction to quantization in Ramond-Ramond backgrounds, whereas for the Green-Schwarz and Berkovits pure spinor strings, we have non-trivial interacting field theories, which aren't well understood. Whichever string model one chooses, an important first step is to straightforwardly quantize the corresponding superparticle in each case. An approach where AdS space is embedded in flat space-time, and embedding constraints are encoded in a BRST charge. This has the advantage of being similar to quantization in flat space-time, which is useful especially in the case of the less-understood Green-Schwarz and Berkovits models.

E.9 Black Holes Microstates in String Theory *(I. Bena)*

String theory is a quantum theory of gravity, and has had several astounding successes in describing properties of black holes. Recent progress points to the possibility that black holes should not be thought of as fundamental objects, but rather as statistical ensembles of a huge number of smooth geometries. Iosif Bena works at understanding black holes, black strings and black rings in string theory, and further establishing this picture of black holes.

One of the long-standing problem in the programme of describing black holes as ensembles of geometries has been that all the geometries that had been constructed correspond to black holes that have zero horizon area. In collaboration with Nick Warner and Chih-Wei Wang [t06/150] we have solved this problem by constructing the first smooth horizon-less microstate geometries that have the charges, angular momenta and mass of a black hole with a classically-large horizon area.

In collaboration with Nick Warner we have written an extensive review of this subject [t07/008], that describes some of the recent progress towards the construction and analysis of three-charge configurations in string theory and supergravity. We also present arguments that many of these microstate geometries are dual to boundary states that belong to the same sector of the D1-D5-P CFT as the typical states, and discuss the implications of this work for the physics of black holes in string theory.

In order to establish that black holes in string theory are ensembles of horizonless solutions, it is also important to construct the most generic such solutions. The article [t07/059] takes a significant step in this direction by constructing the first five-dimensional three-charge horizonless supergravity solutions that only have a rotational U(1) isometry.

In [t06/205], we proposed a microscopic description of black strings in F-theory based on string duality and the Fourier-Mukai transform. These strings admit several different microscopic descriptions involving D-brane as well as M2 or M5-brane configurations on elliptically fibered Calabi-Yau threefolds. In particular our results can also be interpreted as an asymptotic microstate count for D6-D2-D0 configurations in the limit of large D2-charge on the elliptic fiber. The leading behavior of the microstate degeneracy in this limit was shown to agree with the macroscopic entropy formula derived from the black string supergravity solution.

E.10 Permutation Orientifolds of Gepner Models *(K. Hosomichi)*

In the construction of type II string vacua with $\mathcal{N}=1$ supersymmetry in four dimensions, orientifolds play an important role along with branes and fluxes. While we wish to obtain a global picture for the whole variety of such vacua, it would be desirable to understand better each of the ingredients at different vacua. It is known that at some special points in moduli space where the size of the compactification manifold is very small and the geometric description is not applicable, there are vacua admitting an exactly solvable worldsheet description in terms of $\mathcal{N}=2$ minimal models. Such worldsheet theories are called Gepner models.

D-branes and orientifolds in Gepner models were studied in many works, but were constructed mostly from tensor products of the boundary or crosscap states in $\mathcal{N}=2$ minimal models. In Gepner models containing products of minimal models of the same level, one can construct D-branes and orientifolds corresponding to boundary conditions on fields twisted by permutation symmetries. In [**t06/170**] K. Hosomichi gave a general construction of permutation orientifolds in tensor product CFTs as well as their orbifolds, generalizing the standard construction of crosscap states in RCFT. By applying it to Gepner models, some general properties of permutation orientifolds of Calabi-Yau manifolds have been studied.

E.11 Solution of the H_3^+ model on a disc *(K. Hosomichi)*

String theories on Anti-de-Sitter spaces are an important subject where 't Hooft's old idea on large N dual description of gauge theories are given a concrete realization through the open-closed duality in string theory. A large symmetry of the target space also leads us to wonder if the theories might be solvable; different aspects of integrability in these models are studied extensively.

String theories on AdS_3 or its Wick rotated cousin H_3^+, with a suitable NSNS B-field turned on, are known to be described by solvable CFTs called WZW models. The affine $SL(2)$ symmetry in such models allows one to compute various amplitudes explicitly. Recently an interesting equivalence was found between Ward identity associated to the affine $SL(2)$ symmetry (or Knizhnik-Zamolodchikov equation) and that associated to Virasoro algebra, and was used to uncover hidden relations between H_3^+ WZW model and Liouville theory. In [t06/109], [t07/011] K. Hosomichi and S. Ribault (DESY Hamburg) applied it to the boundary problems of the two theories. An interesting correspondence between H_2^+-branes in H_3^+ and FZZT-branes in Liouville theory has been found, based on which some disc structure constants in H_3^+ WZW model have been determined in terms of those in Liouville theory.

E.12 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 based on 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 sigma 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. The complete form of the Bethe equations encoding the spectrum of anomalous dimensions was recently written down, at least for the regime of long operators, by Beisert, Eden and Staudacher. In the paper [t05/190] we have shown that the conjectured equations for the $su(2)$ sectors, up to the global dressing factor, could be reproduced from the Lieb-Wu equations which encode the solution of the Hubbard model in one dimension at half filling. A different, seemingly disconnected link of the dilatation operator with the Hubbard model was later discovered by Beisert. In the paper [t07/029] we have investigated the strong coupling limit of the Bethe ansatz equation. We have identified three different regimes for the excitations in the strong coupling, which were called the giant magnon regime, the plane-wave regime and the near-flat space regime. We were able to compute the leading order anomalous dimension for several states, including the universal scaling function for the twist-two operator. This allowed to check that the proposed Bethe ansatz equations interpolate correctly between the perturbative gauge theory regime and the perturbative string regime.

E.13 Non-singlet excitations in two-dimensional string theory *(I. Kostov)*

The non-singlet sector of the Matrix Quantum Mechanics, the matrix model behind the 2D string theory, is interesting mainly because it possibly contains black holes. In the compactified Euclidean theory, the non-singlet excitations in MQM describes vortices on the world sheet. A condensation of vortices is expected to produce an Euclidean black hole background. Recently, Maldacena realized that non-singlets in MQM can be interpreted as long folded strings in the Lorentzian 2D string theory. The scattering problem for long folded strings were reformulated in [t06/116] in terms of the chiral formalism in MQM. The scattering phase of the folded string is written as an integral over the Fermi sea describing the ground state of MQM. It is shown that the chiral formalism allows to solve the problem of the scattering of any number of folded strings and an explicit formula is given for the scattering amplitude of two folded strings. This problem is similar to the problem of finding the so called mixed correlators in the two-matrix model, solved recently by B. Eynard and N. Orantin.

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CHAPTER F

Cosmology

Observational cosmology is a rapidly evolving field. The statistical properties of the large-scale structure of the universe observed either in galaxy catalogs, in cosmic shear surveys or from the cosmic microwave background anisotropies and polarization, offer new means of determining the cosmological models and addressing the physics of the early universe. The research activities of the laboratory naturally reflect these developments. Two permanent researchers (F. Bernardeau and P. Valageas) specialize in this field and one student (T. Brunier) finished his PhD in 2006. The group will be strengthened by the hiring of Filippo Vernizzi, who is expected to join in September 2008. A review paper describing the stakes of the observational programs currently under development has been presented in [t05/185] for a non-expert audience.

An important topic of modern cosmology is the study of the primordial fluctuations, which were later amplified by gravitational instability to produce the large scale structures of the present Universe. Inflationary scenarios generically predict Gaussian initial metric fluctuations, with an almost scale-invariant power-spectrum. This agrees with current observations, but future Cosmic Microwave Background (CMB) surveys, such as the Planck mission, will allow us to test in much greater detail the statistical properties of the initial conditions. We have studied in detail a class of multiple-field inflation models: this should serve as a guideline to design strategies for detecting primordial non-Gaussianities, and to investigate what can be achieved within realistic inflationary scenarios. Explicit expressions for the temperature correlation functions seen on the CMB have also been derived.

At lower redshifts, where density fluctuations have been sufficiently amplified to give rise to rare astrophysical objects, such as galaxies or supernovae, it is possible to use the image of these distant sources to probe the density fluctuations along their line of sight. Indeed, the fluctuations of the gravitational potential deflect the trajectories of light rays and lead to both a shear and a magnification of the images of these radiative sources. The study of these weak gravitational lensing effects is a traditional topic at SPhT. In particular, an explicit method has been devised to obtain the three-point correlation function of the cosmic shear. This required an ingenious theoretical analysis because of the pseudo-vector nature of the shear which makes high-order correlation functions of the shear much more involved than for a scalar. This quantity is of great interest for observational purposes as it enables one to break the degeneracy between key cosmological parameters but it required involved theoretical. On the other hand, an analysis of weak gravitational lensing effects onto the observed luminosity of distant supernovae has been presented.

The dynamics of the formation of large scale structures in the recent Universe is another topic of research at SPhT. A path-integral formalism derived has been derived to allow one to apply to this problem the usual tools of field theory. The predictions at one-loop order of two different large-N expansions have been obtained for ΛCDM cosmologies and compared with numerical simulations and the standard perturbation theory. This is a timely line of research as future observations will require a significant improvement over the accuracy reached by current theoretical methods to be able to derive useful constraints on cosmology from statistics of the matter distribution on weakly non-linear scales.

Finally, a theoretical analysis of 1-D gravitational systems has been performed within the context of long-range systems. This topic of statistical physics has generated renewed interest in recent years, as long-range interactions give rise to many remarkable features (such as possible non-equivalence of different statistical ensembles and intricate out-of-equilibrium dynamics). Of course, Newtonian gravity is a prominent exemple of long-range systems, and it displays a rich behaviour because of its scale-free nature.

Contents

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

The observations of the CMB anisotropies offer a rich window to the physics of the early Universe. The possibility that non-linear couplings in the metric fluctuations could be observed gives hope that the inflationary sector could be efficiently constrained through CMB observations. Efforts have been devoted to the construction of models of inflation in which such non-linear couplings can be large with very few free parameters [t06/043]. A class of multiple field inflationary models has been identified and shown to be a natural extension of hybrid super-symmetric D-term inflationary models [t07/005]. The phenomenological consequences of such models, in terms of shapes of high order correlation functions has been explored in details in [t06/004]. This study gives insights in how the bi-spectrum and tri-spectrum of the CMB anisotropies are related to the primordial metric couplings.

F.2 Gravitational lensing *(F. Bernardeau, P. Valageas)*

Weak gravitational lensing is responsible for the shearing and magnification of the images of high-redshift sources due to the presence of intervening matter. The distortions are due to fluctuations in the gravitational potential, and are directly related to the distribution of matter and to the geometry and dynamics of the Universe. As a consequence, weak gravitational lensing offers unique possibilities for probing the Dark Matter and Dark Energy in the Universe.

In particular, the observation of the high-order correlation functions of the cosmic shear field, due to gravitational lensing effects, has been recognized as one of the key observations either for constraining the cosmological parameters or for testing the current paradigm of structure formation. It remains that the explicit computation of the three-point correlation function of the shear field for a given cosmological model can be technically involved. A general method for the computation of this function has been presented in [t05/222] and applied to the models of large scale structure that are most widely used, the halo models.

Another effect of cosmological gravitational lensing is to increase the observed scatter of the magnitudes of distant supernovae and to produce an extended high-luminosity tail. Recent studies have claimed that this weak lensing effect has been detected, but the statistics were too small to draw definite conclusions. We have revisited this issue [t06/248] by investigating how many SNeIa are needed to detect with a high confidence this specific weak lensing effect and we have found that 4000 SNeIa are required if the luminosity variance is known beforehand and 45,000 SNeIa are required for non-Gaussian signatures.

We have written a short review on weak-gravitational lensing for non-experts [t05/248] as well as a more detailed review for scientists working in the field [t06/215].

F.3 Formation of large-scale structures *(P. Valageas)*

In order to build analytical tools to study the formation of large-scale structures in the Universe we have developed a path-integral formalism derived from the equations of motion of hydrodynamics (single-stream approximation) [t06/241]. Then, one can apply standard tools of field theory such as large-N expansions. We have presented the results at one-loop order of two such expansion schemes for a ΛCDM cosmology. We have found that they give a response function which exhibits fast oscillations in the non-linear regime with an amplitude which either follows the linear prediction (for the direct steepest-descent scheme) or decays (for the 2PI effective action scheme). On the other hand, the correlation function agrees with the standard one-loop result in the quasi-linear regime and remains well-behaved in the highly non-linear regime. This suggests that these large-N expansions could provide a good framework to study the dynamics of gravitational clustering in the non-linear regime. This is an important goal as one needs an accuracy better than 10% for the matter power-spectrum on weakly non-linear scales to obtain useful constraints on cosmological parameters through observational probes such as weak lensing studies or measures of the baryonic acoustic oscillations.

F.4 Long-range systems *(P. Valageas)*

Inspired by the problem of large-scale structure formation in cosmology we have investigated the properties of a simple one-dimensional self-gravitating system. This system is similar to the popular HMF model studied in statistical physics to investigate systems with long-range interactions. Thus, a thermodynamical analysis [t06/008] shows this 1D system also displays a second-order phase transition at T_{c1} from an homogeneous equilibrium at high temperature to a clustered phase (with a density peak at one of the boundaries of the system) at low temperature. In addition, there also exists an infinite series of unstable equilibria which appear at lower temperatures T_{cn}, reflecting the scale-free nature of the gravitational interaction and the usual Jeans instability. Moreover, we have shown that the collisionless dynamics (governed by the Vlasov equation) yields the same results as the thermodynamical and hydrodynamical analysis except that at low T the equilibrium associated with two density peaks (one at each boundary) becomes stable. Then, we have investigated through analytical and numerical approaches the relaxation of this system [t06/118], which can involve a fast "violent relaxation" phase followed by a slow collisional phase as the system goes through a series of quasi-stationary states. For instance, for the case of the two-peak quasi-equilibrium we have found that the diffusion and dissipation coefficients satisfy Einstein's relation and that the relaxation time scales as $Ne^{1/T}$ at low temperature (N is the number of particles), in agreement with numerical simulations.

F.5 General relativity and quantum field theory

F.5.1 Gravity of a static massless scalar field and a limiting Schwarzschild-like geometry (*M. Gaudin, V. Pasquier*)

In collaboration with V. Gorini, A. Kamenshchik, U. Moschella [t05/264], we study a set of static solutions of the Einstein equations in the presence of a massless scalar field; their connection with the Kantowski-Sachs cosmological solutions is establihed on the basis of some kind of duality transformations. The physical properties of the limiting case of an empty hyperbolic spacetime pseudo-Schwarzschild geometry) are analyzed in some detail.

F.5.2 Lifetime of a massive particle in a de Sitter universe *(J. Bros)*

In collaboration with H. Epstein and U. Moschella, [t06/252], we study particle decay in de Sitter space-time, as given by first order perturbation theory in an interacting quantum field theory. Notwithstanding the absence of an asymptotic theory for de Sitter quantum field theory, it is possible to show that for fields with masses above a critical mass there is no such thing as particle stability, so that decays forbidden in flat space-time do occur there. The lifetime of such a particle also turns out to be independent of its velocity when that lifetime is comparable with de Sitter radius. Particles with lower mass are even stranger: the masses of their decay products must obey quantification rules, and their lifetime is zero.

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CHAPTER G

Particle physics beyond the standard model

Beyond the standard model physics 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), two of which (C. Grojean and G. Servant) are at CERN since 2006. In the past 2 years, 4 post-docs have worked in Saclay (M. Cirelli, M. Frigerio, A. Sil and M. Thormeier) and 2 PhD students have been supervised (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. It is supported by 2 ANR[1] Young researcher grants on neutrino physics (NEUPAC, 2005), and on dark matter and dark energy (DARKPHYS, 2006).

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 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

[1] Agence nationale de la recherche

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 cut-off 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 Higgless 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 student (C. Delaunay) work in this field.

Of course the supersymmetric idea remain 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. 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. Bernardeau. 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, C. Grojean and A. Sil have 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. M. Cirelli, 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.

Contents

G.1 Electroweak Physics

G.1.1 Electroweak symmetry breaking *(C. Grojean, G. Servant)*

The main goal of the LHC is to unveil the mechanism of electroweak symmetry breaking. A crucial issue that experiments should be able to settle is whether the dynamics responsible for symmetry breaking is weakly or strongly coupled. LEP1 has provided convincing indications in favour of weakly-coupled dynamics. Indeed, the good agreement of precision measurements with the Standard Model (SM) predictions showed that the new dynamics cannot significantly influence the properties of the Z boson, ruling out, for instance, the simplest forms of technicolour models, which were viewed as the prototypes of a strongly-interacting electroweak sector. Moreover, the best agreement between experiments and theory was obtained for a light Higgs, corresponding to a weakly-coupled Higgs self-interaction and supersymmetric theories have been considered for many years the most promising candidates for new physics beyond the SM. The situation has swayed back after the LEP2 results. The lack of discovery of a Higgs boson below 114 GeV or of any new states has forced supersymmetry into fine-tuning territory, partially undermining its original motivation. Moreover, new theoretical developments, mostly influenced by extra dimensions and by the connection between strongly-interacting gauge theories and gravity on warped geometries, have led the way to the construction of new models of electroweak symmetry breaking [t06/052][t06/180].

A radical approach to the electroweak symmetry breaking is to model it without a Higgs field. Such models can be constructed in space-time with extra dimension [t05/118][t05/207][t05/230]. A crucial problem that these models have to face is the consistency with electroweak precision measurements. In [t07/088], we computed the oblique corrections in a generic class of models which are holographically dual to technicolour models and we concluded that the only way to obtain a small S parameter is to delocalize the fermions along the extra dimension. The embedding of fermions in warped models provides a nice setup highly suppressing any flavour changing neutral currents. However, the large value top mass usually induces large deviations in the coupling of the bottom quark to the Z gauge boson. In [t06/056], we explained how to reduce these deviations by working on a multi-throat backgrounds.

Another approach to electroweak symmetry breaking is to keep the Higgs boson as an effective field arising from new dynamics which becomes strong at a scale not much larger than the Fermi scale. In [t07/089], we developed a simple model-independent analysis of such composite Higgs scenarios. We constructed an effective low-energy Lagrangian. Phenomenological prospects for the LHC and the ILC include the study of high-energy longitudinal vector boson scattering, strong double-Higgs production and anomalous Higgs couplings.

In [t06/057], we proposed a way to disguise the new physics contributions to the oblique parameters as modifications of triple gauge boson couplings, yet poorly constrained. This is the result of a set of operator identities that related the operators corresponding to the oblique corrections to operators that modify fermion couplings to the gauge bosons as well as operators that modify triple gauge boson couplings.

Our group has been involved into the organization of the workshop 'Physics at TeV collider' in Les Houches, aiming at bringing together theorists and experimentalists working on the phenomenology of the upcoming TeV colliders [t06/054].

A particular feature of the recent Randall–Sundrum models of electroweak symmetry breaking based on $SU(2)_L \times SU(2)_R$ with custodial symmetry is the likely presence of light Kaluza-Klein fermions related to the right-handed top quark. These can be as light as a few hundred GeV and still compatible with EW precision constraints. In [t07/080] we have studied the detectability of four-W final states at the LHC, which arise from the pair-production and tW decay of light Kaluza-Klein bottom quarks as well as light Kaluza-Klein quarks carrying electric charge 5/3. They are produced through standard QCD interactions with a cross section $\sim \mathcal{O}(10)$ pb for masses of several hundreds of GeV. We have considered the process $gg, q\bar{q} \to \tilde{b}_R \bar{\tilde{b}}_R \to W^- t\ W^+ \bar{t} \to W^- W^+ b\ W^+ W^- \bar{b}$ where at least one W boson decays leptonically and the other ones hadronically. A simulation of this signal and its main background was performed, and an analysis strategy outlined which distinguishes the signal from the sizable Standard Model backgrounds. The peak obtained in the dijet mass distribution suggests that it is possible to reach a signal significance beyond the 5σ level.

G.1.2 Supersymmetric Higgs boson production at the LHC *(S. Lavignac, R. Peschanski)*

One of the most promising decay channels for detecting a light Higgs boson at the LHC is $h \to \gamma\gamma$, which in spite of a small branching ratio benefits from a much lower background than the leading channel $h \to b\bar{b}$. However, the latter can become competitive in the diffractive production mode, in which the incident protons are not dissociated but slightly deviated in the collision. Indeed the signal over background ratio is more favourable than in standard non-diffractive Higgs production, although the cross-section is smaller and subject to theoretical uncertainties. In [t05/210], we studied the diffractive production of the lightest supersymmetric Higgs boson and identified a region of the supersymmetric parameter space in which the decay mode $h \to b\bar{b}$ is especially competitive. This region, known as the "anti-decoupling regime", corresponds to a light Higgs boson ($m_h \leq 120$ GeV) with very different couplings from the Standard Model case. There the production cross-section via gluon fusion is significantly enhanced with respect to the Standard Model, and a large signal over background ratio can be achieved with appropriate detectors for the diffracted protons.

G.2 Supersymmetry, flavour and neutrinos

G.2.1 Flavour physics and supersymmetry *(S. Lavignac, C. Savoy, M. Thormeier)*

Supersymmetric extensions of the Standard Model tend to give large contributions to flavour and CP violating processes. In particular, heavy meson mixing, most notably in the kaon sector, and experimental upper limits on lepton flavour violating decays of charged leptons put strong constraints on the flavour structure of the squark and slepton mass terms. These constraints can easily be satisfied by assuming that supersymmetry breaking is flavour universal. However, universality is not expected on general grounds in supergravity, and it is therefore useful to study alternative ways of suppressing the supersymmetric contributions to flavour changing processes. In [t05/117], we studied two supersymmetric scenarios without flavour universality characterized by multi-TeV sfermion masses and by gaugino masses significantly larger than sfermions masses, respectively. Unless gaugino or sfermion masses are pushed towards very large values, flavour violating processes still require a strong suppression of off-diagonal entries in the sfermion mass matrices, as well as of splittings among diagonal entries if the Yukawa couplings have a generic hierarchical structure. The constraints are especially strong in the 1-2 sector and in the slepton sector. We also studied the possibility of an inverted mass hierarchy in the sfermion sector, often invoked as a way to alleviate the supersymmetric flavour problem while maintaining a reasonable amount of fine-tuning in the Higgs potential. We found that the requirement of proper radiative electroweak symmetry breaking puts strong constraints on this scenario, making it less attractive in view of the flavour problem.

The existence of three families (or generations) of quarks and leptons, that differ only by their masses and mixings in the framework of the Standard Model, remains a big mystery in spite of the continuous progress in the measurement of their parameters. In a bottom-up approach to the flavor problem, the first task is to decode the variety of experimental data on fermion mass ratios and mixings. There are indeed several amazing empirical relations between masses and mixing angles as well as among the very hierarchical quark and lepton mass ratios. By translating that information into simple mass matrix textures that reproduce these relations, one makes progress towards the interpretation of these textures in terms of flavor symmetries and their breakings.

Prompted by the recent progress in measurements of the phenomenological fermion masses, which also impoverishes their agreement with previous models, the problem of finding simple fermion mass textures has been recently re-appraised in [t06/072], where two new textures were found in terms of the minimal number of parameters (five) that provides a good fit to the measured mass matrices. Interestingly enough, in this model, the measured matter-antimatter asymmetry in the Standard model is ascribed to one maximal CP violation, namely, a phase $\pi/2$ between fermions of two families. Subsequently, a model has been built [t06/073] with a scheme of spontaneous breaking of the largest flavour symmetry allowed in the Standard model that precisely reproduces one of the proposed textures. On top of that, the model explains another interesting regularity in quark masses: the mass ratios between up-quarks are approximately the square of the corresponding ones for down-quarks!

A systematic classification of the discrete Z_N symmetries of the Minimal Supersymmetric Standard Model consistent with their embedding into an anomaly-free gauge symmetry was performed in [t05/262]. Only two symmetries compatible with nonzero neutrino masses and with the absence of $D = 4$ and $D = 5$ baryon number violating operators were found, a Z_3 symmetry known as baryon triality, and a new Z_6 symmetry. A supersymmetric model of fermion masses in which baryon triality arises as a remnant of a broken anomalous $U(1)$ symmetry was constructed in [t06/251]. A set of independent CP-odd invariants parametrizing CP violation in the Minimal Supersymmetric Standard Model with right-handed neutrinos was constructed in [t07/114].

G.2.2 Leptogenesis and neutrino physics

(M. Frigerio, P. Hosteins, S. Lavignac, C. Savoy)

Explaining the origin of the matter-antimatter asymmetry of the universe is one of the challenges of physics beyond the Standard Model. Among the few mechanisms that are capable of generating the observed baryon asymmetry, leptogenesis offers an interesting connection with neutrino masses. In its simplest realization, a lepton asymmetry is first produced in out-of-equilibrium decays of heavy right-handed neutrinos, and subsequently converted into a baryon asymmetry by non-perturbative sphaleron processes. The same right-handed neutrinos are involved in the mass generation mechanism for the Standard Model neutrinos, known as the "seesaw mechanism", which finds a natural realization in Grand Unified Theories based on the $SO(10)$ gauge group. However, successful leptogenesis is difficult to achieve in the simplest $SO(10)$ models, due to the constraints imposed by the unified symmetry on the right-handed neutrino couplings. In [t06/048] (see also [t06/152]), we studied leptogenesis in a class of $SO(10)$ models with a left-right symmetric seesaw mechanism, in which both heavy right-handed neutrinos and a heavy $SU(2)_L$ triplet scalar contribute to light neutrino masses. We developed a procedure for reconstructing the right-handed neutrino mass spectra that are compatible with the light neutrino masses and mixing, and showed that some of them can lead to successful leptogenesis. Constraints on this class of models from lepton flavour violation were also studied.

Leptogenesis can be realized in many different ways. In [t06/024][t06/125], we considered the possibility that the baryon asymmetry of the universe is generated dominantly from the decays of right-handed neutrinos to right-handed leptons (together with an $SU(2)_L$ singlet scalar), instead of being due to their decays into left-handed leptons. We computed the lepton asymmetry produced by the interaction between right-handed leptons and scalar particles. This new mechanism allows to reproduce experimental data even for right-handed neutrino masses as low as a few TeV, the energy scale of next generation of colliders, thus opening the possibility of direct tests of leptogenesis.

The seesaw mechanism explains the smallness of the neutrino mass via the exchange of superheavy particles. Two seesaw contributions to the neutrino mass, known as type I and type II, are related to each other in gauge theories with left-right symmetry. We showed that, in this class of theories, eight different mass spectra of the superheavy particles reproduce the same low energy phenomenology [t05/180]. A complete analytic and numerical study was performed and the implications for leptogenesis and Grand Unified Theories were investigated [t06/105, t06/106].

The structure of the Yukawa couplings contains useful information for identifying potential symmetries and theories of flavour beyond the Standard Model. Since these theories are defined at a scale that can be much higher than the electroweak scale, it is necessary to take into account the renormalization group running of the Yukawa couplings, especially in the neutrino sector where its effects can be significant. These effects are even potentially larger in flat extra-dimensional models due to an accelerated running. In [t06/146], quantum corrections to the effective neutrinos mass operator were computed at the one-loop level in supersymmetric models with a flat extra dimension. The resulting power-law evolution of the neutrino mass parameters typically leads to small values for all three mixing angles at high energy, where they can even unify.

G.2.3 Singlet extension of the Minimal Supersymmetric Standard Model *(M. Chemtob)*

We have analysed the nonminimal supersymmetric standard model with lepton number violation which is described by a trilinear superpotential of unique form. Motivated by the need to give the model a sound basis we have looked for the cyclic gauged discrete symmetries consistent with the anomaly cancellation constraints. We have next examined certain dominant contributions at tree and one-loop orders which can satisfactorily explain the experimental observations for the light neutrino mass matrix [t06/002].

G.2.4 String Phenomenology *(M. Chemtob)*

We have discussed baryon number violation for gauge unified orbifold models of type II string theory using setups of (Dirichlet) $D6$-branes which extend along the flat Minkowski space-time directions and wrap around 3-cycles of the internal 6-d manifold. This study was motivated by an effect anticipated in M-theory regarding the enhancement of the low energy amplitudes for matter modes localized at fixed points of the internal space dimensions. We have examined the single baryon number violating processes as well as certain higher order processes. We have shown that the string amplitudes are moderately enhanced over those of the equivalent field theory description, in general, with the effect becoming significant in the regime where the gauge symmetry breaking mass scale exceeds the compactification mass scale which corresponds to a gauge unification in a seven dimensional space-time [t07/016].

G.3 Astroparticle physics and Cosmology

G.3.1 Gravitational Waves *(C. Delaunay, C. Grojean, G. Servant)*

Physics of the electroweak phase transition could be indirectly probed by Gravity Wave experiments, specifically by the planned space interferometer LISA.

If there were a first order phase transition in the early universe, there should be an associated stochastic background of gravitational waves. In [t06/089], we pointed out that the characteristic frequency of the spectrum due to phase transitions which took place around the weak scale is precisely in the window that will be probed by future space-based interferometers such as LISA or the Big Bang Observer. Taking into account the astrophysical foreground, we determined the type of phase transitions which could be detected either at LISA, LIGO or BBO, in terms of the amount of supercooling and the duration of the phase transition that are needed. Those two quantities can be calculated for any given effective scalar potential describing the phase transition. In particular, the new models of electroweak symmetry breaking which have been proposed in the last few years typically have a different Higgs potential from the Standard Model. We examined [t06/179] the possibility of reconstructing the Higgs potential through the observation of the gravitational waves background generated during the EW phase transition.

In [t06/128], we argued that the Randall–Sundrum 1 (RS1) model can provide a strong signature in gravitational waves. This signal is a relic stochastic background generated during the cosmological phase transition from an AdS-Schwarschild phase to the RS1 geometry that should occur at a temperature in the TeV range. The key point is that at high temperature, there is an AdS-Schwarschild phase involving a single brane where the graviton amplitude is peaked, whereas at low energies, there are two branes with a slice of bulk AdS in between. One expects a first order phase transition between these two phases, which proceeds through the nucleation of "brane bubbles". An argument for the first order phase transition is provided by the AdS-CFT correspondence that relates the RS model with a 4D confining gauge theory. It is well-known that the confining phase transition of large N ($N \gtrsim 3$) gauge theories is first order (growing more strongly as N is large). In the 4D picture, the stabilized radion (which describes the stabilization of the distance between the two branes) is some glueball state.

We estimated the amplitude of the resulting stochastic signal in gravity waves in terms of the parameters of the potential stabilizing the radion and showed that over much of the parameter region in which the phase transition completes, a signal should be detectable at the planned space interferometer, LISA.

G.3.2 Dark Matter *(M. Cirelli, G. Servant)*

Dark Matter constitutes the most of the matter content of the Universe, as a number of cosmological and astrophysical observations now confirm. However, little is known about its nature and it has not been directly detected yet. There are many candidates of new particles that might constitute the Dark Matter, coming from different theories beyond the Standard Model, and this has been an incredibly rich and varied area of research in the latest twenty years.

In [t07/081], the possibility is investigated that dark matter is made of heavy Dirac neutrinos with mass $m \in [\mathcal{O}(1)$ GeV– a few TeV] and with suppressed but non-zero coupling to the Standard Model Z as well as a coupling to an additional Z' gauge boson. A model-independent analysis was provided for the relic density and direct detection. These WIMP candidates arise naturally as Kaluza-Klein states in extra-dimensional models with extended electroweak gauge group $SU(2)_L \times SU(2)_R \times U(1)$. They can be stable because of Kaluza-Klein parity or of other discrete symmetries related to the baryon number for instance, or even, in the low mass and low coupling limits, just because of a phase-space-suppressed decay width. A typical framework is to start with an $SU(2)_L$ singlet neutrino but charged under $SU(2)_R$. Because the gauge bosons of $SU(2)_R$ are heavy, their interactions with ν_R are quite small and this makes ν_R behave as a WIMP. In addition, electroweak symmetry breaking typically induces a mixing between Z and Z', leading to an effective small coupling of ν_R to the Z. Examples of this type were studied in warped extra dimensions. An interesting aspect of warped models is that the extra Z' typically couples only to the third generation, thus avoiding the usual experimental constraints.

In [t07/052], studies on another model of Dark Matter (DM) have been deepened. The model, called Minimal Dark Matter, had been previously proposed to try an alternative approach to the dark matter problem: it simply consists of the addition of an extra matter multiplet on top of the Standard Model (SM). This is in contrast with more elaborated approaches, where dark matter is framed in more ambitious Beyond the standard model theories as mentioned above. It was found that one of these multiplets (the fermionic quintuplet with hypercharge equal to zero) provides a good DM candidate: thanks to the proper assignment of quantum numbers under the SM gauge group, it is automatically stable, electrically neutral and still allowed by direct searches. The theory is so simple that it allows to compute its phenomenology fully (interactions with nucleons in direct detection, annihilation products etc etc), leading to precise predictions for the next generation of Dark Matter experiments. The exploration of its phenomenology has therefore been pursued, focussing in particular on two aspects: (i) a more precise computation of the cosmological abundance, which requires the inclusion of subtle non-perturbative effects in the computation of the annihilation processes, and (ii) the study of possible signals in astrophysical Cosmic Rays experiments, originating from the fact that the electrically charged partner of the Dark Matter particle may leave tracks in water or ice experiments like Icecube if it crosses them at very high energy after being produced in the cosmic rays. This would represent a new way of detecting Dark Matter, although unfortunately the rate of event looks quite challenging.

G.3.3 Inflation and Dark Energy *(P. Brax)*

Since the release of the WMAP3 data, cosmology has entered a new era where measurements are precise enough to give stringent information about phenomena such as inflation, dark matter or dark energy. In the last two years, I have concentrated on the construction of inflation and dark energy models within the context of beyond the standard model physics.

The origin of the inflaton is unknown. Likely candidates spring from extra dimensional models or string theory. We have studied the possibility that inflation could be driven by a bulk scalar field in 5d [t05/209]. We have compared the model with the WMAP data [t05/148]. In string theory, hybrid inflation is favoured. In particular, the D3/D7 brane system gives an explicit realisation. We have studied the coupling of hybrid inflation to moduli, fields which need to be stabilised in order to avoid the existence of a fifth force. This coupling could modify hybrid inflation drastically [t06/063][t06/202]. At the end of brane inflation, cosmic strings could be formed. We have studied the fermionic zero modes on these strings and proved an index theorem in supergravity [t06/040]. We have also analysed the phenomenology of these vortons and the constraints on their tension [t06/064].

Dark energy is a deep mystery. We have studied the embedding of quintessence in supergravity. A particular emphasis has been put on gravitational tests and variation of constants [t06/066][t06/191]. We have identified necessary conditions to obtain quintessence in spontaneously broken supergravity [t06/204].

Finally, scalar fields leading to quintessence have a small mass which leads to strong violation of the equivalence principle. This can be avoided thanks to the chameleon mechanism. We have studied the effect of chameleon on structure formation. We have also suggested that the PVLAS and CAST results can be interpreted within the context of chameleon theories [t07/092][t07/093].

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CHAPTER H

Strong Interactions

The study of Quantum ChromoDynamics (QCD) is one major subject of particle Physics. It is one of the fundamental interactions and it plays a key rôle, both on a theoretical and phenomenological level.

On a theoretical ground, it is linked to the deep problem of solving a gauge field theory involving fundamental quarks and gluons as quantum fields. The two recent breakthroughs in this field are the connection to string theory, *via* the AdS/CFT correspondence, and the connection to modern statistical Physics, *via* the relation between QCD at high energy/density and fluctuating reaction-diffusion systems.

At a phenomenological level, QCD lies at the heart of experimental investigations at the very high energy colliders, HERA (lepton-hadron), the Tevatron (hadron-hadron), RHIC (heavy ions) and soon the LHC (Large Hadron Collider, at CERN). Upcoming experiments at LHC are the major concerns of particle physics in 2007. There is an urgent need for a better understanding of QCD at high energies both as a background for physics beyond the standard model, and for the yet unexplained aspects of QCD itself.

The last few years have witnessed spectacular advances in fixed-order perturbative calculations, due in particular to the recursion relations found by Witten and his collaborators at the beginning of 2005. This chapter will report on further achievements in this direction: in particular, the tree-level recursion relations of Witten *et al.* have been extended to one loop [t05/114]. More recently, the four-loop scattering in maximally supersymmetric QCD was calculated for the first time [t06/135], enabling to test a conjecture from integrable models.

Over the recent years, the QCD group in SPhT has also made important contributions to the dynamics of QCD at high energy, in particular, the high–energy phase of the hadronic matter — the *Color Glass Condensate* (CGC). This is a high–density (hence weakly–coupled) form of gluonic matter produced via radiative processes in the wavefunction of an energetic hadron; it is characterized by maximal occupation numbers ('gluon saturation') at momenta below some characteristic scale (the 'saturation momentum'), which is rapidly increasing with the energy. One of the most fascinating recent discoveries in this field is the profound link between high–energy evolution, leading to CGC, and a class of stochastic processes in classical statistical physics known as 'reaction–diffusion'. Identified less than three years ago, this correspondence has shed a new perspective, and provided a new paradigm, for understanding the high–energy dynamics in QCD. For instance, subtle aspects concerning the behavior of scattering amplitudes in the high–energy limit have been understood by analogy with the corresponding results in statistical physics. But this cross–fertilization turned out to be profitable for *both* fields: stimulated by the interest in the QCD problem, new results have become available, which have immediate consequences for the statistical problem as well. Further understanding this correspondence, its physical consequences and also its limitations, and identifying the best strategy to overcome such limitations, has represented one of the main activities of the high–energy QCD group in Saclay (together with our external collaborators) over the last couple of years.

This chapter gathers contributions from F. Gelis (at CERN since 01/01/2007), B. Giraud (emeritus), E. Iancu, D. Kosower, A. Morel (emeritus), J.-Y. Ollitrault, R. Peschanski and M. Rho (emeritus). The group has had 5 postdocs (S. Badger, A. Beraudo, D. Forde, Y. Hatta, L. Portugal, G. Soyez) and 3 PhD students (G. Beuf, C. Marquet, C. Vergu) over the last two years. Two PhD students from Brazil, A. Bessa (Rio de Janeiro) and J.T. de Santana Amaral (Porto Alegre), spent one year in Saclay. This activity is supported by two ANR[1] grants on perturbative QCD (QCD@LHC, 2005) and high-density QCD (from RHIC to LHC, 2006).

Contents

[1] Agence nationale de la recherche

H.1 QCD at high energy: Saturation and CGC

H.1.1 Statistical physics and Pomeron loops *(E. Iancu, G. Soyez)*

With increasing energy, a hadron evolves into a system with high gluon density ("Color Glass Condensate", or CGC), characterized by the equilibrium between *splitting* processes, leading to the growth in the particle number, and *recombination* processes, which limit this growth ("gluon saturation"). In the recent years, it has been realized (in particular, thanks to the activity of our group at SPhT) that this evolution is in fact similar to a classical stochastic process known as 'reaction–diffusion'. (See, e.g., the recent review papers [t06/225], [t06/151], based on presentations at conferences, and the proceedings [t07/007])

This observation is interesting since it allows one to study the dynamics in QCD at high energy via methods borrowed from statistical physics, like Monte–Carlo simulations. In full QCD, such studies are however complicated by the intricate structure of the respective evolution equations, which are highly non-local in the four-dimensional transverse phase-space. These equations can be seen as a generalization of the celebrated BFKL equation in which the 'BFKL Pomerons' are allowed to split ($1 \to 2$) or merge with each other ($2 \to 1$), thus generating 'Pomeron loops' [t05/164, t05/165].

In particular, the non-locality of the equations obscures their probabilistic interpretation as a reaction–diffusion process. In order to clarify this issue, we have proposed [t05/138] (in collaboration with D. Triantafyllopoulos, ECT*) a reformulation of these equations in terms of a system of 'color dipoles' which evolves through dissociation (one dipole splitting into two) and recombination (two dipoles merging into one). However, it turns out that the (non-local) vertex describing dipole recombination has an oscillating sign, which makes its probabilistic interpretation problematic. Accordingly, it is currently not clear whether the Pomeron loop equations can be solved via Monte–Carlo techniques.

Given this difficulty to solve the actual QCD equations, we have proposed simpler models in lower dimensions, which allow for explicit solutions and at the same time preserve some non–trivial aspects of QCD. These models are inspired by the reaction–diffusion process in statistical physics, but they go beyond it by including more of the QCD dynamics. Specifically, we have built a model, first in zero transverse dimensions (meaning that the evolution takes place at a single site) [t06/067], then in one transverse dimension (which represents the modulus of the gluon transverse momentum) [t06/148]. What is particularly interesting about these models is that their dynamics is entirely fixed by the requirement of Lorentz invariance for the S–matrix. This constraint is known to play an important role in QCD as well, and indeed the structure of the equations in the toy model is quite similar to that of the Pomeron loop equations in QCD. For these two versions of the model we have provided explicit solutions (including analytic ones for the zero–dimensional case), which illustrate the dramatic effects of the Pomeron loops on the high-energy evolution. These effects are in agreement with previous studies of the reaction–diffusion process, and thus comfort our expectations that similar effects should hold in QCD as well.

H.1.2 Diffusive scaling *(Y. Hatta, E. Iancu, C. Marquet, G. Soyez)*

One of the remarkable features of the high–energy evolution with Pomeron loops is the extreme sensitivity of the results to *particle (gluon) number fluctuations* in the course of the evolution. Such a sensitivity was a priori unexpected in the context of saturation, where the occupation numbers are large, but in fact it can be traced back to the fact that the high–density gluon distribution at some energy has been created via evolution from a low–density system at some lower energy. For this low–density system, the fluctuations are naturally important, and their effects are then amplified by the evolution towards high density and saturation.

As a consequence of fluctuations, the evolution becomes *stochastic*, with an average dispersion between the different events which grows with the energy. An 'event' typically refers to the scattering between the evolving hadron and a simple external projectile — a 'color dipole' made with a quark and a antiquark —, so like in deep inelastic scattering (DIS). The fluctuations have a strong impact on the shape of the scattering amplitude as a function of the dipole size r: whereas the *event–by–event* amplitude shows 'geometric scaling' (meaning that its shape is approximately preserved by the evolution, up to a rescaling of r), in the *average* amplitude this scaling is washed out by dispersion and eventually replaced (at sufficiently high energy) by a new scaling law, that we have dubbed *'diffusive scaling'* [t06/001] (see also [t06/142]). This collaboration also included D. Triantafyllopoulos.

Such a scaling should eventually show up in all the cross–sections for DIS, either inclusive, or diffractive [t06/001]. However, the current experimental results at HERA appear to support geometric scaling, thus suggesting that the energies available there are not yet high enough to allow for a significant growth of fluctuations. But the situation at LHC should be more favorable in that sense: our analysis [t06/044] shows that the *transition from geometric scaling to diffusive scaling* with increasing energy could be observed by measuring particle production at increasingly forward rapidities in proton-proton, or proton-nucleus, collisions at LHC.

H.1.3 Traveling waves *(C. Marquet, R. Peschanski, G. Soyez)*

In [t05/091] and [t05/136], we derive parametric travelling-wave solutions of non-linear QCD equations. They describe the evolution towards saturation in the geometric scaling region. The method, based on the expansion in the inverse of the wave velocity, leads to a solvable hierarchy of differential equations, both for fixed and running coupling constant. A universal parametric form of travelling waves emerges from the first two orders of the expansion. and compares well with numerical simulations of the original Balitsky-Kovchegov (BK) equation, even at non-asymptotic energies. Using this universal parametrization, we find evidence for a traveling-wave pattern of the dipole amplitude determined from the gluon distribution extracted from deep inelastic scattering data (see also [t05/183]).

In [t05/195] (in a collaboration with R. Enberg), using the BK equation as an explicit example, we show that nonlinear QCD evolution leads to an instability in the propagation toward the infrared of the gluon transverse momentum distribution. This effect takes the mathematical form of rapidly moving new traveling wave solutions of the BK equation, which we investigate by numerical simulations. These traveling wave solutions are different from those governing the transition to saturation, which propagate towards the ultraviolet. This mechanism could play a role in the rapid decrease of the mean free path in the Color Glass Condensate scenario for heavy ion collisions.

In [t05/141] (which also involved A.Bialas), we study the asymptotic solutions of a version of the BK evolution with discrete steps in rapidity. We derive a closed iterative equation in momentum space. We show that it possesses traveling wave solutions and extract their properties. We find no evidence for chaotic behaviour due to discretization.

H.1.4 The strong fluctuations limit *(C. Marquet, R. Peschanski, G. Soyez)*

In [t05/142, t05/200] we investigate the behaviour of the QCD evolution towards high-energy, in the limit where the fluctuation contribution is large. Our solution for the equivalent stochastic Fisher equation predicts the amplitude as well as the whole set of correlators in the strong noise limit. The speed of the front and the diffusion coefficient are explicitely obtained, exhibiting through an exactly solvable model the general trend of QCD evolution with fluctuations.

In [t06/026], we establish a connection between the cascading of gluon momenta modeled with the diffusive approximation of the Balitsky-Fadin-Kuraev-Lipatov (BFKL) kernel and the thermodynamics of directed polymers on a tree with disorder. Using known results on the low-temperature spin-glass phase of this statistical-mechanic problem we describe the dynamical phase space of gluon transverse momenta near saturation including its fluctuation pattern. It exhibits a nontrivial clustering structure, analoguous to "hot spots", whose distributions are derived and possess universal features in common with other spin-glass systems. (see also [t06/117]).

H.1.5 Liouville field theory for gluon saturation *(E. Iancu)*

As previously explained, the gluon number fluctuations have a large impact on the results of the high-energy QCD evolution, via the correlations that they induce in the low-density regime. In particular, we expect these fluctuations to generate strong inhomogeneities in the gluon distribution in the impact parameter space (the two-dimensional space transverse to the collision axis), leading to a granular structure at high energy. In a scattering process, the dense regions should appear as 'black spots', while the more dilute ones should exhibit different nuances of grey. Such inhomogeneities should occur on relatively short distances, of the order of the inverse saturation momentum, hence they can be described in perturbation theory. However, by lack of explicit solutions to the 'Pomeron loop' equations, such an explicit description is still missing.

To fill this gap, we have proposed in collaboration with L. McLerran [t07/013] an effective theory for the gluon distribution in impact parameter space — a local field theory in two dimensions —, which is based on symmetry arguments (notably, the conformal symmetry of the relevant evolution equations in QCD) together with general physical considerations (like the role of the uncertainty principle in correlating the size of the black spots to the typical transverse momenta of the gluons inside the spots).

The requirement of conformal invariance uniquely selects this theory to be the same as the theory describing (according to Polyakov) quantum gravity in $D = 2$; this is known as Liouville theory.

H.1.6 Probability distribution of the stochastic saturation scale *(C. Marquet, G. Soyez)*

An event-by-event scattering amplitude is characterised by a saturation scale which is a random variable. The statistical ensemble of saturation scales formed with all the events is distributed according to a probability law whose cumulants have been recently computed. In [t06/062], we obtain the probability distribution from the cumulants. We prove that it can be considered as Gaussian over a large domain that we specify and our results are confirmed by numerical simulations.

H.1.7 Dipole correlation in impact parameter space *(Y. Hatta)*

In the framework of the QCD dipole model at high energy, we have analytically evaluated the dipole pair density in certain limits and shown the existence of power-law correlations between small-x gluons in the transverse plane. Based on this result, we have demonstrated that the correlation explicitly breaks the factorization of target-averaged scattering amplitudes. These results are presented in [t07/014], written in collaboration with A.H. Mueller.

H.1.8 Non-forward saturation and vector mesons *(C.Marquet, R. Peschanski, G.Soyez)*

In [t07/019], following recent predictions that the geometric scaling properties of deep inelastic scattering data in inclusive gamma*-p collisions are expected also in exclusive diffractive processes, we investigate the diffractive production of vector mesons. Using analytic results in the framework of the BK equation at non-zero momentum transfer, we extend the QCD-inspired saturation model to parametrise the momentum transfer dependence. We obtain a good fit to the available HERA data and make predictions for deeply virtual Compton scattering measurements.

H.1.9 Traveling waves at NLO *(G. Beuf, R. Peschanski)*

In [t06/138], in collaboration with S. Sapeta (Jagiellonian University, Cracow), and in [t07/023], we derive the asymptotic traveling-wave solutions of the nonlinear BK equation for rapidity evolution in momentum-space, with one-loop running coupling constant and equipped with the BFKL kernel at next-to-leading logarithmic accuracy, conveniently regularized by different resummation schemes. Traveling waves allow to define "universality classes" of asymptotic solutions, i.e. independent of initial conditions and of the nonlinear damping. A dependence on the resummation scheme remains, which is analyzed in terms of geometric scaling properties. We derive these solutions for the recent QCD formulations of the BK equation with running coupling constant obtained from quark-loop calculation. While the associated linear solutions depend in different ways with observables and higher-order effects, we show that the asymptotic traveling-wave solutions all belong to the same universality class whose solutions are given. Hence the influence of saturation stabilizes the QCD evolution with respect to higher order effects and leads to universal features at high enough rapidity, such as the form of the traveling waves, the intercept of the saturation scale and geometric scaling in square-root of the rapidity.

H.1.10 Pomeron loops with running coupling *(E. Iancu, L. Portugal, G. Soyez)*

Previously, all studies of the high-energy QCD evolution with Pomeron loops have been performed at the level of the leading–order (LO) formalism, which is already quite cumbersome. Yet, from studies of the mean field approximation (MFA) — the BFKL or BK equations — one knows that the next-to-leading order (NLO) corrections (in particular, the running of the QCD coupling) can have important consequences, both quantitatively and qualitatively — in particular, they considerably slow down the evolution. It is therefore essential to understand the NLO effects also beyond the MFA, that is, in the full evolution including gluon–number fluctuations.

Since the Pomeron loop equations in QCD are known only to LO, we turned ourselves to the one–dimensional model introduced in [t06/148], which mimics the relevant QCD evolution at fixed impact parameter. In Ref. [t07/095] (in a collaboration including A. Dumitru and D. Triantafyllopoulos), we have generalized this model to a running coupling and then explicitly solved it, via Monte–Carlo. Our results show that the consequences of the running are truly dramatic: up to rapidities $Y \sim \ln s$ as high as $Y = 200$ (corresponding to trans-Planckian energies), the fluctuations are strongly suppressed by the running, so that the results of the complete evolution with

Pomeron loops are almost indistinguishable from those of the MFA (the BK equation).

This suggests that Pomeron loop effects can be safely neglected in applications to LHC. A word of caution is however necessary: our study has been concerned only with asymmetric situations (dilute projectile vs. dense target), so its generalization to the symmetric proton–proton collisions needs to be also investigated before drawing firm conclusions for LHC.

H.2 QCD at high energy: Diffraction, BFKL

H.2.1 Diffractive Higgs production *(R. Peschanski)*

Central diffractive production of the Higgs boson has recently received much attention as a potentially interesting production mode at the LHC. In [t05/178], we review some of the wishes and realities encountered in this field. Theoretical open problems of diffractive dynamics are involved in making accurate predictions for the LHC, among which the most crucial is understanding factorization breaking in hard diffraction.

In [t05/210], in collaboration with M. Boonekamp, J. Cammin, C. Royon (from DAPNIA, Saclay) and S. Lavignac we give detailed predictions for diffractive SUSY Higgs boson and top squark associated productions at the LHC via the exclusive double pomeron exchange mechanism. We study how the SUSY Higgs cross section and the signal over background ratio are enhanced as a function of tg β in different regimes. The prospects are particularly promising in the "anti-decoupling" regime, which we study in detail. We also give the prospects for a precise measurement of the top squark mass using the threshold scan of central diffractive associated top squark events at the LHC.

In [t07/003], in collaboration with M. Rangel, G. Alves, J. Barreto, (Rio de Janeiro Federal University, Brazil) and C. Royon, we present predictions for the diffractive production of χ mesons in the central rapidity region usually covered by collider detectors. The predicted cross sections are based on the Bialas-Landshoff formalism for both exclusive and inclusive production with a new adaptation with kinematics appropriate for small-mass diffractive production. The results agree with the Tevatron data and are extrapolated, highlighting the exclusive χ_c production at LHC energies. A possible new measurement at the Tevatron using the DØforward detectors is investigated.

In [t06/027], in collaboration with C. Royon, L. Schoeffel (from DAPNIA, Saclay) and E. Sauvan (CPPM, Marseille), the proton diffractive structure function $F_2^{D(3)}$ measured in the H1 and ZEUS experiments at HERA are analysed in terms of perturbative QCD in the perspective of the QCD extrapolation to the Tevatron and the LHC. For present data from H1 and ZEUS the gluon distributions are found to be quite different and we give the corresponding sets of quark and gluon parton distributions for the Pomeron, extracted from the two experiments. An extrapolation to the Tevatron range is compared with CDF data on single diffraction. Using the double Pomeron formulation in central diffractive dijet production we show that the Tevatron mass fraction is much sensitive to the high β tail of the gluon in the Pomeron, suggesting a new way of handling the otherwise badly known gluon distribution in the Pomeron. Extending in [t06/111] this study in collaboration with C. Royon, L. Schoeffel, S.Sapeta and E. Sauvan, we describe the most recent data on the diffractive structure functions from the H1 and ZEUS Collaborations at HERA using four fifferent models. First, a Pomeron Structure Function (PSF) model, in which the Pomeron is considered as an object with parton distribution functions. Then, the Bartels Ellis Kowalski Wusthoff (BEKW) approach is discussed, assuming the simplest perturbative description of the Pomeron using a two-gluon ladder. A third approach, the Bialas Peschanski (BP) model, based on the dipole formalism is then described. Finally, we discuss the Golec-Biernat-Wüsthoff (GBW) saturation model which takes into account saturation effects. The best description of all avaible measurements can be achieved with either the PSF based model or the BEKW approach. The comparison of all predictions allows us to identify interesting differences in the behaviour of the effective pomeron intercept and in the shape of the longitudinal component of the diffractive structure functions.

H.2.2 BFKL beyond leading logarithms *(C. Marquet, R. Peschanski)*

In [t06/060], in collaboration with C. D. White (Cambridge University) and R.S. Thorne (University College, London), we calculate the impact factor coupling a virtual photon to a gluon via a massive quark-antiquark pair at Leading Logarithmic (LL) order, but with the imposition of the correct gluon kinematics. Exact analytical results are presented in triple Mellin space with respect to scaled Bjorken x, gluon transverse momentum and heavy quark mass. The application of these results to the calculation of approximate Next-to-LL (NLL) coefficient functions needed to relate structure functions to the BFKL gluon is presented.

In [t06/112] and [t06/187], in collaboration with O. Kepka, C. Royon (DAPNIA, Saclay) and C. Marquet (Brookhaven), we show that the forward-jet measurements performed at HERA allow for a detailed study of corrections due to next-leading logarithms (NLL) in the Balitsky-Fadin-Kuraev-Lipatov (BFKL) approach. While the description of the $d\sigma/dx$ data shows small sensitivity to NLL-BFKL corrections, these can be tested by the triple differential cross-section $\mathrm{d}\sigma/dxdk_T^2dQ^2$ recently measured. These data can be successfully described using a renormalisation-group improved NLL kernel while the standard next-leading-order QCD or leading-logarithm BFKL approaches fail to describe the same data in the whole kinematic range.

H.2.3 Saturation effects on diffraction *(C. Marquet)*

In the limit where the number of colors is large, the hierarchy of equations describing the high-energy QCD evolution of a dilute hadron was derived in [t05/100], with A. Mueller, A. Shoshi and S. Wong. When merged together with the equations for the evolution a dense hadron, the resulting hierarchy includes Pomeron loops in the evolution. The phenomenological consequences, which likely require asymptotically high energies, are discussed in [t06/082] and [t06/119] for inclusive and diffractive DIS; the new diffusive scaling regime is presented.

In two fruitful collaborations with experimentalists from DAPNIA, the theory of the small-x regime of QCD has been confronted to available data. Searches of BKFL and saturation signals at hadron colliders were performed with C. Royon [t05/124][t05/166], and the first analysis of the geometric scaling of diffraction data in deep inelastic scattering (DIS) was carried out with L. Schoeffel [t06/055]. In a theoretical work with K. Golec-Biernat, the measurement of diffractive jet production was proposed as an ideal process to look for evidence of saturation [t05/064][t05/134].

All these developements are gathered in the PhD Thesis [t06/108] (see also [t05/159][t06/137] for reviews at conferences).

H.2.4 Phenomenology of gluon saturation *(F. Gelis)*

The physics of parton saturation is expected to be relevant at small momentum fraction x in Deep Inelastic Scattering (DIS) and also in purely hadronic collisions. In fact, both DIS and asymmetrical collisions like proton-nucleus collisions provide an interesting framework in order to study the effects of gluon saturation.

With Mehtar-Tani [t05/194], we have rederived the solution of Yang-Mills equations in the presence of sources moving on the light-cone in opposite directions (the solution is approximated to linear order in one of the two sources and exact in the other source). Our choice of gauge leads to a much simpler solution compared to those that had been obtained before, paving the way to more complicated computations.

With Fujii and Venugopalan [t05/232, t06/030], we have studied the effects of saturation on the production of pairs of heavy quarks and of quarkonia states in proton-nucleus collisions. This is a follow up of our previous study on the saturation induced breaking of k_t-factorization. Our study concludes to a suppression at forward rapidities similar to what has been observed for inclusive charged hadrons by the BRAHMS experiment at RHIC.

With Jalilian-Marian [t06/103], we have pursued our study of the Drell-Yan process in proton-nucleus collisions, and how it may be affected by saturation effects. In this work, we have considered the so-called Lam-Tung relations. These identities, that relate the various Drell-Yan structure functions, are known to be valid up to NLO in QCD in the absence of multiple scatterings. They are therefore very sensitive to rescattering and saturation effects.

With Borghini [t06/075], we have studied the distribution in the number of scattered partons when a fast parton penetrates through a nucleus. This is relevant for proton-nucleus collisions in the fragmentation region of the proton. We have shown how the number of struck partons depends on the saturation scale and on the momentum resolution with which one detects these recoils. We also calculated the correlation between the multiplicity of the recoils and the impact parameter of the collision.

With Stasto and Venugopalan [t06/041], we have studied the “limiting fragmentation” phenomenon. Within a unified description based on gluon saturation, we were able to reproduce the limiting fragmentation curves at hadronic collisions from 20 GeV to 2 TeV.

With Peschanski, Schoeffel and Soyez [t06/141], we have reconsidered the “geometrical scaling” observed in DIS reactions at HERA. We have devised a simple estimator that can be used to search for scaling relations in a data set, without a precise a priori knowledge of the scaling law (i.e. with our method, one can scan among a family of potential scaling laws in order to find the one that agrees best with the data set, if any).

H.3 Quantum fields at finite temperature

H.3.1 Physics of the quark-gluon plasma *(F. Gelis)*

The Landau-Pomeranchuk-Migdal effect is an interference effect that modifies the radiation spectrum of a fast charged particle moving through a dense medium of scattering centers: a destructive interference comes from the fact that the emission time of a soft photon is larger than the mean free path of the emitter in the medium. With Baym, Blaizot and Matsui [t06/010], we have shown that the formalism that describes the LPM suppression can be obtained very simply within a kinetic description of the system of emitters. In our approach, the integral equation that sums the multiple scatterings is nothing but a linearized Boltzmann equation.

With Bessa, de Carvalho, Fraga [arxiv:0705.1531], we have extended a semi-classical expansion to the calculation of the free energy in a quantum field theory. In this approach, one expands around non trivial classical solutions (that fulfill the appropriate boundary conditions at finite T) instead of the vacuum.

H.3.2 Thermodynamics of $N = 4$ SYM *(J.-P. Blaizot, E. Iancu)*

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 (more generally, non–local self–energies) 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. This is why *naive* perturbation theory, by which we mean the straightforward expansion (say, of the thermodynamic potential) in powers of the coupling g, is very poorly convergent at finite temperature, and hence useless except for unrealistically small values of the coupling.

In previous work, we have shown that a systematic and also efficient way to include the effects of the thermal masses within the framework of perturbation theory is via *self—consistent resummations* of the (perturbatively computed) self–energies. This method not only solves the convergence problem alluded to above, but also leads to results which, in the context of QCD, are in a good agreement with the lattice results for the entropy down to temperatures as low as $2.5T_c$, where the running coupling $g(2\pi T)$ is quite strong. (T_c is the deconfinement temperature.) Namely, the corresponding value of the t'Hooft coupling $\lambda \equiv g^2 N_c$ is as large as $\lambda \sim 5 \div 6$, leading to speculations that the deviations seen in the lattice data from the ideal–gas behavior could be attributed to strong–coupling effects (like in a liquid).

To test such ideas, we have applied [t06/163] our resummation technique to $\mathcal{N} = 4$ supersymmetric Yang–Mills (SYM) theory, where the perturbative expansion of the entropy suffers from the same lack-of-convergence problem as in QCD, but for which the strong–coupling limit has been also studied, via the AdS/CFT correspondence. We have thus found that the thermodynamics in this theory remains within the realm of *resummed* perturbation theory up to values of λ at which the entropy has dropped to about 85% of the Stefan-Boltzmann value (which in QCD would correspond to temperatures above 2.5 T_c). This comforts our previous finding that the lattice results in QCD above $2.5\,T_c$ are well described by resummed perturbation theory. On the other hand, for larger values of λ, the strong–coupling techniques appear to better suited (at least, in $\mathcal{N} = 4$ SYM).

H.3.3 Thermodynamics of $D = 3$ QCD *(A. Morel)*

The thermodynamics of pure gauge QCD result from long range properties which the infrared singularities make very difficult to study within perturbation theory, and require resummation techniques to be set under control. Numerical simulations of 4-dimensional QCD (QCD_4) are however very expensive. It is hoped that QCD_3, while requiring less computing resources, contains relevant information on the role of (stronger) IR singularities in the confined regime. Data from large scale simulations of QCD_3 are collected and first results are presented in [t06/092] on the free energy and the pressure. A careful analysis of finite size effects is under way and extrapolations to the continuum performed correspondingly.

H.4 Heavy Ion Collisions

H.4.1 Initial conditions in nucleus-nucleus collisions *(F. Gelis)*

Another area where gluon saturation plays an important role is the physics of high energy heavy ion collisions. There, one does not want to probe saturation, but instead to use parton saturation as an ingredient in the calculation of the properties of the system immediately after the impact of the two nuclei.

With Kajantie and Lappi [t05/125] (see also [t05/187] [t05/188]), we have computed in this framework the inclusive spectrum of the quarks produced shortly after the collision. This involves solving numerically the Dirac equation in a classical color field (itself obtained by solving numerically the Yang-Mills equations), and turned out to be very computationally intensive. From this study, we concluded that all the light quarks are produced very early in the collision process, and in numbers that are grossly compatible with chemical equilibration.

With Venugopalan [t06/009, t06/047, t06/203, t07/037], we have systematically developed the formalism to study particle production in a quantum field theory coupled to strong time-dependent sources. In fact, the previous study of quark production in nucleus-nucleus collisions uses some of these results, and triggered this more general study. In particular, we were able to bring this formalism to a state where it becomes possible to compute 1-loop corrections to the existing leading order results.

Moreover, the calculation of these one-loop corrections is an important step in the study of an instability that may play a crucial role in the thermalization of the produced particles. The quantum fluctuations, that are normally suppressed, are amplified by this instability and eventually become as large as the leading order contribution. With Fujii and McLerran [t06/139], we have calculated the spectrum of these fluctuations at a very short time after the collision.

H.4.2 Collective phenomena, transport and flow *(J.-Y. Ollitrault)*

On April 18, 2005, a press release announced that a new state of matter had been discovered in ultrarelativistic nucleus-nucleus collisions (see [t06/101] for a review) at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven: a liquid of strongly interacting quarks and gluons, with the lowest possible shear viscosity. A universal lower bound on the viscosity/entropy ratio, $1/4\pi$ has been conjectured by Kovtun, Starinets and Son (KSS, hep-th/0405231), using the AdS/CFT correspondence, and many heavy-ion physicists now believe that the viscosity at RHIC is as low as the KSS bound.

Our works in the last two years aim at a reassessment of this “perfect liquid” scenario. Our first study [t05/126] was essentially qualitative, and based on a thorough observation of RHIC data: we argued that both the centrality dependence of elliptic flow, v_2, and the large magnitude of v_4 (the fourth harmonic of the azimuthal distribution) observed at RHIC are not those of a perfect liquid. The latter point was based on our earlier observation [t05/107] that ideal hydrodynamics predicts a simple relation $v_4/v_2^2 = 0.5$, while viscous effects should result in larger values.

Our point of view was independently confirmed by theoretical arguments: the “perfect liquid” scenario was based on the observation that the magnitude of v_2 at RHIC was as large as predicted by ideal-fluid calculations. However, it was realized in the last 2 years that these early calculations underestimated the eccentricity of the initial almond (hence the magnitude of elliptic flow) as a consequence of two effects: fluctuations in the wave functions of incoming nuclei, which are important for small nuclei and/or central collisions. These fluctuations are studied analytically in [t06/077]. The second effect is perturbative gluon saturation (aka Color Glass Condensate, CGC). These recent advances also point to a reassessment of the perfect liquid scenario.

Our present work is to model quantitatively deviations from the perfect liquid. Microscopically, elliptic flow is generated by collisions among particles, and this can also be computed using Boltzmann transport theory. Previous Boltzmann calculations were unable to reproduce the hydrodynamic values. A master student, Clément Gombeaud, has implemented a new covariant algorithm to solve the Boltzmann equation [t07/028] and results (in particular elliptic flow) smoothly converge to hydrodynamics as the mean free path decreases, as expected on general theoretical grounds. Using these results, together with the improved knowledge of initial conditions (fluctuations+CGC), we were able to reproduce accurately the centrality and system-size dependence of elliptic flow at RHIC [t07/049]. Our results clearly show that RHIC data are roughly 25% below the hydrodynamic value, and suggest that the viscosity/entropy ratio is about twice larger than the KSS bound.

H.5 Perturbative gauge theories

H.5.1 Amplitudes in pQCD: the unitarity method (*D. Kosower*)

Over the last two years, my research has focused on perturbative gauge theories, and in particular on computations of amplitudes in perturbative QCD; on computations in maximally supersymmetric gauge theory, allowing new quantitative comparisons to string theory in an anti-de Sitter background; and on a new approach to parton-shower computations, matching fixed-order matrix elements in perturbative QCD with leading-logarithmic resummation.

The unitarity method, which I developed long ago with Z. Bern (UCLA), L. J. Dixon (SLAC), and D. Dunbar (Swansea), provides a powerful method for computing amplitudes in gauge theories. For applications to perturbative QCD, it must either use as ingredients tree amplitudes computed in D dimensions, or must be complemented by other techniques for the rational, cut-free terms. In a series of papers ending with [t05/114], Bern, Dixon, and I showed how to use an on-shell recursion relation at one loop to compute such rational terms. This paper showed how to compute the rational terms in amplitudes which also have non-vanishing cut terms. These on-shell recursion relations are extensions to one loop of the tree-level relations of Britto, Cachazo, Feng, and Witten (BCFW).

Darren Forde, then a postdoc in the Service, and I applied this new one-loop on-shell recursion relation to the computation of a certain class of QCD amplitudes with arbitrary multiplicity. We computed, in [t05/149], gluon amplitudes two color-adjacent negative-helicity gluons with all others carrying positive helicity. These are the one-loop corrections to the maximally-helicity violating (MHV) amplitudes, also known as Parke-Taylor amplitudes at tree level. We had previously derived, in [t05/115], some new all-n formulæ at tree level for massive amplitudes using the BCFW recursion relations (see also [t06/093]).

I continued collaborating with Bern, C. Berger (SLAC), Dixon, and Forde, to apply these techniques to new amplitudes. We computed the rational parts of several six-gluon helicity amplitudes in [t06/036], and extended the earlier computation of adjacent-helicity amplitudes to all MHV all-n amplitudes in [t06/070].

With Bern and Dixon, I co-authored an invited review article, [t07/039], on the topic of on-shell methods combining unitarity and recursion relations in perturbative calculations, which will appear in the *Annals of Physics*.

The unitarity method has also been applied very fruitfully to computations in the $\mathcal{N} = 4$ supersymmetric gauge theory. This theory is of interest as a laboratory for studies of gauge-theory amplitudes, and because of its connection, via the AdS/CFT duality conjecture of Maldacena, to string theory. Developments in recent years in string theory and integrable models have made possible a number of quantitative tests of this correspondence. Calculations in which I have participated have played an important role in these tests.

Several years ago, in a paper co-authored with C. Anastasiou, Bern, and Dixon, we pointed out that a special relation exists between amplitudes at different perturbative orders in the maximally supersymmetric gauge theory. Relations between infrared-divergent terms are expected in order to enable cancellations of these singularities in physical quantities, but in this theory these relations — essentially allowing one to express an amplitude at any loop order in terms of the one-loop amplitude and three new constants at each order — extend to the finite terms as well. Bern, M. Czakon (U. of Wurzburg), R. Roiban (Penn State), V. A. Smirnov (Moscow INR) and I tested this iteration relation in [t06/032] for the five-point amplitude, where it also holds. This in turn implies that it most likely holds for all n-point MHV amplitudes at two loops. The iteration relation also turns out to hold for three-loop four-point amplitudes (as shown by Bern, Dixon, and Smirnov), and has recently been extended to the strong-coupling domain in an interesting paper of Alday and Maldacena.

The first of the three new constants required at each loop order turns out to be the so-called 'soft' or 'cusp' anomalous dimension that is the coefficient of the large-spin anomalous dimension of single-trace operators. This anomalous dimension, which corresponds to masses of spinning-string states, can be computed within the spin-chain model of single-trace operators, using an equation derived from a Bethe ansatz. That equation leaves undetermined an overall phase (the so-called 'dressing factor') corresponding to an overall phase of the world-sheet S-matrix. Through three loops, this phase is unity for algebraic reasons. It can be determined from gauge theory via a four-loop computation, which Bern, Czakon, Dixon, Smirnov and I performed. As reported in [t06/135], it gives the first perturbative evidence for a non-trivial dressing factor. It also turns out to be in agreement with a simple modification to the original integrable-model equation, and thus supports the latter's interpolation from weak to strong coupling (where the anomalous dimension had previously been computed using world-sheet perturbation theory). Bern, J. J. Carrasco (UCLA), H. Johansson (UCLA), and I took the first steps in extending this computation to one higher order — five loops — in [t07/050], where the integrand was written down in terms of a set of 34 integrals.

These results were presented at several conferences and workshops: at PANIC '05 [t06/031] (Santa Fe, New Mexico, Oct. 24–28, 2005); *From Twistors to Amplitudes* (Queen Mary College, London, Nov. 3–5, 2005); at WHEPP, (Bhubaneswar, India, Jan. 3–14, 2006); in a joint session of the 11$^{\text{th}}$ Marcel Grossman Meeting and the AEI Potsdam *Integrability in Gauge and String Theory* workshop (Berlin, Germany, Jul. 24–28, 2006); at the 21$^{\text{st}}$ Nordic String Meeting (Stockholm, Feb. 15–17, 2007); at the opening conference of the Galileo Galilei Institute program on Strings and Cosmology (Florence, Italy, Mar. 21–23, 2007); the summary talk at LoopFest VI (Fermilab, Apr. 16–18, 2007), as well as at several by-invitation workshops: Loops & Legs 2006 [t06/096] (Eisenach, Germany, Apr. 24–28, 2006), and *High Precision for Hard Processes at the LHC* (Zurich, Switzerland, Sep. 6–9, 2006).

H.5.2 Standard Model processes at 1-loop for the LHC *(S. Badger)*

Since arriving at the SPhT in October 2006 I have continued my work in the area of on-shell methods for perturbative gauge theories with specific references towards Standard Model processes at 1-loop relevant for the LHC.

Together with Nigel Glover (Durham) and Kasper Risager (Niels Bohr Institute, Copenhagen) I have completed a calculation of the n-point, ϕ-MHV amplitudes [t07/044] using the unitarity bootstrap method of Bern, Dixon and Kosower. The ϕ field considered is a massive complex scalar field coupling to the self-dual component of the gluon field and is related to the Higgs field by $H = \phi + \phi^\dagger$ These amplitudes represent part of the full set of helicity amplitudes needed for the process $H \to n$ jets and our results are sufficient to give the first analytic results for the 4 jet process. These results have also been summarised in a talk presented at the QCD session of the 42nd Rencontres de Moriond in March 2007 [t07/051].

It is clear at the energy scales the LHC will reach multi-particle processes involving heavy SM particles (top quarks, W and Z bosons) will be extremely important when searching for new physics. Since traditional Feynman techniques are extremely inefficient current work is to extend the on-shell unitarity bootstrap to include massive propagating particles, in particular to study processes relevant for $t\bar{t} \to n$ jets.

H.5.3 Factorisation of amplitudes *(C. Vergu)*

In 2003 Witten proposed a new duality linking $\mathcal{N} = 4$ super-Yang-Mills and a string theory in twistor space. The conformal properties of the scattering amplitudes are manifest in the dual string theory because the conformal group acts linearly on the twistor space.

After Witten's paper, several prescriptions were developed for computing scattering amplitudes in the dual $\mathcal{N} = 4$ gauge theory. At first, it was not obvious that all these prescriptions are equivalent. Moreover, while some properties of the resulting amplitudes were obvious in some formulations, they were not obvious in the others.

In [t06/188] I showed that tree-level scattering amplitudes computed ith the connected prescription of Roiban, Spradlin and Volovich have the right factorisation properties. This is important because the tree-level amplitudes are completely determined by their singularities (poles) which, in turn, are linked to the factorisation properties.

H.6 QCD and string theory

H.6.1 Hadrons from strings *(M. Rho)*

Strong–coupled QCD has been recently accessed via holographic duality in string theory, leading to predictions on certain properties of matter at high temperature probed at RHIC and to be probed at LHC. By astute exploitation of D-brane probes, a holographic dual QCD could be constructed that has correct features of both confinement and chiral symmetry breaking. It has been shown [t07/045][t07/064] in the D4/D8 model constructed by Sakai and Sugimoto that the bulk theory gives rise to chiral dynamics that agrees with chiral perturbation theory of QCD. Baryons are shown to emerge as instantons in (4+1) dimensions or equivalently as skyrmions in the infinite tower of vector mesons in (3+1) dimensions. The celebrated vector dominance, hitherto unexplained theoretically, comes out naturally in this theory. This development promises to shed new light on the dynamics of baryons.

H.6.2 QGP and Gauge/String Correspondence (*R. Peschanski)*

In a couple of works done in collaboration with R. Janik (Cracow), we have used the AdS/CFT correspondence to study the non-equilibrium dynamics of a strongly coupled gauge plasma, which is expected to mimic some of the properties of the quark-gluon plasma produced in heavy ion collisions.

In [t05/201], we build up a boost-invariant formalism to study the strongly interacting plasma. With the help of holographic renormalization, we show that perfect fluid hydrodynamics emerges at large times as the unique nonsingular asymptotic solution of the nonlinear Einstein equations in the bulk. The gravity dual can be interpreted as a black hole moving off in the fifth dimension.

Then in [t06/061] we derive the equation for the quasi-normal modes corresponding to the scalar excitation of a black hole moving away in the fifth dimension. On the gauge-theory side, the dominant solution of the equation describes the decay back to equilibrium of a scalar excitation of the perfect fluid. Its characteristic proper-time can be interpreted as a thermalization time of the perfect fluid, which is a universal (and numerically small) constant in units of the unique scale of the problem. This may provide a new insight on the short thermalization-time puzzle encountered in heavy-ion collision phenomenology.

H.7 Hadronic matter

This direction of research has focused on two principal themes: (1) Strongly interacting matter at high temperature relevant to relativistic heavy ion interactions, and (2) dense hadronic matter relevant to the interior of compact stars.

H.7.1 Hot matter near the critical temperature *(M. Rho)*

Hadronic matter in the vicinity of the critical temperature T_c for chiral restoration is described [t05/120] in terms of an ideal liquid above T_c and hadronic freedom below T_c. The spectrum of bound states above T_c is predicted on the basis of the Bielefeld–Brookhaven lattice data [t05/157] and the spectrum below T_c is calculated using the vector manifestation of hidden local symmetry of Harada and Yamawaki [t05/156][t06/176][t06/233].

H.7.2 Mesons at finite temperature *(A. Beraudo)*

In [t07/038], we investigate the properties of scalar and pseudo-scalar mesons at finite temperature and quark chemical potential in the framework of the Nambu-Jona-Lasinio (NJL) model coupled to the Polyakov loop (PNJL model) with the aim of taking into account features of both chiral symmetry breaking and deconfinement. In the phase of broken chiral symmetry a narrower width for the sigma meson is obtained with respect to the NJL case; on the other hand, the pion still behaves as a Goldstone boson.

In [t07/038], the Schrödinger equation for the charmonium and bottomonium states at finite temperature is solved by employing an effective temperature dependent potential given by a linear combination of the color singlet free and internal energies obtained on the lattice from the Polyakov loop correlation functions. The melting temperatures and other properties of the quarkonium states are evaluated. The consistency of the potential model approach with the available lattice data on the quarkonium temporal correlators and spectral functions is explored.

H.7.3 Kaon condensation in compact stars *(M. Rho)*

• **Dense matter**: Kaon condensation at a density $\sim (3 \div 4)n_0$ – where n_0 is the normal nuclear matter density – is shown [t05/179] to be a doorway to quark matter (e.g., color superconductivity) and to play an important role in gravitational collapse of a compact star into a black hole. This phenomenon is efficiently described starting from the vector manifestation fixed point of hidden local symmetry [t05/158].

H.8 Low-energy nuclear physics

H.8.1 Retrieving nuclear information from protons propagating through a thick target *(B. Giraud)*

In [t07/024], we study whether or not the broadening of the Coulomb angular distribution prevents the retrieval of nuclear-interaction information from measuring the angular distributions of charged particles scattered from a thick target. For this purpose, we study multiple scatterings with both the nuclear and

Coulomb interactions included and we do not make small-angle expansion. Conditions for retrieving nuclear information from high-energy protons propagating through a block of material are obtained.

H.8.2 Existence of Density Functionals for Excited States and Resonances *(B. Giraud)*

In [t06/237], we show how every bound state of a finite system of identical fermions, whether a ground state or an excited one, defines a density functional. Degeneracies created by a symmetry group can be trivially lifted by a pseudo-Zeeman effect. When complex scaling can be used to regularize a resonance into a square integrable state, a DF also exists.

H.8.3 Nuclear Structure *(P. Bonche)*

[t05/096] Solution of the Skyrme HF + BCS equation on a 3D mesh
[t06/189] Spectroscopy and single-particle structure of the odd- Z heavy elements ^{2}55Lr, ^{2}51Md and ^{2}47Es
[t06/229] Shape coexistence in neutron-deficient Kr isotopes: Constraints on the single-particle spectrum of self-consistent mean-field models from collective excitations
[t06/234] Observation of a Rotational Band in the Odd-Z Transfermium Nucleus $^251_101$Md

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CHAPTER I

Non-equilibrium Dynamics, Disordered Systems and Glass transition

One of the major success of statistical physics in the last century is the theoretical explanation of phase transitions as well as the foundation and the development of equilibrium statistical mechanics. Nowadays, one of the most active domain of research is out-of equilibrium physics. This turns out to be relevant in extremely different contexts. In fact a physical system can be out of equilibrium for several reasons: (i) it can be driven into a non-equilibrium steady state by external boundary conditions or by driving forces. An example are mechanically driven granular media. Or (ii), by changing a control parameter (temperature, pressure,...), its dynamics can become so slow, even infinitely slow, that it never achieves either thermal equilibrium or a steady state. An example is provided by glass-forming liquids in which the relaxation timescales increases so fast that they inevitably fall out of equilibrium and become rigid amorphous materials. Another important topic of modern statistical physics is disordered and glassy systems. Although phase transitions in homogeneous systems are well understood by now, many crucial and fascinating problems remain open for systems with quenched disorder (as spin glasses, directed polymers in random media, etc) and, more general, for glassy systems (glass-forming liquids, colloids, granular media).

The present activity of SPhT in statistical mechanics has connections with all the above subjects. The approaches followed by our group encompass the entire spectrum of statistical physics. A lot of attention is devoted to simplified lattice models that are studied in detail through exact solutions, numerical simulations, rigorous analysis, mean field approximations, etc. These models are very instructive because they often encode essential physical mechanisms and, at the same time, they can be fully analyzed. Examples are the asymmetric exclusion process, zero range process, kinetically constrained models, directed polymers in random media, spin glass models, etc. More realistic systems are also studied. An example are interacting particle systems, as e.g. hard spheres, displaying slow and glassy dynamics. These systems are studied by field theory, numerical simulations and phenomenological arguments. Finally, also a direct collaboration with experimentalists (especially of the SPEC-CEA) takes place on problems related to glass and jamming transitions.

This chapter involves 45 contributions of 10 permanent members: R. Balian (emeritus), A. Billoire, G. Biroli, T. Garel, C. Godrèche (since 2006), O. Golinelli, A. Lefèvre (since 2005), J.-M. Luck, K. Mallick and C. Monthus; one postdoc: F. Zamponi; and three PhD students: A. Andreanov, S. Prolhac and T. Sarlat. Members of this group have also research activity in other areas. A seminar in statistical physics is held once per week (on Monday). A joint working group with experimentalists [1], mainly from the close laboratory SPEC-CEA , takes place bi-weekly. Its main focus is on glassy systems.

Contents

[1] Three experimental groups are involved: the one of O. Dauchot (granular media), D. L'Hôte (glass-formers and coulomb glasses), E. Vincent (spin glasses).

I.1 Models of non-equilibrium dynamics

I.1.1 Dynamics of the condensate in zero-range processes *(C. Godrèche and J.-M. Luck)*

For stochastic processes leading to condensation, the condensate, once it is formed, performs an ergodic stationary-state motion over the system. In [t05/090] we analyse this motion, and especially its characteristic time, for zero-range processes. The characteristic time is found to grow with the system size much faster than the diffusive timescale, but not exponentially fast. This holds both in the mean-field geometry and on finite-dimensional lattices. In the generic situation where the critical mass distribution follows a power law, the characteristic time grows as a power of the system size.

I.1.2 Nonequilibrium stationary states with Gibbs measure for two or three species of interacting particles *(C. Godrèche and J.-M. Luck)*

In [t06/035] we construct explicit examples of one-dimensional driven diffusive systems for two and three species of interacting particles, defined by asymmetric dynamical rules which do not obey detailed balance, but whose nonequilibrium stationary-state measure coincides with a prescribed equilibrium Gibbs measure. The measures considered in this construction only involve nearest-neighbor interactions. For two species, the dynamics thus obtained generically has five free parameters, and does not obey pairwise balance in general. The latter property is satisfied only by the totally asymmetric dynamics and the partially asymmetric dynamics with uniform bias, i.e., the cases originally considered by Katz, Lebowitz, and Spohn. For three species of interacting particles, with nearest-neighbor interactions between particles of the same species, the totally asymmetric dynamics thus obtained has two free parameters, and obeys pairwise balance. The emerging picture is that asymmetric (nonequilibrium) stochastic dynamics leading to a given stationary-state measure are far more constrained (in terms of numbers of free parameters) than the corresponding symmetric (equilibrium) dynamics.

I.1.3 Nonequilibrium phase transition in a non-integrable zero-range process *(C. Godrèche)*

[t06/130] is an endeavour to determine analytically features of the stationary measure of a non-integrable zero-range process, and to investigate the possible existence of phase transitions for such a nonequilibrium model. The rates defining the model do not satisfy the constraints necessary for the stationary measure to be a product measure. Even in the absence of a drive, detailed balance with respect to this measure is violated. Analytical and numerical investigations on the complete graph demonstrate the existence of a first-order phase transition between a fluid phase and a condensed phase, where a single site has macroscopic occupation. The transition is sudden from an imbalanced fluid where both species have densities larger than the critical density, to a critical neutral fluid and an imbalanced condensate.

I.1.4 Tagged particle correlations in the asymmetric simple exclusion process: Finite size effects *(C. Godrèche)*

[t07/047] is a study of finite size effects in the variance of the displacement of a tagged particle in the stationary state of the Asymmetric Simple Exclusion Process (ASEP) on a ring of size L. The process involves hard core particles undergoing stochastic driven dynamics on a lattice. The variance of the displacement of the tagged particle, averaged with respect to an initial stationary ensemble and stochastic evolution, grows linearly with time at both small and very large times. At intermediate times, it shows oscillations with a well defined size-dependent period. These oscillations arise from sliding density fluctuations (SDF) in the stationary state with respect to the drift of the tagged particle, the density fluctuations being transported through the system by kinematic waves. Tagged particle correlations for a fixed initial configuration, drawn from the stationary ensemble, following earlier work by van Beijeren are also investigated. The time dependence of this correlation is determined by the dissipation of the density fluctuations. The exactly solvable linearized theory captures the essential qualitative features seen in the finite size effects of the tagged particle correlations in the ASEP. Moreover, this linearized model also provides an exact coarse-grained description of two other microscopic models.

I.1.5 Structure of the stationary state of the asymmetric target process *(C. Godrèche and J.-M. Luck)*

The target process is a novel migration process, dual to the zero-range process (ZRP) in the sense that, while for the ZRP the rate of transfer of a particle only depends on the occupation of the departure site, it only depends on the occupation of the arrival site for the target process. By duality a given ZRP is associated to a unique target process, and vice-versa. For symmetric dynamics the two dual processes have the same stationary-state product measure. Here the latter exhibits a continuous condensation transition at some finite critical density ρ_c, irrespective of the dimensionality. The novelty [t07/057] comes from the case of asymmetric dynamics, where the target process has a nontrivial fluctuating stationary state, whose characteristics depend on the dimensionality. In one dimension, the system remains homogeneous at any finite density. In dimension two and above, the asymmetric target process exhibits a phase transition at a threshold density ρ_0 much larger than ρ_c. The system is homogeneous at any density below ρ_0, whereas for higher densities it exhibits an extended condensate elongated along the direction of the mean current, on top of a critical background with density ρ_c.

I.1.6 Algebraic Bethe Ansatz for non-equilibrium models *(O. Golinelli, K. Mallick)*

The Asymmetric Simple Exclusion Process (ASEP) is a driven lattice gas that can be viewed as a special case of the general class of driven lattice gas models defined by Katz, Lebowitz and Spohn. This stochastic particle system was introduced forty years ago as a biophysical model for protein synthesis on RNA and, independently, as a purely mathematical tool for the study of interaction of Markov processes. Since then, the ASEP has been used to study a wide range of physical phenomena, such as hopping conductivity in solid electrolytes, transport of macromolecules through thin vessels, reptation of polymer in a gel, traffic flow, surface growth, sequence alignment and molecular motors. From a theoretical point of view, the ASEP plays a seminal role in the study of non-equilibrium processes: many exact results for the ASEP in one dimension have been derived using two complementary approaches, the Matrix Product Ansatz and the Bethe Ansatz.

In our work [t06/178], we study the algebraic structure underlying the ASEP. Using the algebra generated by the local jump operators (which is a special case of a Temperley-Lieb algebra) we explicitly construct the hierarchy of operators (or generalized hamiltonians) that commute with the Markov operator, which describes the dynamics of the system. We show that the transfer matrix, which is the generating function of that hierarchy, can be interpreted as a discrete Markov process with long-range jumps. This transfer matrix appears in anisotropic percolation problems as well as in sequence matching models. We give a general combinatorial formula for the connected hamiltonians obtained by taking the logarithm of the transfer matrix. This formula, which was first conjectured by using a symbolic calculation program, is rigorously proved in [t07/066] by a method that does not depend on the particular representation of the local update operators but only on the algebraic relations they satisfy.

I.1.7 Matrix Ansatz for non-equilibrium models *(O. Golinelli, K. Mallick)*

In [t05/160], we construct a generalized Matrix Product Ansatz for the asymmetric exclusion process. In this Matrix Product Ansatz, the components of all the eigenvectors of the ASEP Markov matrix can be expressed as traces of products of non-commuting operators. We derive the relations between the operators involved and show that they generate a quadratic algebra. Our construction provides explicit finite dimensional representations for the generators of this algebra and shows that there is a close relation between the Matrix method and the Algebraic Bethe Ansatz, at least in the case of the ASEP. If such relation were true in general, this approach would provide a technique for constructing the quadratic algebras involved in many non-equilibrium models from first principles rather that having to postulate them a priori.

I.1.8 The quantum measurement process: Lessons from an exactly solvable model *(R. Balian)*

Insight on the old problem of quantum measurement is gained by analysing such an operation as a dynamical process in non-equilibrium statistical physics [t05/131][t07/043]. A realistic model, where the apparatus simulates a magnetic dot and where the tested system is a spin, is exactly solved. Several time scales are exhibited, characterizing the establishment and disappearance of correlations and the registration. As in the solution of the irreversibility paradox in statistical mechanics, the irreversibility of the measurement emerges from the Schrödinger dynamics, through statistical arguments based on the large number of degrees of freedom of the apparatus and on the time scales of the process. The reduction of the state, as well as the possibility of interpreting the quantum measurement process in terms of classical probabilities and classical correlations, emerge likewise from the general laws of quantum mechanics.

I.2 Spin glasses and glassy behavior of light

I.2.1 Numerical estimate of finite size corrections to the free energy of the SK model using Guerra–Toninelli interpolation *(A. Billoire)*

I use an interpolating Hamiltonian, introduced recently by Guerra and Toninelli in order to prove the existence of the free energy of the Sherrington–Kirkpatrick spin glass model in the infinite volume limit, to investigate numerically [t05/196][t07/030] the finite size corrections to the free energy of this model. The results agree with a $(1/12N)\ln(N/N_0)$ leading behavior at T_c, where N is the number of spins of the model, giving an estimate of the scale N_0, and are compatible with a $1/N^{2/3}$ behavior below T_c. I also show [t07/030], reanalyzing existing data, that the internal energy behaves also like $1/N^{2/3}$ for $T < T_c$, in contradiction with claims made in the literature.

I.2.2 Ward-Takahashi identities and a candidate "droplet" Lagrangean for the Ising spin glass *(C. De Dominicis)*

In [t05/132], in search for a microscopic description of "droplet-like" properties for the Ising spin glass, we revisited the two-packet model of Bray and Moore, which is replica-symmetric and enjoys zero modes but only up to the one-loop order. We show how an appropriate change in the limits of the basic parameters of the model allows for a derivation of Ward–Takahashi identities, thus ensuring the existence of zero modes to all orders. Other difficulties are still plaguing the two-packet model however, due to the persistence of so-called Hadamard couplings.

I.2.3 Dynamics of the modes in laser cavities *(F. Zamponi)*

The aim of these studies, performed in collaboration with L. Angelani, C. Conti and G. Ruocco (Universita' "La Sapienza", Roma) is to analytically investigate the dynamics of the excited modes in multi-mode laser cavities, eventually in the presence of a disordered amplifying medium.

In particular, in the paper [t06/185] we report on a statistical approach to mode-locking transitions of multi-mode laser cavities. We show that the equations for the interacting modes can be mapped onto a statistical model exhibiting a first order thermodynamic transition, with the average mode-energy playing the role of inverse temperature. The transition corresponds to a phase-locking of modes. Extended modes lead to a mean-field like model, while in presence of localized modes, as due to a small disorder, the model has short range interactions. We show that simple scaling arguments lead to observable differences between transitions involving extended modes and those involving localized modes. We also show that the dynamics of the light modes can be exactly solved in the mean-field case, predicting a jump in the relaxation time of the coherence functions at the transition.

I.3 Low-temperature frozen phase of the directed polymer in a random medium

I.3.1 Ground state energy distribution *(T. Garel and C. Monthus)*

In order to probe with high precision the tails of the ground-state energy distribution of disordered spin systems, Körner, Katzgraber and Hartmann have recently proposed an importance-sampling Monte-Carlo Markov chain in the disorder. In [t06/083], we combine their Monte-Carlo procedure in the disorder with exact transfer matrix calculations in each sample to measure the ground state energy distribution $P_d(E_0)$ for the directed polymer in a random medium of dimension $d = 1, 2, 3$. In $d = 1$, we check the validity of the algorithm by a direct comparison with the exact result, namely the Tracy-Widom distribution. In dimensions $d = 2$ and $d = 3$, we measure the negative tail up to ten standard deviations, which correspond to probabilities of order $P_d(E_0) \sim 10^{-22}$. Our results are in agreement with Zhang's argument, stating that the left tail exponent $\eta(d)$ directly related to the fluctuation exponent $\theta(d)$ via the simple formula $\eta(d) = 1/(1 - \theta(d))$.

I.3.2 Statistics of low-energy excitations *(T. Garel and C. Monthus)*

In [t06/013], we have measured the statistics of low energy excitations as a function of their size l for a directed polymer of length L in a random medium of space dimension $d = 1, 2, 3$. In the regime $1 \ll l \ll L$, our results are in full agreement with the droplet power-law form, whereas the statistics of system-size excitations $l \sim L - O(1)$ involves another exponent.

I.3.3 Weights statistics and Derrida-Flyvbjerg singularities *(T. Garel and C. Monthus)*

To characterize the localization properties in the low-temperature phase in $d = 1$ and $d = 3$, we analyse in [t07/018] the statistics of the weights $w_L(\vec{r})$ of the last monomer as follows. We numerically compute the probability distributions $P_1(w)$ of the maximal weight $w_L^{max} = max_{\vec{r}}[w_L(\vec{r})]$, the probability distribution $\Pi(Y_2)$ of the parameter $Y_2(L) = \sum_{\vec{r}} w_L^2(\vec{r})$ as well as the average values of the higher order moments $Y_k(L) = \sum_{\vec{r}} w_L^k(\vec{r})$. We find that there exists a temperature $T_{gap} < T_c$ such that (i) for $T < T_{gap}$, the distributions $P_1(w)$ and $\Pi(Y_2)$ present the characteristic Derrida-Flyvbjerg singularities at $w = 1/n$ and $Y_2 = 1/n$ for $n = 1, 2...$ In particular, there exists a temperature-dependent exponent $\mu(T)$ that governs the main singularity at $n = 1$ (ii) for $T_{gap} < T < T_c$, the distribution $P_1(w)$ does not reach $w = 1$ anymore. The histograms of spatial correlations also display Derrida-Flyvbjerg singularities for $T < T_{gap}$. Both below and above T_{gap}, the study of typical and averaged correlations is in full agreement with the droplet scaling theory.

I.4 Phase transitions in disordered systems

I.4.1 Localization-delocalization transition *(T. Garel and C. Monthus)*

We have studied this transition in 1 + 3 dimension from various points of view in [t06/022], [t06/053] and [t07/015] (see also [t06/006]). In particular in [t07/015], we have investigated the multifractal properties at criticality.In close analogy with models of the quantum Anderson localization transition, where the multifractality of critical wavefunctions is well established, we analyse the statistics of the position weights $w_L(\vec{r})$ of the end-point of the polymer of length L via the moments $Y_q(L) = \sum_{\vec{r}}[w_L(\vec{r})]^q$. In [t07/032], we have then compared with the critical weight statistics for the directed polymer on the Cayley tree (mean-field version) and for Derrida Random Energy Model.

I.4.2 Distribution of pseudo-critical temperatures *(T. Garel and C. Monthus)*

According to recent progresses in the finite-size scaling theory of disordered systems, thermodynamic observables are not self-averaging at critical points when the disorder is relevant in the Harris criterion sense. This lack of self-averageness at criticality is directly related to the distribution of pseudo-critical temperatures $T_c(i, L)$ over the ensemble of samples (i) of size L. We have studied these phenomena in various disordered models : (i) the wetting transition and Poland-Scheraga models of DNA denaturation with different loop exponents [t05/144, t06/007] (ii) the selective interface delocalization transition [t05/177] (iii) the random transverse field Ising chain [t07/048]

I.4.3 Multifractal statistics of the local order parameter *(T. Garel and C. Monthus)*

Disordered systems present multifractal properties at criticality. In particular, the moments $\overline{\rho^q(r)}$ of the local order parameter $\rho(r)$ scale with a set $x(q)$ of non-trivial exponents $x(q) \neq qx(1)$. In [t07/062], we apply these ideas to random polymer models that can be studied numerically for large sizes and good statistics over the samples. We study the bidimensional wetting or the Poland-Scheraga DNA model with loop exponent $c = 1.5$ (marginal disorder) and $c = 1.75$ (relevant disorder). Finally, we argue that the presence of finite Griffiths ordered clusters at criticality determines the asymptotic value $x(q \to \infty) = d$ and the minimal value $\alpha_{min} = D(q \to \infty) = d - x(1)$ of the typical multifractal spectrum $f(\alpha)$.

I.5 Glass transition and glassy dynamics

I.5.1 Dynamics of interacting particles and time-reversal symmetry *(A. Andreanov, G. Biroli, A. Lefèvre)*

Mode-Coupling Theory (MCT) has provided many quantitative predictions for the behaviour of dynamic correlations of glass-forming liquids in the vicinity of the glass transition. Despite these successes, MCT has been hard to extend to non-equilibrium situations such as the low-temperature — or high-density — phase or in the presence of an applied shear. Following a formal analogy between MCT equations and those governing the dynamics of the p-spin model, field theory has been advocated as a good tool to derive MCT-like self-consistent equations for the dynamics of very slow glass-forming liquids. This route was followed by Das and Mazenko, who managed to derive MCT equations from non-linear hydrodynamics using several uncontrolled approximations. We found that their equations violate time-reversal symmetry (TRS), which is a symmetry of equilibrium dynamics, and has extremely important consequence, as the Fluctuation-Dissipation Relation (FDR). The FDR can be extended to non-equilibrium situations, where it is central in the understanding of phenomena such as aging. It is thus important to derived equations which preserve TRS or violate it as late as possible. We showed that in dynamical field theories used for interacting particle systems, TRS is associated to a non-linear transformation of the fields which mixes correlations at different orders, thus making it impossible to obtain closed equations for two-point correlation functions without trivially violating FDR. We provided a solution to this problem by introducing extra fields in the theory, which correspond to the local force driving density fluctuations and its conjugated field. With these fields, the TRS acts linearly on the fields, making it possible to derive Schwinger-Dyson equations which are strongly simplified by the use of FDR [t05/191]. These equations must be seen as a starting point for deriving approximate dynamic equations, which preserve TRS. Our study shows that the smearing of the ideal glass transition due to coupling with currents exhibited by Das and Mazenko is actually a mere consequence of a too naive approximation which did not respect TRS. We showed that when TRS is properly taken into account, the equation giving the non-ergodic parameter is non-trivial at any order in perturbation theory, for both Brownian and Newtonian interacting particles. Thus if the glass transition is cut-off — as it should be in glass-forming liquids — the mechanism is non-perturbative.

I.5.2 Dynamics of interacting particles : a stochastic view *(A. Andreanov, G. Biroli, A. Lefèvre)*

Systems of classical interacting particles divide into two main classes. There are systems where density is conserved: particles diffuse with interactions between them and/or with their environment. On the other hand there are systems where density is not conserved, where particles "react" together, leading to destruction or creation of particles, coalescence, or transformation of species. These two classes constitute active fields on their own and the techniques used to study them are quite different. In particular, for reaction-diffusion system, one very useful technique is provided by the field theoretic formalism introduced by Doi and Peliti. Unfortunately, in cases where one is interested directly in the evolution and the correlation functions of the density field, this formalism is quite cumbersome because it does not focus directly on the density field. Writing the probability of stochastic histories as a path integral, we derived a field theory which keeps track of the natural microscopic fluctuations of the density field [t06/033]. This theory bridges the gap between the systems of particles with conserved density and those with reaction-diffusion, providing a unified framework. The formalism can be mapped onto the one of Doi and Peliti using a Cole-Hopf transform previously used in some specific cases for interpreting the nature of the fluctuations. Our approach shows that this transformation is very general and provides its physical origin. In addition, it corrects several earlier uses of this mapping, where it was used as a map between commuting classical fields rather than between quantum operators. Furthermore, this stochastic path integral approach makes easy to get hydrodynamic limits in many systems, shed new light on the derivation of large deviation functional and allows to obtain continuum stochastic equations on the density field valid near a critical point (e.g. for the zero-range process).

I.5.3 A new time regime in the dynamics of ideal glasses *(A. Andreanov, A. Lefèvre)*

Mean-field p-spin glass models have been extensively studied. They have a rich phenomenology and have been widely used as a paradigm for structural glasses. One of the important prediction of these models is the existence in the glassy phase — and at the approach of it — of two well separated time sectors, corresponding to the timescales of slow and fast degrees of freedom. Roughly speaking, the former come from structural motion, and the latter from local fluctuations around this slow evolution of the structure; in the glassy phase, the older the system, the more frozen the structural motion. On short timescales, the dynamics is time-translation invariant and verifies fluctuation dissipation relations (FDR), reflecting the equilibrium nature of the local motion, while on longer timescales (i.e. at least of the order of the age of the sample), the dynamics depends explicitly on the age of the sample, and a reparametrization $t \to h(t)$ of time is needed in order to collapse the curves of correlation functions for different ages. However, in the infinite-age limit, this parametrization is not fixed by the dynamic equations, which are indeed invariant under time reparametrizations. We focused on the intermediate time regime, around the plateau of correlation functions, which corresponds to time differences when structural relaxation starts occuring. We showed that the scaling of correlation and response functions in this regime are related to those in the stationary and aging sectors, derived equations for the scaling functions, and introduced a parameter of FDR violation which interpolates between 1 and the ratio of the bath and effective temperatures in the aging sector. We showed that the only form of $h(t)$ compatible with accurate numerical results for the scaling factors in the plateau regime is a stretched exponential, whose exponent has been related to those describing the stretching of the plateau and the decay of the energy. Surprisingly, the stretching exponent found in the p-spin model is very close to zero at low enough temperature. This suggest that small deviations from simple aging observed in numerics and experiments may be attributed to a small but non-vanishing stretching exponent.

I.5.4 Theory of dynamical heterogeneity, cooperativity and dynamic correlations in glass-forming liquids *(G. Biroli)*

Fragile glass-forming liquids display an extremely fast rise of their relaxation time (or viscosity) as the temperature is lowered, much faster than predicted by a simple thermal Arrhenius activation formula. The likely underlying physical reason is that larger and larger regions of the liquid have to move in a correlated way to allow for a substantial motion of individual particles. Although the idea of a cooperative length has been discussed in the context of glasses for many years, it is only recently that proper measures of dynamical correlations were proposed theoretically and measured in numerical simulations. In [t06/122], [t06/121], [t06/120], [t06/071] we have developed theoretical approaches to study and predict the behavior of dynamical correlations in glass-formers. These approaches, based on extension of the Mode Coupling Theory of the glass transition, field theoretical methods and Kinetically constrained models, have been tested succesfully in molecular dynamics simulations (performed by us and other groups). Major results are the succesfull prediction of the critical properties related to dynamical heterogeneities and the introduction of new dynamical response functions that allow to quantify dynamical correlations in glass-forming liquids.

I.5.5 First direct experimental evidence of a growing length scale for glass-forming liquids and granular materials *(G. Biroli)*

A direct experimental evidence of a growing length-scale approaching the glass transition was a long-standing issue. We developed new theoretical tools and introduced new dynamical response functions that allowed us, in collaboration with the SPEC and Montpellier experimental groups, to tackle this problem. The results, published in Science, [t05/198] opened the way to a complete characterization of dynamical correlations in glass-forming liquids. Indeed, in [t07/096] we gathered all available data to obtain the temperature dependence of the dynamic correlation volume, V_{corr}, for a large number of supercooled liquids over an extremely wide range of relaxation timescales from the glass transition up to the onset of slow dynamics. We found that V_{corr} ystematically grows when approaching the glass transition. It does so in a modest manner close to the glass transition, which is consistent with an activation-based picture of the dynamics in glassforming materials. For higher temperatures, there appears to be a regime where V_{corr} behaves as a power-law of the relaxation time which is consistent with Mode-Coupling Theory.

I.5.6 Jamming Percolation and Glass Transitions in Lattice 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 in a series of publications. We have focused on Kinetically Constrained Models. These are systems of spins or hard core particles whose thermodynamics is trivial but that are characterized by *kinetic constraints*: particles cannot move if surrounded by too many others and this causes extremely slow dynamics at high density or low temperature. In [t05/163], [t05/192], [t05/214], [t06/034], [t06/228] we have introduced a new class of model. We have shown physically, and proven rigorously, that they exhibit a dynamical glass transition: above a critical density, ρ_c, ergodicity is broken due to the appearance of an infinite spanning cluster of jammed particles. The fraction of jammed particles is discontinuous at the transition, while in the unjammed phase dynamical correlation lengths and timescales diverge as $\exp[C(\rho_c - \rho)^{-\mu}]$. We have also shown that dynamic correlations display two-step relaxation similar to glass-formers and jamming systems. These are the first finite dimensional models without quenched disorder proven to have a glass transition.

I.5.7 Checking for Optimal Solutions in Some NP-Complete Problems *(M. Bauer, H. Orland)*

For some weighted NP-complete problems, checking whether a proposed solution is optimal is a non-trivial task. Such is the case for the traveling-salesman problem, or the spin-glass problem in 3 dimensions. In [t05/154], we consider the weighted tripartite matching problem, a well-known NP-complete problem. We write mean-field finite temperature equations for this model, and derive their zero-temperature limit. We show that any solution of the zero-temperature equations provides an exact absolute ground state of the system. As a consequence, we propose a criterion which can be checked in polynomial time, such that given a putative optimal solution, if the criterion is satisfied, then the solution is indeed optimal. This criterion is generalized to a class of variants of the multiple-traveling-salesmen problems.

I.6 Granular media and Jamming transition

I.6.1 Dynamical Heterogeneity close to the Jamming Transition in a Sheared Granular Material *(G. Biroli)*

In [t05/119] we have shown the first direct experimental evidence that the jamming transition (or more precisely the appearance of macroscopic rigidity) of driven granular media is accompanied by growing dynamic lengthscales and dynamic heterogeneity very similar to the ones analyzed in the context of the glass transition. The results of this work, which has been done in collaboration with the experimental group of O. Dauchot (SPEC/CEA), strongly suggest that the jamming transition is a critical phenomenon. The critical properties of the transition were investigated in a subsequent work [t07/094]. Focusing on dense horizontally vibrated bidisperse granular monolayer, we showed that correlation time and length soar on both sides of the transition, as the volume fraction varies over a remarkably tiny range. We characterized the dynamics of individual grains, which becomes super-diffusive at the jamming transition, signalling long-ranged temporal correlations. Correspondingly, the system exhibits long-ranged four-point dynamical correlations in space that obey critical scaling at the critical density.

I.6.2 Statics and dynamics of dense granular systems *(J.-M. Luck)*

The investigation of the dynamics of dense granular systems at or near their jamming limit has been pursued by extending the framework of a stochastic model introduced previously. The model [t05/153] consists of a column of grains under the influence of a low vibrational intensity. Grains are anisotropic and possess a discrete orientational degree of freedom. Gravity induces non-local and non-symmetric effective interactions, both upwards and downwards. The model has three key control parameters: a dynamical length, an interaction length, and a parameter taking account of granular shape. A rich phase diagram with four dynamical phases (ballistic, activated, logarithmic and glassy) is revealed. The statistics of the jamming time and of the attractors reached by zero-temperature dynamics is investigated in detail for each of these phases. Of particular interest is the glassy phase, where intermittency and a strong deviation from Edwards' flatness are manifested [t07/022].

I.7 Book, review, lecture notes and "News and Views"

I.7.1 Random Fields and Spin Glasses: A Field Theory Approach *(C. De Dominicis)*

Disordered magnetic systems enjoy non-trivial properties which are different and richer than those observed in their pure, non-disordered counterparts. These properties dramatically affect the thermodynamic behaviour and require specific theoretical treatment. The book [t06/169], by Irene Giardina and Cirano De Dominicis, deals with the theory of magnetic systems in the presence of frozen disorder, in particular paradigmatic and well-known spin models such as the Random Field Ising Model and the Ising Spin Glass. This is a unified presentation using a field theory language which covers mean field theory, dynamics and perturbation expansion within the same theoretical framework. Particular emphasis is given to the connections between different approaches such as statics vs. dynamics, microscopic vs. phenomenological models. The book introduces some useful and little known techniques in statistical mechanics and field theory.

I.7.2 ASEP: an integrable model for non-equilibrium statistical mechanics *(O. Golinelli and K. Mallick)*

In the article [t06/159], we review basic integrability techniques applied to the asymmetric exclusion process (ASEP) and describe some of the exact results derived with the help of the Bethe Ansatz. In particular, we explain how the algebraic Bethe Ansatz can be applied to ASEP and how the Bethe equations allow to calculate the spectral gap. Furthermore, we show that an analysis of the symmetry of these algebraic equations by exchanging their roots allows to predict the existence of multiplets in the spectrum. We also prove that the Gallavotti-Cohen relation manifests itself as a symmetry of the Bethe equations.

I.7.3 Statistical mechanics of nonequilibrium states *(F. Zamponi)*

The statistical mechanics of nonequilibrium stationary states of dissipative systems and, in particular, the large deviations of some specific observables attracted a lot of interest in the past decade. Part of this interest concentrated on the "fluctuation relation", which is a simple symmetry property of the large deviations of the entropy production rate (related to the dissipated power). The fluctuation relation is a parameterless relation and is conjectured to hold in some generality. The discovery of this relation motivated many studies: and experiments specifically designed to its test have been reported on turbulent hydrodynamic flows and Rayleigh-Bénard convection, on liquid crystals, on a resistor, on granular gases. Unfortunately, despite this great experimental effort, the situation is still very confused. After many debates, numerical simulations established that the relation holds very generally for reversible chaotic dissipative systems: while experiments gave promising results but revealed also some difficulties in the interpretation of the data that generated many controversies. Experience revealed that to test this relation one has to face many difficulties, and that each experiment has to be interpreted by considering its own specificities. The aim of my paper [t06/184] is to review some of these difficulties, discovered in more than one decade of trials, in the hope that new experiments will be performed allowing to clarify many aspects that are still poorly understood.

I.7.4 From urn models to zero-range processes: statics and dynamics *(C. Godrèche)*

The aim of these lecture notes ([t06/132]) is a description of the statics and dynamics of zero-range processes and related models. After revisiting some conceptual aspects of the subject, emphasis is then put on the study of the class of zero-range processes for which a condensation transition arises.

I.7.5 Jamming: A new kind of phase transition? *(G. Biroli)*

In [t07/097], a Nature Physics News and Views, we have summarized and discussed the theoretical and experimental evidences that support the interpretation of the jamming transition in granular assemblies as a bona fide phase transition. We have focused in particular on the phenomenon of dynamical heterogeneity.

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CHAPTER J

Condensed matter

Condensed-matter research at SPhT for the period 2005-2007 has largely been focused on collective quantum phenomena in correlated electronic systems. It can be organized in four main directions.

The first direction is the physics of quantum criticality in heavy fermions compounds (Sec. J.1). These compounds, which can be described by conduction band electrons interacting with localized ($f-$ orbitals of rare earth ions) magnetic moments (Kondo lattice models), exhibit complex behavior due to the subtle competition between the kinetic energy of the charge carriers and their magnetic (Kondo) interaction with the localized spins. Our studies in this field have relied on field-theory techniques to deal with critical phenomena, and close connection to experimental groups. One central question in the field is the origin of the anomalous metallic properties — so-called "non-Fermi-Liquid" behavior — close to quantum phase transitions. The "Kondo breakdown" theory developed recently in our group seems to be a significant step toward a solution of this long-standing problem.

The second direction is high-temperature superconductivity, and more generally doped Mott insulators. In strongly correlated materials, the interaction between electrons can induce a Mott transition between a metal and an insulator, observed for example as a function of pressure in some transition metal oxides, and as a function of doping in high-temperature superconductors. The transition appears at intermediate coupling where electrons are neither delocalized in Bloch waves nor localized on the atoms, thus standard theoretical methods (e.g. band theory) fail. In the recent years, "Dynamical Mean Field Theory" (DMFT) has become a method of choice in this subject. The work at SPhT has mainly been focussed on cluster extensions of DMFT and also some aspects of realistic calculations with DMFT. In particular, it was recently shown that the cluster DMFT gives a new picture of the d-wave superconducting state ("two gaps picture"), in nice agreement with recent Raman scattering experiments performed at ESPCI[1] in Paris.

Mott insulators are also studied for their magnetic properties, and their spin liquid phases in 2D in particular (Sec. J.5). Such states of matter are not characterized by some spontaneous symmetry breaking, but by the existence of deconfined fractional excitations (spin $\frac{1}{2}$ spinons) and some "hidden" topological "order", the study of which

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is our third direction of research. One driving force in this subject is the regular discovery of new magnets with exotic properties. Some other part of our activity was indeed oriented toward real compounds and/or quantitative studies of realistic spin models. On the other hand, some works were focused on particular limits of frustrated spin models, the so-called dimer models.[2]. These effective descriptions allowed us to address conceptual questions such as how to detect/characterize the topological order in a wave-function (Sec. J.5.2) or study new types of phase transitions (not governed by symmetry breaking, Sec. J.7.1) in these systems.

The fourth direction is the study of one-dimensional systems and (related) quantum impurity problems (Sec. J.6). Physically, the one-dimensional systems can be nanofabricated quantum wires, carbon nanotubes or fractional quantum Hall liquid edges. As for the "impurities", they can model various devices such as quantum dots, small Josephson junctions, or tunneling points between (chiral) edges of a quantum Hall droplet. These systems offer stimulating opportunities to apply methods of mathematical physics (quantum field theory, conformal invariance and integrability - some major themes of the SPhT activity) to solve strongly interacting problems of condensed-matter physics. Our group has obtained some important results in the study of out-of-equilibrium properties these last two years (potentially accessible to experiments in the neighboring SPEC) such as the full counting distribution of the charge transfered by tunneling between two $\nu = \frac{1}{3}$ fractional quantum Hall edges, or, through the development of an "IR perturbation theory", the low temperature expansion of the conductance in the interacting resonant level model.

The works in condensed matter theory described below involved 12 persons among which 6 are permanent researchers (J. Jacobsen,[3] G. Misguich, O. Parcollet, V. Pasquier, C. Pépin and H. Saleur), 2 are long-term visitors (A. Komnik[4] and G. Kotliar[5]), 4 are post-docs (C. Bena[6] and I. Paul, F. Alet and E. Boulat[7]), and 3 are Ph. D students (J. Rech,[8] A. Benlagra[9] and S. Furukawa[10]). We also stress that 3 permanent researchers (J. Jacobsen, V. Pasquier and H. Saleur) have a large part of their research activity in other areas (conformal field theory, mathematical physics, and classical disordered systems) and the condensed-matter activity naturally benefited from the expertise in their field. Part of this research activity is supported by an ANR[11] on strongly correlated electrons (ECCE, 2006).

Contents

[2] A dimer is spin singlet state formed by two neighboring spins on the lattice.
[3] from the LPTMS of Orsay University and in delegation at the SPhT
[4] from fall 2005 to summer 2006, supported by the Humboldt foundation and H. Saleurs's international reintegration grant (European Commission - Marie Curie Actions).
[5] From fall 2005 to summer 2006, supported by a "Pascal Chair" of the region Ile-de-France.
[6] From fall 2006, supported by a Marie Curie grant.
[7] They all three finished their post-docs at the SPhT in Fall 2005.
[8] Fall 2003 - June 2006. Advisers: C. Pépin and P. Coleman (Rutgers University).
[9] From Sept. 2006. Adviser: C. Pépin.
[10] Fall 2005 - Fall 2006, adviser: G. Misguich. He spent one year at the SPhT (and Univ. Paris-6) supported by the "Collège Doctoral Franco-Japonais".
[11] Agence nationale de la recherche

J.1 Itinerant electrons and localized spins *(I. Paul, C. Pépin, J. Rech)*

J.1.1 Quantum critical end point of the Kondo volume collapse *(I. Paul, C. Pépin)*

The Kondo volume collapse describes valence transitions in f-electron metals, and is characterized by a line of first order transitions in the pressure-temperature phase plane terminated at critical end points. It has been extensively studied in the eighties in the context of Ce and Yb based intermetallics and led usually to first order transitions. For example, in the transition between the α and γ phases of Ce, or the related behavior in YbIn Cu_4, critical fluctuations are irrelevant. However, this line of first order phase transitions in the temperature-pressure phase plane is terminated by critical end points on the high, and sometimes low temperature. These critical end points are tunable. In the case where the lower end point is tuned to $T = 0$, a quantum critical end point emerges. We analyze in [t06/161] the quantum critical end point, when the lower end point is tuned to $T = 0$, and determine the specific heat, thermal expansion, and compressibility. We find that it sits in the same universality class as the quantum critical Ising ferromagnet. We find that the inclusion of quantum critical fluctuations leads to a novel bifurcation of the first order phase line. Finally, we show that critical strain fluctuations can cause both, superconductivity and non-Fermi liquid behavior near the critical point.

J.1.2 Quantum critical behavior in itinerant electron systems: Eliashberg theory and instability of a ferromagnetic quantum critical point *(J. Rech, C. Pépin)*

Hertz-Millis-Moriya (HMM) is knows as the standard theory of quantum critical points in itinerant electron systems. When fermions interact with a critical mode at zero temperature, the scattering through this mode shorten their lifetime so that, at part of the Fermi surface the electron lifetime becomes infinitely short. The standard Landau Fermi liquid theory of metals is violated, leading to anomalous exponents in the temperature dependence of the thermodynamic and transport properties. The HMM theory consists in integrating the fermions out of the Fermi surface and studying the resulting effective bosonic theory. The step of integrating the fermions out remains however very questionable. If the system is decomposed into its charge and spin channels, a singularity is obtained in the spin channel; thus, although the integration of the fermions remains probably valid in the charge channel (for QCp of the Ising type) it is violated when an SU(2) symmetry is present in the system. In this study [t06/162], we review the Eliashberg theory for itinerant ferromagnetic QCPs. We perform the first diagrammatic power counting of the divergences in frequency and show that the role of the electron's curvature is crucial in order to be able to re-sum the diagrams. We show that the singularities around the QCP are associated with anomalies in the static limit of the vertex. We recover the $-|q|$ singularity of the static spin susceptibility in the Fermi liquid regime while the singularity goes to $-|q|^{3/2}$ in the quantum critical regime.

J.1.3 Kondo breakdown and hybridization fluctuations in the Kondo-Heisenberg lattice *(I. Paul, C. Pépin)*

The breakdown of the Landau theory of the Fermi liquids, experimentally observed in heavy fermion compounds still remains a mystery for the theoretician. The resistivity is linear or quasi-linear for many compounds around zero temperature phase transitions, the specific heat coefficient doesn't saturate, as it should do in a well behaved Fermi liquid. For a very long time, We have looked for a QCP of magnetic nature, to explain the unusual properties of these materials, but none of the magnetic QCP for itinerant electrons provided a strong enough violation of the Fermi liquid theory to explain the experiments. New experimental observations and band structure studies showed recently that the compound Yb Rh_2 Si_2 doped with a small amount of Ge had more valence fluctuation that one would expect for a true heavy Fermi compound. This incited us to look for a new type of QCP, not directly associated to magnetic transitions. We found one [t06/164], in the Kondo-Heisenberg lattice, for which the effective hybridization between the two type of electrons, the localized spinons and the conduction electron band goes to zero at zero temperature. At this fixed point, the Fermi surface volume changes abruptly while the spinon Fermi surface gets completely "hot". Moreover, this QCP has a multiscale character, with above a small energy scale E^*, a marginal Fermi liquid regime, including a resistivity in T LogT in 3 dimensions, and logarithmically divergent specific heat variation. This very interesting QCP, that we called the "Kondo breakdown" is the first effective field theory which leads to a regime quasi-linear in temperature for the resistivity in 3D.

In addition we found that a phase with an hybridization modulated in space, analogous to the Fulde Ferell Larkin Ovshinikov superconductor can occur in this system. It's again the first evidence for such a phase in heavy fermion compounds.

J.1.4 Kondo breakdown as a selective Mott transition in the Anderson lattice *(C. Pépin)*

In [t06/168], we pursue the study of the Kondo breakdown QCP, this time in the context of the experimentally more relevant model of the Anderson lattice, with a small dispersion of the f-fermions. Our main finding is that, in this model the Kondo breakdown QCP coincides with a selective Mott transition of the f-impurities. It's the first evidence for a Mott transition in the Anderson lattice, and interestingly, that opens the road to search for the presence of the Kondo breakdown QCP using more evolved mean field treatments like Dynamical Mean Field Theories. In the Anderson lattice, the Kondo breakdown, is at the same time a Mott transition and a vanishing of the effective hybridization between the two bands; as such it can be considered as a "non Ginzburg Landau" QCP relying two apparently un-related phases at the QCP.

J.2 Cuprate oxides and high-temperature superconductivity

See also Sec. J.3.2

J.2.1 Two energy scales in the superconducting state of underdoped cuprates *(G. Kotliar)*

The superconducting temperature T_c of hole-doped high-temperature superconductors has a dome-like shape as a function of hole concentration, with a maximum T_c at "optimal" doping. On the underdoped side, the superconducting state is often described in terms of one energy scale, associated with the maximum of the d-wave gap (at the antinodes), which increases as the doping decreases. In [t07/087], electronic Raman scattering experiments are reported that show a second energy scale in the gap function: the slope of the gap at the nodes, which decreases with decreasing doping.

J.2.2 Magnetism of lightly dopped $La_{2-x}Sr_xCuO_4$ *(G. Misguich)*

In [t06/019] we studied how the magnetic properties of La_2CuO_4, a Mott insulator, is affected by the introduction of a small concentration x of Sr (at higher concentrations, $La_{2-x}Sr_xCuO_4$ becomes a high-temperature superconductor). For $x < 0.02$, the system remains insulating and each Sr atom (randomly distributed over the sample) traps one hole in its vicinity, which in turn induces a spiral-like distortion of the antiferromagnetic spin background. The plane (in spin space) of the spiral is however not fixed and leads to one free angle per impurity. At small impurity concentration, these spirals interact and we mapped the problem onto a disordered classical $O(2)$ "spin" model with dipole-dipole like interactions. By numerical Monte-Carlo simulations taking into account realistic parameters (Dzaylonshinkii-Moriya anisotropies, etc.) we obtained a good quantitative agreement with various experiments, including the elastic and incommensurate neutron scattering peaks [Matsuda *et al.* (2002)].

J.3 Dynamical Mean-Field Theory (DMFT)

J.3.1 DMFT and electronic structure computations *(O. Parcollet and G. Kotliar)*

A first direction of research is the mixing of DMFT with realistic electronic structure computation methods. A review was published on this topic in 2006 [t05/199] in collaboration with G. Kotliar (completed during his stay at SPhT and at Polytechnique on a "Pascal Chair" of the region Ile-de-France in 2005-2006.) Moreover, an LDA[12]+DMFT calculation of the cobaltates was presented in [t07/082] to address in particular the debated issue of the existence of Fermi surface pockets, predicted by LDA but not observed in ARPES[13] experiments.

J.3.2 Cluster DMFT *(O. Parcollet)*

The second direction is the cluster extensions of DMFT. Their study was continued, and in particular their application to high-Tc superconductors, beyond the normal state (Cf previous report), to the superconducting state [t07/084]. In the underdoped regime, the formalism leads to a natural decomposition of the photoemission energy-gap into two components. The first one, stemming from the anomalous self-energy, dominates near the nodes and decreases with decreasing doping. The second one has an additional contribution from the normal self-energy inherited from the normal-state pseudo-gap. It is dominant near the antinodes and increases as the Mott insulating phase is approached. This calculation is in good agreement with the recent experimental results (see next section).

Finally, the development of effective low-energy methods is also of crucial importance. In [t07/085], a rotationally-invariant generalization of slave-boson formalism to multiorbital models was presented. When combined with Cluster-DMFT, this method can address some effects of spatial correlations, such as the generation of the superexchange and the momentum dependence of the quasiparticle weight.

J.4 Ultra-cold atomic gases

J.4.1 Quantum melting of a crystal of dipolar ultra-cold bosons *(O. Parcollet)*

Due to recent spectacular experimental progresses, ultra-cold atom gas can now be studied in strongly correlated regime. In collaboration with X. Waintal (CEA/SPEC) and C. Mora (ENS Paris) [t07/086], we studied the first order phase transition between a solid and a superfluid in a 2D boson gas with long range dipolar interaction between the bosons. We characterize the window of experimentally accessible parameters in the context of ultracold bosons and show that observing the quantum melting should be within grasp once one is able to form cold heteronuclear molecules.

J.5 Quantum antiferromagnets and spin liquids

J.5.1 Kagome-lattice antiferromagnet $ZnCu_3(OH)_6Cl_2$ *(G. Misguich)*

After many years of theoretical investigations, the spin-$\frac{1}{2}$ Heisenberg (antiferromagnetic) model on the kagome lattice remains poorly understood. The recent synthesis of $ZnCu_3(OH)_6Cl_2$ [Shores *et al.*, (2005)], a magnetic insulator where the active ions (Cu^{2+}) form perfect kagome lattices, gave a new impetus to the field. In particular, the first experimental investigations point to a "quantum spin liquid" behavior. In [t07/083] we compared the magnetic susceptibility data to high-temperature series expansion and finite-size exact diagonalizations. The susceptibility turns out to be well fitted by that of the Heisenberg model (interaction $\sim$ 190 K) and a few percent of magnetic impurities. We also analyzed the specific heat of this compound and showed evidence for some entropy deficit at low temperature ($\sim$ 10 K), an indication that the Heisenberg model alone is not enough to describe the system at very low energy.

J.5.2 Conventional orders, topological orders and entanglement *(S. Furukawa and G. Misguich)*

Identifying spontaneously broken symmetries (SBS) in strongly interacting systems is a central problem in condensed-matter theory, and numerical methods can often be used for this purpose. The conventional approach is to look at various correlation functions to detect long-range orders. When using numerical exact diagonalizations (on finite-size systems), one can also detect SBS by looking at the *quantum numbers of the low-energy eigenstates of the Hamiltonian*. In [t06/199] we reviewed this method in the context of quantum spin systems and presented some new applications to the spin-$\frac{1}{2}$ Heisenberg model on the kagome lattice and on a variant of the kagome lattice (so-called "expanded kagome").

In [t05/249] and [t06/018] we introduced a third method to look for SBS. It has the advantage of providing a systematic (numerical) procedure to construct the order parameters (from the low-energy wave functions and associated reduced density matrices). Some

[12] Local Density Approximation

[13] Angular Resolved Photoemission Spectroscopy

quantum systems are "topologically ordered" (systems with fractional excitations). In such cases, the method mentioned above allows to prove the absence of any *local* order parameter. In [t06/198], this was done for the resonating valence-bond liquid phase of the triangular lattice quantum dimer model. In [t06/200], we pushed further the characterization of this phase through the use of reduced density matrices and performed one of the very first numerical calculation of the "topological entanglement entropy" [Kitaev and Preskill (2006); Levin and X.-G. Wen (2006)].

J.6 One-dimensional systems, quantum impurities and nanosystems

J.6.1 Emission and absorption noise in the fractional quantum Hall effect *(C. Bena)*

In spite of intense theoretical and experimental exploration over the past years, many features of one-dimensional strongly interacting systems have not yet been clarified. For example, charge fractionalization, which has been observed in fractional quantum Hall effect(FQHE) edge states has not been observed directly in carbon nanotubes. Shot noise is a powerful tool to extract information about the charge and statistics of the elementary excitations of a system.

In [t07/077], we (collaboration with I. Safi, LPS Orsay) computed the high-frequency finite-temperature non-symmetrized noise in a FQHE sample and compared the results to the symmetrized noise. We focused on the auto-correlations of chiral outgoing branches, and the cross-correlations between outgoing branches with opposite chiralities. We found that these are entirely even in frequency. The most striking feature observed is a singularity at the Josephson frequency (JF) (proportional to the applied voltage, and to the filling factor). This feature appears as a cusp in a noninteracting system, while for an interacting system the noise exhibits an inverse power-law divergence at the JF, and decays to zero for frequencies larger than the JF. We also analyzed the dependence on frequency of the non-symmetrized noise in the total current, and found that the emission noise is roughly equal to the noise in the outgoing chiral branches, however the absorption noise exhibits a positive peak slightly below the JF, and a negative dip slightly above the JF.

J.6.2 Full counting statistics of the current/voltage distribution in nanosystems *(H. Saleur and A. Komnik)*

Recent years have seen tremendous experimental progress towards the determination of full counting statistics of the current or voltage distribution in a variety of nanosystems, raising deep questions about the influence of the environment and of the interactions in particular on the third and higher cumulants. Such properties of transport out of equilibrium escape traditional methods of approach in low dimensional systems, and H. Saleur in our group has, for a long while, been interested in the development of new non perturbative methods to tackle them, based on ideas from integrable and conformal quantum field theory. In the period considered, he succeeded, in a collaboration with A. Komnik [t06/085] in determining the second and third cumulants for the problem of tunneling between edges in the fractional quantum Hall effect, obtaining the first such exact result in the presence of interactions, finite temperature and driving voltage. One of the striking features of the result is that the fractional charge appears much easier to measure from the third than the second cumulant - the "small backscattering limit" extending to much lower temperatures and or higher gate voltages.

J.6.3 Exact solution of an interacting resonant level model *(H. Saleur, E. Boulat)*

In the same period, steady progress was made in the exact solution of the new interacting resonant level model (IRLM), which is an ideal benchmark to study some of the theoretical approaches developed by N. Andrei and his collaborators ("open Bethe ansatz"). In a collaboration with E. Boulat [t07/061] we developed a systematic understanding of the UV and IR fixed points based on rotations of the usual conformal boundary conditions. We then used this, together with our knowledge of the scattering matrix of the anisotropic Kondo problem, to develop a meaningful method of perturbation by irrelevant operators around the IR fixed point, and determine in this way the exact low temperature expansion of the conductance up to the sixth order. This expansion exhibits clearly an exciting and unexpected phenomenon of Coulomb "unblocking".

J.6.4 Non-equilibrium transport properties of Anderson impurity models *(A. Komnik)*

In a series of contributions we have studied the non-equilibrium transport properties of the Anderson impurity, which is the most generic set-up for modelling charge/spin transport phenomena in nanostructures. In the focal point of research was the so-called full counting statistics (FCS), representing the probability to transfer a certain amount of charge during some fixed (very long) time interval. Along with the perturbative treatments in the weak interaction limit [t05/255] and in the deep Kondo regime [t06/242] we have also succeeded even in calculation of the full spin-resolved FCS non-perturbatively in a certain parameter regime (Toulouse point) [t06/240] using an exact analytic solution of the problem. This result gives one a unique opportunity to study the mutual statistics of charge as well as of spin transport across such constrictions. A generalization of these approaches to multi-terminal geometries turned out to reveal a number of very interesting effects, the most notable of which are the so-called Hanbury Brown-Twiss correlations [t06/243]. These can help to study the nature of current carrying excitations in future experiments. The most fundamental finding of our analysis is the fact that the charge transport takes place not only by single electrons but by transmission of correlated electron pairs as well. This interesting phenomenon leads to sophisticated universal and parameter-free ratios of FCS probability function cumulants to the current scattered back from the impurity. We are convinced that these quantities will become experimentally accessible in the nearest future.

J.6.5 Large-N limits for the Anderson model *(O. Parcollet, J. Rech)*

In [t06/110], a conserving many-body treatment of a family of fully screened infinite U Anderson models is presented that has a smooth cross-over into the Fermi liquid state, with a finite scattering phase shift at zero temperature and a Wilson ratio greater than one. This work, which has potential applications to non-equilibrium quantum dots and quantum critical mixed valence systems, is a continuation of the work on large-N limit completed during J. Rech's Ph.D. (Cf previous report). Moreover, in [t05/205], we generalized the Schwinger boson large-N approach to the fully screened Kondo model in order to include antiferromagnetic interactions between two impurities. This approach describes the "Varma Jones" quantum phase transition between a valence bond state and a heavy Fermi liquid.

J.6.6 Spin dynamics of Nanomagnet *(O. Parcollet)*

In [t05/208], a detailed paper was published, complementing our first PRL [t04/177] (Cf. previous report) on the influence of the Coulomb blockade on the spin dynamic of a nanomagnet of large spin connected to magnetic leads via tunnel barriers and on the generalization of the Landau-Lifshitz-Gilbert equation for this system.

J.7 Classical dimer models

J.7.1 Unconventional transition in a 3D classical dimer model *(F. Alet, G. Misguich, V. Pasquier, J. Jacobsen)*

We studied a model of statistical mechanics where the configurations are hard-core dimer coverings of the 3D cubic lattice [t06/197]. Each dimer occupies two sites in such a way that each site is covered by one and only one dimer. In addition to this hard-core constraint, an energy equal to -1 times the number of square plaquettes with two parallel dimers is associated to each configuration. This model is the three-dimensional generalization of a two-dimensional model introduced and studied by us [t06/160].

At low temperature the plaquette interaction favors the six-fold degenerate regular (crystalline) arrangements of dimers. At high temperature the dimers are no longer ordered but their correlations decay algebraically with distance (with the same $\sim r^{-3}$ dependence as the interaction energy of two classical magnetic dipoles). This phase has been dubbed "Coulomb phase". We showed that, using appropriate *dual* variables, the Coulomb phase maps onto the ordered phase of an $O(2)$ spin model, which gapless Goldstone modes are related to the algebraic decay of dimer-dimer correlations. In fact, the most intriguing properties of this dimer model concern the phase transition between the low temperature crystal and the Coulomb phase. Our Monte-Carlo simulations (directed-loop (or "worm") algorithm performing efficient non-local updates). indicate that the transition is *continuous* (2nd order) and we estimated the critical exponents. This result is somewhat in contradiction with the usual Landau-Ginsburg approach to critical phenomena based on the concept of symmetry breaking and fluctuations of the associated order parameter. In the present case, this approach would generically predict a *first order* transition. From this point of view, the dimer model studied here may be related to recent theories for "non Landau-Ginsburg-Wilson" quantum phase transitions in 2D quantum antiferromagnets (Senthil *at al.*, Science 2004). The main question (still open at present) is to understand what are the fields needed (order parameter of the crystal phase? Vector potential of the Coulomb phase? something else?) for a description of the long-distance properties at the critical point, and what is the associated field theory.

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CHAPTER K

Biological Systems and Soft Condensed Matter

The Biological Systems and Soft Condensed Matter group comprises two permanent physicists (T. Garel and H. Orland), one post-doc (G. Vernizzi, presently at Northwestern University, USA), one graduate student (M. Bon), and has received important contributions from four other members of the lab (F. David, B. Duplantier, J.L. Jacobsen and C. Monthus). In addition, we have had the opportunity to host an experimental biophysicist expert of DNA, Jean-Louis Sikorav, who is spending one year in our lab.

There has been a renewed interest for the statistical physics of biopolymers at the SPhT. Problems such as the phase diagram of random RNA with or without tension, or the enumeration of random RNA structures as a function of their genii, have been investigated. The increasing importance of RNA as a key player in the regulation of the biological networks of the cell (it is now believed that more than 80% of the junk DNA is translated into non-coding RNA) has encouraged us to pursue our classification of real RNA folds in terms of their topological genus. The ultimate goal of this methodology, which is still in progress, is to eventually predict the secondary structures with pseudoknots of real RNA sequences.

Proteins perform many of the important tasks in a cell (enzymes, ion transport, motors, etc.), and may be associated with many diseases (viruses, prions, Alzheimer disease, Parkinson, etc.). A better understanding of the kinetics of folding may allow to understand how to improve or inhibit the folding of specific proteins, an important direction of research in the design of drugs. A collaboration with an Italian group, which has access to powerful computational facilities, has led to the elaboration of a general theory of protein folding, in terms of instantons (as in field-theories). This method allows to calculate the dominant paths between denatured states and the native state of a protein. In addition, the study of long runs of molecular dynamics around the native state has allowed to show convincingly the self-similar nature of the free energy landscape of proteins.

Molecular motors are known for being the most effective way to translate chemical energy into mechanical energy. In some cases, the mechanical yield may be close to 1. In these far from equilibrium systems, Einstein and Onsager relations are violated, and the maximum efficiency of the motor is obtained for a maximum violation of Onsager symmetry relations.

All the above studied biopolymers are strongly charged and are immersed in ionic solutions in the cell. We have pursued our research on electrolytes and polyelectrolytes. In particular, hydration effects are well know to be of crucial importance in biology, and we have thus devised a new method to take into account the dipolar moments of water beyond the linear response regime (non linear susceptibilities). The effect of ions and solvent on the aggregation and adsorption of single stranded DNA at a water-air interface has also been studied experimentally.

Sec. K.1 presents a comprehensive survey of Brownian motion, written on the occasion of the centenary of Einstein's 1905 articles; it also presents the english translation of an unpublished lecture given by Einstein in 1910, the manuscript of which was recently discovered.

Sec. K.2 presents some statistical physics models applied to biological systems. The possible existence of a glass transition in RNA has been studied using both field theoretical and sophisticated numerical methods. The number of pseudoknotted self-avoiding homopolymers as a function of their genus has been studied numerically, in order to compare it to biological sequences and evaluate the effect of sequence design. Finally, a simple tight binding model for an RNA or single stranded DNA has been used to show that these semi-conducting biopolymers become more rigid when an electric current flows through them.

In Sec. K.3, the topological classification of RNA pseudo-knots is applied to all known RNA structures. These structures are extracted from the PseudoBase (an RNA pseudoknot database) or from the PDB (a biopolymer database). We find that most RNA with sequences shorter than 200 bases have a genus of 1 or 2. We also show that RNA folds of large rybozomes (around 3000 bases) can be decomposed into primitive pseudoknots, with genii never larger than 8.

Sec. K.4 addresses questions related to protein dynamics. The problem of protein folding can be formulated, in the framework of Langevin dynamics, as a path integral with fixed boundaries (denatured state and native state). The stationary phase method allows to find the paths which dominantly contribute to the transition probability. These paths can be calculated numerically and compared to molecular dynamics simulations.

Sec. K.5 is devoted to the study of Coulombic effects in soft and biological matter. We first present an analytic study of the two-dimensional Manning condensation, and show that it leads to an infinite number of unbinding transitions, as was observed numerically. We then present a study of polyelectrolyte brushes grafted to charged surfaces in presence of counterions. These brushes are studied using the Self-Consistent-Mean-Field theory, and the results match very well numerical methods. In the last articles, the effect of the dipoles of water is studied, using a generalization of the Poisson-Boltzmann method. This generalized equation is applied to a model system of water and ions enclosed between two oppositely charged plates, so as to maximize the non-linear effects in the dielectric constant. The same method is applied to describe a folded protein immersed in water and ions. This allows to calculate the hydration layer (water concentration) near the surface, and the local hydrophobicity of the protein.

Contents

K.1 Brownian motion *(B. Duplantier)*

[t05/225] provides a extended survey of Brownian motion in physics and mathematics. It begins with the history of Brownian motion, with detailed emphasis on the fundamental contributions of Brown, Sutherland, Einstein, Smoluchowski, Langevin and Perrin to its experimental observation, its theory and its experimental verification. Some emphasis is put on the 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 a (spherical) suspended Brownian particle. The various subsequent derivations of increasing generality given by Einstein and Langevin are presented in detail. The relevance of Brownian motion to biophysics is illustrated by the theory of 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 importance of Brownian motion in mathematics, starting from the work by Bachelier and Wiener, is illustrated. 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 progress in the conformal random geometry of the planar Brownian curve and of the conformal invariance, quantum gravity and multifractal concepts associated with it. A short version (in French) appeared in the book "Einstein et les horizons de la physique", published for a conference at the National French Library [**?**].

[t05/226] is the first translation from German to English of a previously unpublished lecture by A. Einstein (*"On Boltzmann's Principle and Some Immediate Consequences Thereof"*), delivered in 1910 at a meeting of the Zürich Physical Society, and recently discovered in Zürich. It presents in a vivid way Einstein's point of view on Statistical Mechanics and Causality 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 an original demonstration of the well-known physical formula for the diffusion coefficient D of a Brownian 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. Comments have been added to place this work in the context of the emergence of quantum physics at that time. An extended comment has also been added to generalize Einstein's approach to arbitrary moments and arbitrary potentials.

K.2 Statistical Physics of Biopolymers

K.2.1 Random RNA *(F. David)*

I am interested in the problem of the secondary structure of long RNA strands (m-RNA for instance) and the role of base disorder on the secondary structure. Unlike protein folding, which exhibits a strong interdependence between secondary and tertiary structure, RNA folding may be studied at the level of secondary structures due to a clear separation of energy scales. Since the pioneering work of Bundschuh and Hwa, several authors have studied the statistical physics of RNA secondary structures for random sequences, in particular at SPhT. It is commonly believed that these systems undergo a freezing transition upon lowering the temperature.

The nature of the freezing transition and the properties of the low temperature/strong disorder glassy phase are still very poorly understood, even at the level of statics. In particular topological constraints (planarity) induce frustration and compete with long range forces. This is therefore a difficult and fascinating problem at the interface beween the physics (and the mathematics) of disordered systems, and quantitative biology.

Field Theory for Random RNA: In 2006 Lässig and Wiese (LW) pioneered a field theoretical approach for the transition to the glass phase. They showed their model to be renormalizable at first order in perturbation theory

In [t06/069] together with K.J. Wiese (LPTENS-Paris) I formulate a systematic and consistent field theory for Random RNA folding, based on formulation of the model in terms of random walks, random-matrix-like auxiliary fields to implement topological constraints, and on the use of a multilocal operator product expansion to analyse UV and IR divergences. We show that this field theory is renormalizable to all orders in perturbation theory. This establishes the consistency of the first order calculation of Lässig-Wiese. Moreover renormalizability allows us to work in the new (and simpler) scheme of open polymers, and to compute for the first time the critical exponents at 2-loop order. It also allows to prove some exact scaling identities. A detailed publication with the details of the proof and of the 2 loop calculations is in preparation.

Random RNA under tension: In [t07/012], together with C. Hagendorf (SPhT and LPTENS-Paris) and K.J. Wiese (LPTENS-Paris), we study RNA under tension and the force-induced denaturation transition. This problem is also interesting, since recently extension-force curves have been measured, by attaching beads to the RNA-molecule and pulling on it, using an optical trap; recent numerical simulations are also available, but no analytical approach to this problem have been done. We construct a renormalizable field theory for RNA under tension, and find a second-order phase transition at a critical applied force $f = f_c$. We compute at one and two loops the effect of the disorder.

K.2.2 RNA Freezing transition *(T. Garel and C. Monthus)*

To characterize the pairing specificity of RNA secondary structures as a function of temperature, we analyse in [t06/158] the statistics of the pairing weights as follows : for each base (i) of the sequence of length N, we consider the $(N-1)$ pairing weights $w_i(j)$ with the other bases $(j \neq i)$ of the sequence. We numerically compute the probability distributions $P_1(w)$ of the maximal weight, the probability distribution $\Pi(Y_2)$ of the parameter $Y_2(i) = \sum_j w_i^2(j)$, as well as the average values of the moments $Y_k(i) = \sum_j w_i^k(j)$. We find that there are two important temperatures $T_c < T_{gap}$. For $T < T_c$, there exists frozen pairs of all sizes, whereas for $T_c < T < T_{gap}$, there exists frozen pairs, but only up to some characteristic length diverging as $\xi(T) \sim 1/(T_c - T)^\nu$ with $\nu \simeq 2$. The similarities and differences with the weight statistics in Lévy sums and in Derrida's Random Energy Model are discussed.

K.2.3 Topology of pseudoknotted homopolymers *(Vernizzi G., Ribeca P., Orland H., Zee A.)*

In this article [t05/127], we consider the folding of a self-avoiding homopolymer on a lattice, with saturating hydrogen bond interactions. Our goal is to numerically evaluate the statistical distribution of the topological genus of pseudoknotted configurations. The genus has been recently proposed for classifying pseudoknots (and their topological complexity) in the context of RNA folding. We compare our results on the distribution of the genus of pseudoknots, with the theoretical predictions of an existing combinatorial model for an infinitely flexible and stretchable homopolymer. We thus obtain that steric and geometric constraints considerably limit the topological complexity of pseudoknotted configurations, as it occurs for instance in real RNA molecules. We also analyze the scaling properties at large homopolymer length, and the genus distributions above and below the critical temperature between the swollen phase and the compact-globule phase, both in two and three dimensions.

K.2.4 Are better conducting molecules more rigid? *(Eom Y.-H., Jeong H., Yi J., Orland H.)*

In this paper [t06/088], the variation of the stiffness of various materials is studied from the point of view of the electronic band characteristics. As far as the electronically generated stiffness κ_e is concerned, the relevant factors are the orbital overlap t, the gap width u between the valence band and the conduction band, and the electron filling fraction γ. A perturbative calculation leads to the approximate expression $\kappa_e \sim t^2\gamma/\sqrt{u^2+t^2}$. This shows that materials with a large overlap and narrow band gap should be stiffer. The electro-stiffness also depends on the electron filling-fraction. We find that $\kappa_e(\gamma) \leq \kappa_e(1/2)$. These kinds of behavior are confirmed by numerical calculations. In addition, we study the length variation of flexible molecules under a voltage bias. The nonlinear variation of the bending rigidity is shown to give rise to a length contraction or dilation, depending on the voltage bias.

K.2.5 Secondary structures in proteins *(J. L. Jacobsen)*

In [t06/196], we study the formation of secondary structures in proteins, using a simplified two-dimensional model. For this purpose, we use an efficient algorithm to sample hamiltonian paths. We find in particular that the constraint that conformations are compact significantly amplifies the presence of secondary structures.

K.2.6 Conformational entropy of muscle proteins *(J. L. Jacobsen)*

In [t07/035], we study a model of a self-avoiding polymer confined within two walls, in the presence of an external force. Using techniques of exact enumeration, we compute the entropy of the model for a length up to 55 monomers. The force-extension phase diagram has striking similarities with observations made on muscle proteins.

K.3 RNA folding

K.3.1 Large-N Random Matrices for RNA Folding *(Vernizzi G., Orland H.)*

In this paper [t05/129], we review a recent formulation of the RNA folding problem as an $N \times N$ matrix field theory. It is based on a systematic classification of the terms in the partition function according to their topological character. In particular large-N terms yield the secondary structures, whereas pseudoknots are obtained by calculating the $1/N^2$ corrections. We also describe a Monte Carlo algorithm for the prediction of RNA secondary structures with pseudoknots, based on this topological approach.

K.3.2 Topological classification of RNA structures *(Bon M., Vernizzi G., Orland H., Zee A.)*

We present here in [t06/090] a novel topological classification of RNA secondary structures with pseudoknots. It is based on the topological genus of the circular diagram associated to the RNA base-pair structure. The genus is a positive integer number, whose value quantifies the topological complexity of the folded RNA structure. In such a representation, planar diagrams correspond to pure RNA secondary structures and have zero genus, whereas non planar diagrams correspond to pseudoknotted structures and have higher genus (see Fig. K.3.2). We analyze real RNA structures from the databases wwPDB and Pseudobase, and classify them according to their topological genus. We compare the results of our statistical survey with existing theoretical and numerical models. We also discuss possible applications of this classification and show how it can be used for identifying new RNA structural motifs.

K.4 Protein dynamics

K.4.1 Dominant Pathways in Protein Folding *(Faccioli P., Sega M., Pederiva F., Orland H.)*

In [t05/235], we present a method to investigate the kinetics of protein folding on a long time-scale and the dynamics underlying the formation of secondary and tertiary structures during the entire reaction. The approach is based on the formal analogy between thermal and quantum diffusion: by writing the solution of the Fokker-Planck equation for the time-evolution of a protein in a viscous heat-bath in terms of a path integral, we derive a Hamilton-Jacobi variational principle from which we are able to compute the most probable pathway of folding. The method is applied to the folding of the Villin Headpiece Subdomain, in the framework of a Go-model. We have found that, in this model, the transition occurs through an initial collapse phase driven by the starting coil configuration and a later rearrangement phase in which secondary structures are formed and where all computed paths display strong similarities. This method is completely general, does not require the prior knowledge of any reaction coordinate and represents an efficient tool to perform ab-initio simulations of the entire folding process with available computers.

K.4.2 Quantitative Protein Dynamics from Dominant Folding Pathways *(Sega M., Faccioli P., Pederiva F., Garberoglio G., Orland H.)*

In [t07/108], we develop a theoretical approach to the protein folding problem based on out-of-equilibrium stochastic dynamics. Within this framework, the computational difficulties related to the existence of large

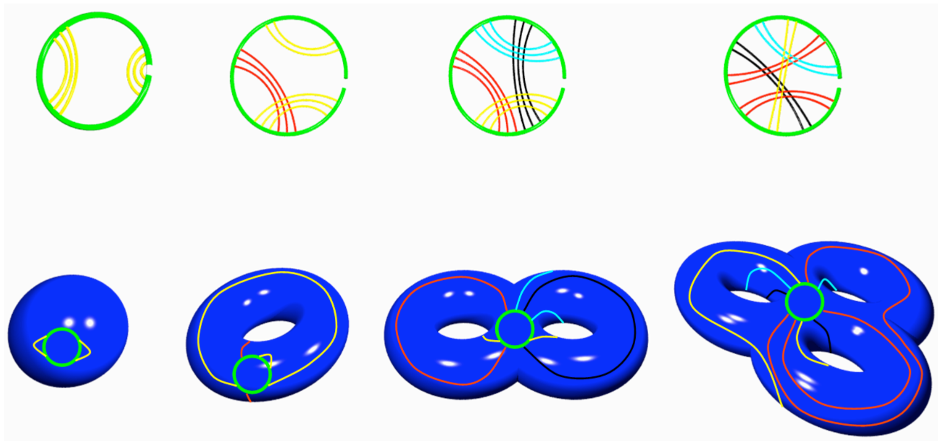

Figure K.1: Any RNA circular diagram can be drawn on a closed oriented surface with a suitable number of "handles" (the genus $g = 0$ is a sphere, $g = 1$ is a torus, $g = 2$ is a double torus and so forth).

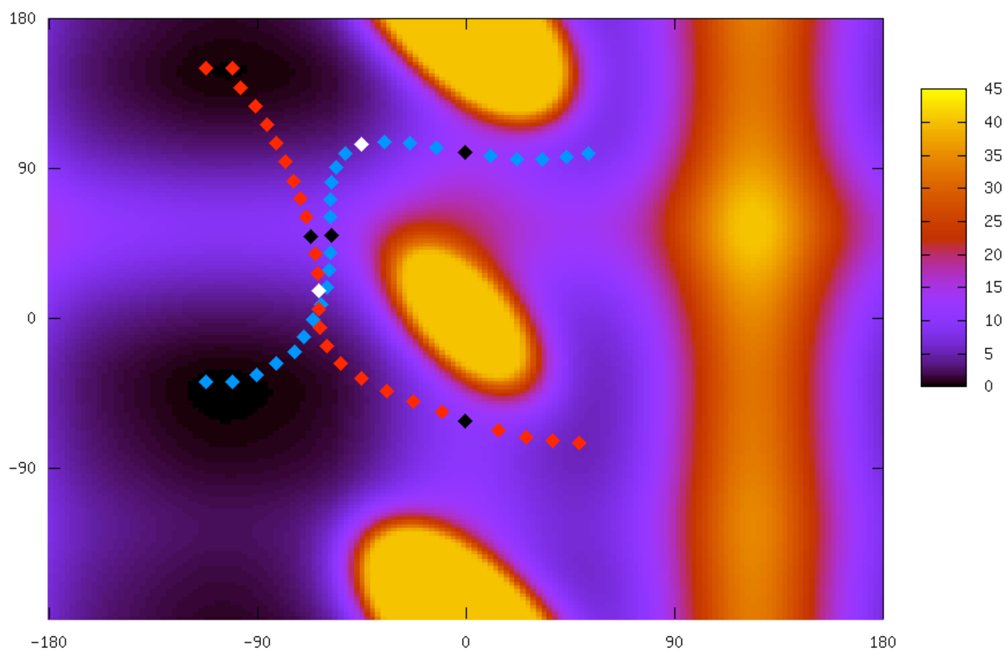

Figure K.2: Dominant folding paths between a metastable state (blue squares) and the native state (red squares) of alanine-dipeptide. In the background, the free energy profile for the ϕ and ψ dihedrals is shown (in units of kJ/mol). Black squares identify the minimum residence time conformations, and the white squares the transition states defined by commitment.

time scale gaps in the protein folding problem are removed and simulating the entire reaction in atomistic details using existing computers becomes feasible. In addition, this formalism provides a natural framework to investigate the relationships between thermodynamical and kinetic aspects of the folding. For example, it is possible to show that, in order to have a large probability to remain unchanged under Langevin diffusion, the native state has to be characterized by a small conformational entropy. We discuss how to determine the most probable folding pathway (see Fig. K.4.2), to identify configurations representative of the transition state and to compute the most probable transition time. We perform an illustrative application of these ideas, studying the conformational evolution of alanine di-peptide, within an all-atom model based on the empiric GROMOS96 force field.

K.4.3 Anharmonicity and Self-Similarity of the Free Energy Landscape of Protein G *(Pontiggia F., Colombo G., Micheletti C., Orland H.)*

The near-native free energy landscape of protein G is obtained from $0.4\mu s$-long atomistic molecular dynamics simulations in explicit solvent. A theoretical and computational framework is used in [t06/212] to assess the time-dependence of salient thermodynamical features. While the quasi-harmonic character of the free energy is found to degrade in a few ns, the slow modes display a very mild dependence on the trajectory duration. This property originates from a striking self-similarity of the free energy landscape embodied by the consistency of the principal directions of the local minima, where the system dwells for several ns, and of the virtual jumps connecting them.

K.5 Coulombic effects in soft and biological systems

K.5.1 Manning condensation in two dimensions *(Burak Y., Orland H.)*

In [t05/155], we consider a macroion confined to a cylindrical cell and neutralized by oppositely charged counterions. Exact results are obtained for the two-dimensional version of this problem, in which ion-ion and ion-macroion interactions are logarithmic. In particular, the threshold for counterion condensation is found to be the same as predicted by mean-field theory. With further increase of the macroion charge, a series of single-ion condensation transitions takes place. Our analytical results are expected to be exact in the vicinity of these transitions and are in very good agreement with recent Monte-Carlo simulation data.

K.5.2 Self-Consistent Field study of Polyelectrolyte Brushes *(Seki H., Suzuki Y., Orland H.)*

In [t07/109], we formulate a self-consistent field theory for polyelectrolyte brushes in the presence of counterions. We numerically solve the self-consistent field equations for weak coupling cases and study the monomer density profile, the distribution of counterions, and the total charge distribution. We study the scaling relations for the brush height and compare them to the prediction of other theories. We find a weak dependence of the brush height on the grafting density. We fit the counterion distribution outside the brush by the Gouy-Chapman solution for a virtual charged wall. We calculate the amount of counterions outside the brush and find that it saturates as the charge of the polyelectrolytes increases in the weak coupling case.

K.5.3 Dipolar Poisson-Boltzmann Equation: Ions and Dipoles Close to Charged Surfaces *(Abrashkin A., Andelman D., Orland H.)*

In [t07/111], we present an extension to the Poisson-Boltzmann model where the dipolar features of solvent molecules are taken explicitly into account. The formulation is derived at mean-field level and can be extended to any order in a systematic expansion. It is applied to a two-plate system with oppositely charged surfaces. The ion distribution and profiles in the dipolar order parameter are calculated and can result in a large correction to the inter-plate pressure.

K.5.4 PDB_Hydro: incorporating dipolar solvents with variable density in the Poisson-Boltzmann treatment of macromolecule electrostatics *(Azuara C., Lindahl E., Koehl P., Orland H., Delarue M.)*

In [t06/091], we describe a new way to calculate the electrostatic properties of macromolecules that goes beyond the classical Poisson-Boltzmann treatment. The solvent region is no longer modeled as an homogeneous dielectric media but rather as an assembly of self-orienting dipoles of variable density, resulting in a variable dielectric profile. We have previously described a web-based implementation of the method (http://lorentz.immstr.pasteur.fr/index2.php) that both numerically solves this equation and uses the resulting water density profiles to place water molecules at preferred sites of hydration. This allows for the tentative prediction of the dimerisation interface in homodimeric proteins, or lipid binding regions in membrane proteins, which appear as hydrophobic patches on the solvent accessible surface. Here we give a full description of the method and discuss how the model was calibrated with only two adjustable parameters (the size and dipolar moment of the solvent). We have validated the method in a number of different ways and present new applications. In particular, we have checked that a simple solvation energy derived from it is able to distinguish between the true structure and a set of decoys of a given protein. Furthermore, the solvent density profiles curves and its derivative allow to derive mean values for atomic solvation parameters (analogous to surface tension coefficients) and these were found to be highly correlated to Eisenberg and MacLachlan Atomic Solvation Parameters (1984) without any parameter fitting (CC=0.96).

K.5.5 Aggregation and adsorption at the air-water interface of bacteriophage ΦX174 single-stranded DNA *(Douarche C., Goldar A., Sikorav J.-L.)*

This is an experimental work (submitted) performed in collaboration with Carine Douarche and Arach Goldar (Service de Biologie Intégrative et de Génétique Moléculaire, CEA/Saclay). We have studied the phase behavior of phage ?X174 single-stranded DNA in very dilute solutions in the presence of salts, both in water (H_2O) and heavy water (D_2O). DNA solubility depends on the nature of the salts and their concentrations and on the nature of the solvent. The appearance of attractive interactions between the monomers of the DNA chains in the bulk of the solution is strictly correlated with an adsorption of the chains at the air-water interface. We have characterized this correlation in two types of aggregation processes, the condensation of DNA induced by the trivalent cation spermidine and its salting out in the presence of high (molar and above) concentrations of monovalent (sodium) cations, both in water and heavy water. The overall solubility of single-stranded DNA is decreased in D_2O compared to H_2O. The respective roles of DNA hydration and electrostatic factors can be distinguished in the phase separations observed. DNA adsorption involves attractive van der Waals forces, and these forces are also operating in the bulk aggregation process.

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CHAPTER L

Summary of Publications

Physical Review D (particles, fields, gravitation and cosmology)	33
Physical Review Letters	28
Journal of High Energy Physics *(electronic)*	24
Nuclear Physics B (particle physics, field theory and statistical systems)	23
Nuclear Physics A (nuclear and hadronic physics)	22
Journal of Statistical Mechanics, Theory and Experiment *(electronic)*	19
Physical Review E (statistical, nonlinear, and soft matter physics)	17
Physics Letters B (nuclear physics and particle physics)	16
Journal of Physics A (general and mathematical)	13
Physical Review B (condensed matter and materials physics)	10
European Physical Journal B (condensed matter physics)	7
Physics Reports	5
Europhysics Letters	5
Journal of Cosmology and Astroparticle Physics *(electronic)*	4
Progress in mathematical physics	4
Physical Review C (nuclear physics)	4
Journal of Physics G (nuclear and particle physics)	4
Astronomy and Astrophysics	3
Classical and quantum gravity	3
Nature Physics	3
Science	1
Review of Modern Physics	1

Journals in which only 1 or 2 papers were published are not all listed. Please note that the publications covered by the present report are those *submitted* between June 2005 and May 2007. Some are not yet published, so that the above numbers are in fact lower bounds.

CHAPTER M

Awards

Christophe GROJEAN
Jean-Thibaud prize awarded by the Academy of Lyon for his contributions to theoretical particle physics beyond the standard model.
November 2006.

Giulio BIROLI
Young Scientist Award of IUPAP (International Union of Pure and Applied Physics), jointly with Tomohiro Sasamoto (Chiba University, Japan), for his groundbreaking works on glassy systems. This prize was awarded for the first time.
March 2007.

CHAPTER N

Fundings and Grants

N.1 Individual Marie-Curie Fellowships (FP6)

Person	Type	Topic	Dates
Cyrille Marquet	Outgoing International Fellowship	Study of newly-discovered matter in very energetic collisions of hadrons or heavy ions	01/06/2007-01-06-2010
Cristina Bena	Intra-European Fellowship	*TSINANO:* Transport in Strongly Interacting Nanosystems	06/11/2006-06/11/2008
Hubert Saleur	International Reintegration Grant	Nano Physics and Quantum Field Theory	15/11/2004-15/11/2006
Iosif Bena	International Reintegration Grant	Strings and Black Holes	1/12/2006-30/11/2008
Graziano Vernizzi	Intra-European Fellowship	Study of DNA and RNA structures with Matrix Theory	06/02/2004-01/09/2005

N.2 European Research Training Networks (Marie Curie RTN, FP6)

Local contact	Topic	Coordinator	Dates
Ivan Kostov	*ENIGMA, European Network in Geometry, Mathematical Physics, and Applications*	Gregorio Falqui (SISSA, Trieste)	01/01/2005-31/12/2008
François David	*ENRAGE, Random Geometry and Random Matrices: From Quantum Gravity to Econophysics*	Renate Loll (Utrecht)	01/09/2005-31/08/2009
Carlos Savoy	*The Quest For Unification: Theory Confronts Experiment*	Ignatios Antoniadis (Ecole polytechnique, Palaiseau)	01/10/2004-31/09/2008
Pierre Vanhove	*ForcesUniverse (Constituents, Fundamental Forces and Symmetries of the Universe)*	Dieter Lüst (Munich)	01/01/2005-31/12/2008

N.3 Other international exchange and networking programmes

Coordinator	Type	Topic	Dates
Giulio Biroli	CNRS-NSF exchange programme		2007-2009
François David	Jules Verne exchange programme (Iceland)	*Physical Applications of Random Graph Theory*	01/01/2004-31/12/2006
François Gelis	CAPES-COFECUB exchange programme (Brazil)	*QCD at high temperature and high density*	01/01/2004-31/12/2006
Christophe Grojean	ECONET exchange programme	*Origin of electroweak symmetry breaking and new physics at the TeV scale*	01/2004-12/2005
Christophe Grojean	CNRS-NSF exchange programme		2006-2008
David Kosower	ECONET exchange programme (Russia, Poland)	*2-loop Feynman integrals and beyond*	01/01/2005-31/12/2006
Ivan Kostov	Sakura exchange program (Japan)	*Matrix Models and String Theory*	01/01/2006-31/12/2007
Ivan Kostov	Rila exchange program (Bulgaria)	*Random geometry, quantum gravity and conformal theories*	01/01/2007-31/12/2008
Jean-Yves Ollitrault	CEFIPRA (Indo-French Centre for the Promotion of Advanced Research) exchange programme	*Hot and dense Matter in Quantum Chromodynamics*	01/2005-12/2007
Robi Peschanski	ECONET exchange programme		01/2004-12/2005
Robi Peschanski	Marie-Curie Transfer of knowledge	*COCOS: Correlations in complex systems*	01/2007
Hubert Saleur	ESF (European Science Foundation) Research Networking Programme	*INSTANS: Interdisciplinary Statistical and Field Theory Approaches to Nanophysics and Low-Dimensional Systems*	10/2005-10/2010

N.4 National (ACI and ANR) grants

ACI stands for "Actions concertées incitatives du Ministère de la recherche" (until 2005).
ANR stands for "Agence nationale de la recherche" (since 2005).

Local contact	Type	Name/topic	Coordinator	Dates
Christophe Grojean	ACI Jeunes chercheurs	*ACI Grojean*	Christophe Grojean	09/2002-08/2005
Catherine Pépin	ACI Jeunes chercheurs	*ACI Pépin*	Catherine Pépin	09/2003-08/2006
Bertrand Duplantier	ACI IMPBIO	*(Informatique, mathématique et physique en biologie moléculaire): Gene Phys*	Edouard Yeramian (Institut Pasteur)	09/2004-08/2006

Emmanuel Guitter	ACI Masses de Données	*GEOCOMP (Compression de données de nature géométrique)*	Gilles Schaeffer (Ecole polytechnique)	09/2004-08/2007
Stéphane Nonnen-macher	ANR JCJC[1]	*Resochaoquan: Résonances et décohérence en chaos quantique*	Stéphane Nonennmacher	05/12/2005-05/12/2008
Stéphane Lavignac	ANR JCJC	*Neupac: Non-standard properties of neutrinos, and their impact on astrophysics and cosmology*	Cristina Volpe (Orsay University)	05/12/2005-05/12/2008
Philippe Di Francesco	ANR Blanc	*GIMP: Geometry and integrability in mathematical physics*	Paul Zinn-Justin (Orsay University)	01/12/2005-01/12/2008
Carlos Savoy	ANR Blanc	*Phys@col-cos: Physics beyond the Standard Model: implications for colliders and cosmology*	Abdelhak Djouadi (Orsay University)	01/12/2005-01/12/2008
David Kosower	ANR Blanc	*QCD@LHC: QCD, Twistors, and LHC*	David Kosower	06/12/2005-06/12/2008
Hubert Saleur	ANR Blanc	*INT-AdS/CFT: Integrable structures and the AdS/CFT conjecture: spin chains and non-linear supersymmetric sigma models*	Hubert Saleur	06/11/2006-06/11/2008
Ruben Minasian	ANR Blanc	*BHTSV: Structure of vacuum, topological strings and black holes*	Ruben Minasian	06/11/2006-06/11/2009
Géraldine Servant	ANR JCJC	*DARKPHYS: Dark matter and dark energy: a challenge for particle physics*	Géraldine Servant	06/11/2006-06/11/2010
Edmond Iancu	ANR Blanc	*From RHIC to LHC:: Strong interactions in the high-energy limit*	Edmond Iancu	06/11/2006-01/11/2010
Michel Bauer	ANR Blanc	*SLE: Probabilistic tools and conformal invariance in field theory: SLE and other growth processes*	Denis Bernard (ENS Paris)	06/11/2006-01/11/2010
Catherine Pépin	ANR Blanc	*ECCE: Extreme conditions correlated electrons*	D. Braithwaite (CEA Grenoble)	06/11/2006-06/11/2009

[1] Jeunes chercheuses et jeunes chercheurs

CHAPTER O

Training

O.1 Habilitation thesis

Bertrand Eynard
The 2-matrix model, biorthogonal polynomials, Riemann-Hilbert problem, and algebraic geometry (Le modèle à deux matrices : polynômes biorthogonaux, problème de Riemann-Hilbert, géométrie algébrique [t05/047]), Université Paris VII, September 15, 2005.

O.2 PhD Defences

Tristan Brunier
Search for signatures of new physics in cosmological surveys (Recherche de signatures d'une physique non-standard dans les relevés cosmologiques[t06/133]), supervised by F. Bernardeau, Université Paris XI, October 27, 2006.
Cyrille Marquet
Quantum chromodynamics at high energy, theory and phenomenology at hadron colliders (Chromodynamique quantique à haute énergie, théorie et phénoménologie appliquée aux collisions de hadrons[t06/108]), supervised by R. Peschanski, Université Paris VI, September 18, 2006.
Jérôme Rech
Macroscopic quantum phenomena in strongly correlated fermionic systems (Phénomènes quantiques macroscopiques dans les systèmes fortement corrélés [t06/065]), supervised by C. Pépin, Université Paris XI, June 19, 2006.
Gerhard Götz
Lie superalgebras and string theory in $AdS_3 \times S^3$ (Superalgèbres de Lie et théorie des cordes dans $AdS_3 \times S^3$ [t06/045]), supervised by V. Schomerus, Université Paris VI, January 27, 2006.
Nicolas Chatillon
Warped brane worlds and supersymmetry breaking (Mondes branaires courbés et brisure de supersymétrie [t05/145]), supervised by P. Brax, Université Paris VI, September 30, 2005.
Jérémie Bouttier
Statistical physics of random surfaces and bijective combinatorics of planar maps (Physique statistique des surfaces aléatoires et combinatoire bijective des cartes planaires [t05/097]), supervised by P. Di Francesco and E. Guitter, Université Paris VI, June 10, 2005.

O.3 Current PhD Students (June 2007)

Name	Supervisor	*Topic*	Dates
Alexei Andreanov	G. Biroli	*Glassy transition in supercooled liquids*	10/2004-09/2007
Adel Benlagra	C. Pépin	*Quantum Critical Points in strongly correlated electron systems*	10/2006-09/2009
Guillaume Beuf	R. Peschanski	*Quantum Chromodynamics at high energy and/or high density*	10/2006-09/2009
Michael Bon	H. Orland	*Statistical Physics of Genome*	10/2006-09/2009
Jean-Emile Bourgine	I. Kostov	*Matrix quantum mechanics and two-dimensional black holes*	10/2006-09/2009
Constantin Candu	H. Saleur	*Field theory of disordered systems*	10/2005-09/2008
Cédric Delaunay	C. Grojean	*Electroweak symmetry breaking: origin and consequences*	10/2005-09/2008
Pierre Hosteins	S. Lavignac	*Neutrino Masses and Physics Beyond the Standard Model*	10/2004-09/2007
Nicolas Orantin	B. Eynard	*From matrix models to topological string theories: counting surfaces with algebraic geometry*	10/2004-09/2007
Sylvain Prolhac	K. Mallick	*Exact methods in statistical physics of systems out of equilibrium*	10/2006-09/2009
Thomas Sarlat	A. Billoire and G. Biroli	*Theoretical models of the Glassy tranditions: from mean field to three dimensions*	10/2006-09/2009
Emmanuel Schenck	S. Nonnenmacher	*Open quantum systems and semiclassical methods*	10/2006-09/2009
Cristian Vergu	D. Kosower	*Twistors, strings, and supersymmetric gauge theories*	10/2005-09/2008
Dmytro Volin	D. Serban	*Integrable structures in supersymmetric gauge theories and string theories*	10/2006-09/2009

O.4 Postdocs

Name	Supervisor	Origin	Financial Support	Dates
Fabien Alet	G. Misguich G.	ETH Zurich, Switzerland	CEA	04/10/2004-30/09/2005
Simon Badger	D. Kosower	Durham University, UK	ANR	01/10/2006-30/09/2008
Cristina Bena	H. Saleur	Rutgers University, USA Egide,	Marie Curie EIF	02/10/2006-12/11/2008
Andrea Beraudo	E. Iancu	Torino University, Italy	INFN (Italy)	01/05/2006-01/05/2007
Edouard Boulat	H. Saleur	Rutgers University, USA	Marie-Curie IRG	15/11/2004-01/09/2005
Michael Chesterman	P. Vanhove	Karlstad University, Sweden	CEA	01/10/2005-30/09/2007
Marco Cirelli	C. Savoy	Yale University, USA	Egide + INFN (Italy)	01/11/2006-30/09/2007
Darren Forde	D. Kosower	Durham University, UK	CEA	01/10/2004-30/09/2006
Michele Frigerio	S. Lavignac	UC Riverside, USA	CEA	01/10/2005-31/08/2007
Yoshitaka Hatta	E. Iancu	Brookhaven, USA	CEA	01/10/2006-01/10/2008
Kazuo Hosomichi	I. Kostov	Toronto University, Canada	CEA	03/10/2005-02/10/2007
Andreas Komnik	H. Saleur	Freiburg University, Germany	Marie Curie IRG	01/01/2006-31/07/2006
Kalle Kytölä	M. Bauer	Helsinki University, Finland	Marie Curie RTN	06/11/2006-06/11/2007
Indranil Paul	O. Parcollet	Rutgers University, New jersey	CEA	03/11/2003-02/11/2005
Licinio Portugal	F. Gelis	Rio de Janeiro University, Brazil	COFECUB CAPES Fellowship	07/11/2006-30/10/2007
Arunansu Sil	C. Savoy	Delaware University, USA	Egide	24/10/2006-31/05/2007
Grégory Soyez	R. Peschanski	Liège, Belgium	FNRS (Belgium)	01/10/2004-26/09/2006
Marc Thormeier	S. Lavignac	Bonn University, Germany	ANR	04/08/2006-03/03/2007
Dionysis Triantafyllopoulos	E. Iancu	Columbia University, USA	CEA	29/09/2003-28/09/2005
Graziano Vernizzi	H. Orland	Spinoza Institute, Utrecht	Marie Curie EIF	06/02/2004-31/08/2005
Francesco Zamponi	G. Biroli	ENS, Paris	CEA	01/09/2006-31/08/2007

O.5 Internships

Supervisor	Student	Level	Topic	Dates
I. Bena	Clément Ruef	Master 2 Physique	*Trous noirs et théorie des cordes*	02/04/2007-31/07/2007
Ph. Brax	Sophie Grezes-Rueff	Master 2 Noyaux, Particules et Cosmologie	*Cosmologie théorique sur des modèles d'inflation*	07/05/2007-20/06/2007
A. Capdepon	Soufiane Kada	Master 2, Ingénieur en informatique	*Développement et mise en place du système de gestion des publications*	19/02/2007-19/08/2007
A. Capdepon	Soufiane Kada	Master 2, Ingénieur en informatique	*Web*	02/05/2006-01/09/2006
C. Cataldi	Célia Zaffanella	BTS 1ère année Assistante de direction	*Gestion des dossiers de visiteurs longue durée*	14/05/2007-30/06/2007
F. David	Christian Hagendorf	Master 2	*Théorie quantique des champs et systèmes désordonnés*	09/01/2006-26/02/2006
B. Eynard	Antoine Baker	Master 1 Physique	*Matrices aléatoires*	20/02/2007-27/07/2007
B. Eynard	Guillaume Boudarham	Master 2 Physique théorique	*Introduction aux matrices aléatoires*	15/01/2007-05/03/2007
F. Gelis	Fabiana Munhoz	Ingénieur Polytechnique	*Introduction à la chromodynamique quantique et au "color glass consendate"*	10/04/2006-10/07/2006
C. Grojean	Cédric Delaunay	Master 2 Sciences de la matière	*Brisure de symétrie électro-faible*	04/04/2005-31/07/2005
E. Iancu	Clémentine Broutin	Ecole polytechnique 3ème année	*QCD rendue simple*	10/04/2007-06/07/2007
A. Lefèvre	Jean-Pierre Testaud	Ecole polytechnique 3ème année	*Etude des matériaux prévitreux*	10/04/2007-06/07/2007
K. Mallick	Julien Randon	Master 2	*Bethe Ansatz et Physique Statistique hors équilibre*	05/12/2005-12/01/2006
G. Misguich	Alexandre Monza	Master 2 Physique	*Théorie de la matière condensée et magnétisme quantique*	15/01/2006-15/03/2006
C. Monthus	Yaouen Fily	Master 2	*Physique statistique des systèmes désordonnés*	16/01/2006-16/03/2006
J-Y. Ollitrault	Clément Gombeaud	Master 1	*Simulation d'une équation de transport relativiste*	19/04/2006-11/08/2006
H. Orland	Michael Bon	Ecole polytechnique 3ème année Biotechnologie	*Etude topologique des protéines et de l'ARN*	03/01/2006-31/01/2006 01/04/2006-31/07/2006
P. Valageas	Julien Vandeportal	Master 2 Physique chimie	*Structure à grande échelle de l'univers : régime non-linéaire*	01/02/2007-29/06/2007
S. Nonnenmacher	Emmanuel Schenck	Master 2	*Modèles discrets de diffusion quantique*	09/01/2006-03/03/2006

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[t05/047] B. Eynard. *Le modèle à deux matrices : polynômes biorthogonaux, problème de Riemann-Hilbert, géométrie algébrique.* (2005), arXiv:math-ph/0504034. Université Paris VII, 2005-09-15.

[t05/097] J. Bouttier. *Physique statistique des surfaces aléatoires et combinatoire bijective des cartes planaires.* (2005). Université Paris VI , 2005-06-10.

[t05/145] N. Chatillon. *Mondes branaires courbés et brisure de supersymétrie.* (2005). Université Paris VI , 2005-09-30.

[t06/045] G. Goetz. *Superalgèbres de Lie et la théorie des cordes dans* $AdS_3 \times S^3$. (2006). Université Paris VI , 2006-01-27.

[t06/065] J. Rech. *Phénomènes quantiques macroscopiques dans les systèmes fortement corrélés.* (2006). Université Paris XI , 2006-06-19.

[t06/108] C. Marquet. *Chromodynamique quantique à haute énergie, théorie et phénoménologie appliquée aux collisions de hadrons.* (2006). Université Paris VI , 2006-09-18.

[t06/133] T. Brunier. *Recherche de signatures d'une physique non-standard dans les relevés cosmologiques.* (2006). Université Paris XI , 2006-10-27.

CHAPTER P

Teaching

P.1 SPhT Lectures

These lectures take place every Friday afternoon at SPhT. The lectures marked with a ∗ are part of the PhD program of the University of Paris [1].

Who	Topic		Dates
Emmanuel Guitter (SPhT)	*Méthodes combinatoires pour l'énumération des graphes planaires*		30/09/2005-21/10/2005
Larry Schulman (Clarkson University, USA)	*Time-related issues in statistical mechanics*	∗	18/11/2005-16/12/2005
François Gelis (SPhT)	*Interactions à haute énergie en QCD, et applications aux collisions d'ions lourds*	∗	06/01/2006-03/02/2006
Daniel Estève (Service de Physique de l'état Condensé CEA, Saclay)	*Introduction au calcul quantique et aux circuits à bits quantiques*	∗	24/02/2006-07/04/2006
Pierre Binétruy (Laboratoire Astroparticules et Cosmologie Université Paris VII)	*Aspects théoriques des astroparticules*	∗	12/05/2006-30/06/2006
Bertrand Eynard (SPhT)	*Cours Introductif de Géométrie Algébrique pour Physiciens*		08/09/2006-29/09/2006
Satya Majumdar (Lab. de Phys. Théorique et Modèles Statistiques, Orsay)	*Brownian functionals and their applications*	∗	10/11/2006-12/12/2006
Olivier Babelon (Lab. de Phys. Théorique et Hautes Energies, Universités Paris VI et VII)	*Petite introduction aux systèmes intégrables classiques et quantiques*	∗	19/01/2007-16/02/2007
François David(SPhT)	*Théorie statistique des champs avancée*	∗	09/03/2007-06/04/2007
Didina Serban (SPhT)	*Intégrabilité et la conjecture AdS/CFT*		27/04/2007-11/05/2007

[1] ED107: Ecole doctorale de physique de la région parisienne

P.2 University

Who	**Level**	**Where**	**Topic**
Francis Bernardeau	M2[2]	Ecole normale supérieure	*Cosmology*
François David	M2	Ecole normale supérieure	*Statistical field theory (40 hours)*
Bertrand Duplantier	M1[3]	Ecole polytechnique	*Physics of polymers and biological membranes (36 hours) [t05/104][t06/206]*
Bertrand Duplantier	Master	EPFL, Lausanne	*Physics of Biological Polymers (16 hours) [t07/069]*
Alexandre Lefèvre	L3[4]	ESPCI, Paris	*Exercices in statistical physics (20 hours)*
Kirone Mallick	L3[5]	ESPCI, Paris	*Mathematical physics for physicists (40 hours)*
Kirone Mallick	M1	Ecole polytechnique	*Wiener measure and path integral (6 hours) [t05/240]*
Kirone Mallick	M1	Ecole polytechnique	*Rigorous results in out-of-equilibrium statistical mechanics (6 hours)*
Ruben Minasian	M2	Ecole normale supérieure	*Mathematical methods for theoretical physics (36 hours)*
Jean-Yves Ollitrault	L3	Ecole polytechnique	*Exercises in Quantum Physics (28 hours)*
Jean-Yves Ollitrault	M1	Ecole polytechnique	*Exercises in Particle physics (36 hours)*
Olivier Parcollet	M2	Ecole normale supérieure, parcours Physique quantique	*Exercises in quantum field theory (18 hours)*
Olivier Parcollet	M2	Ecole normale supérieure	*Many-body problem (18 hours)*

P.3 Summer schools

Who	**Where**	**Topic**	**Dates**
Giulio Biroli	Les Houches, International school on *Statistical physics of glasses, spin glasses, information processing and combinatorial optimization*	*The glass transition (6 hours)*	02/2006
Bertrand Duplantier	Les Houches Summer School, session LXXXIII, *Mathematical Statistical Physics*	*Conformal Random Geometry [t05/243]*	07/2005
Bertrand Duplantier	Cargèse Summer School, *ADN and Chromosomes*	*Brownian Motion (3 hours)*	07/2006
Bertrand Eynard	School of the ENRAGE network, Barcelona	*Introduction to matrix models (3 hours)*	04/2007
Christophe Grojean	Les Houches summer school	*Electroweak symmetry breaking (4.5 hours)*	08/2005

[2] M2 is the second year of the master
[3] M1 is the first year of the master
[4] L3 is the third year of undergraduate studies
[5] L3 is the third year of undergraduate studies

Christophe Grojean	Summer Institute, Asian Pacific Center for Theoretical Physics, Pohang, South Korea,	*Electroweak symmetry breaking*	08/2006
Christophe Grojean	Trends in Theoretical Physics, South American Center for Physics and Mathematics, Buenos Aires, Argentina	*Electroweak symmetry breaking*	05/2007
Christophe Grojean	Rio-Saclay meeting, Rio de Janeiro, Brazil	*Electroweak symmetry breaking*	12/2006
David Kosower	Summer School on Strings, Gravity and Cosmology University of British Columbia, Vancouver, Canada	*On-Shell Methods in Gauge Theories*	08/2006
David Kosower	Parma School of Theoretical Physics, Parma, Italy	*New Formal Developments in QFT*	09/2006
Stéphane Lavignac	Rio-Saclay meeting, Rio de Janeiro, Brazil	*Grand-unified theories*	12/2006
Kirone Mallick	Tata Institute, Mumbai, India	*Bethe Ansatz for Non-Equilibrium Statistical Mechanics (4 hours)*	
Jean-Yves Ollitrault	Universität Bielefeld, Germany, Block Course on Heavy Ion Phenomenology	*Relativistic hydrodynamics (3 hours)*	09/2005
Carlos Savoy	Rio-Saclay meeting, Rio de Janeiro, Brazil	*Supersymmetry*	12/2006
Géraldine Servant	Annecy, GDR Meeting	*Dimensions supplémentaires et implications astro-physiques/cosmologiques (3 hours)*	04/2006
Géraldine Servant	Les Houches Summer School,	*Extra-dimensional cosmology (3 hours)*	08/2006
Géraldine Servant	First Rio-Saclay meeting, Rio de Janeiro, Brazil	*Baryogenesis (3 hours)*	12/2006

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[t05/104] L. Auvray, F. Devreux, and B. Duplantier. *Physique des membranes et polymères biologiques*, (2005). Majeures de Physique 2 et de Chimie du Vivant, Département de Physique, 250 pages, 2005-01-01.

[t05/240] K. Mallick. *La formule de Feynman-Kac : quelques applications à la mécanique quantique et à la physique statistique*, (2005). Cours de rentrée de Majeure de Mathématiques Pures de l'“X”, Ecole polytechnique, Palaiseau, France, 2005-09-01.

[t05/243] B. Duplantier. *Conformal Random Geometry*. Mathematical Statistical Physics, Les Houches Session LXXXIII. Elsevier, Amsterdam, (2006), arXiv:math-ph/0608053.

[t06/206] L. Auvray, B. Duplantier, and C. Sykes. *Physique des polymères et membranes biologiques*, (2007). Majeures de Physique, Physique et Chimie du Vivant, Mécanique : option fluides et solides, Département de Physique, 282 pages, 2007-01-01.

[t07/069] B. Duplantier. *Physique des polymères biologiques*, (2007). Troisième cycle de physique de Suisse romande,, EPFL, Lausanne, Suisse, January-February 2007.

CHAPTER Q

Seminars, Conferences

Q.1 Weekly Seminars

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

Day	**Topic**	**Organizers**
Monday 11:00	*Mathematical Physics Seminar*	S. Nonnenmacher, V. Pasquier
Monday 14:15	*Statistical Physics Seminar*	A. Lefèvre
Tuesday 11:00	*General Seminar of SPhT*	B. Duplantier
Wednesday 14:15	*Cosmology and Particle Physics Seminar*	F. Bernardeau, S. Lavignac
Thursday 11:00	*Condensed Matter Theory Seminar*	O. Parcollet
Friday 11:00	*Matrices, Strings and Random Geometries Seminar*	I. Kostov, P. Vanhove

Q.2 Claude Itzykson Meetings: Scientific programs

Q.2.1 The Tenth Itzykson Meeting: *Quantum Field Theory Then and Now* (June 15-17, 2005)

Organizers : M. Bauer, Ph. Di Francesco, H. Saleur et J-B Zuber (SPhT, Saclay)

A. Voros: *1d Schrödinger equation as an exactly solvable model*
P. Zinn-Justin: *Nilpotent orbits and the Yang-Baxter equation*
R. Dijkgraaf: *Baby universes in topological string theory*
M. Bousquet-Melou: *Embedded trees*
J. Keating: *Random matrix theory and number theory*
E. Martinec: *Quantum cosmology in two dimensions*
J-B Zuber: *About Claude Itzykson*
J. Teschner: *On tachyon condensation and open-closed duality in c=1 string theory*
P. Le Doussal: *Field theory of pinned systems and applications*
D. Bernard: *Schramm-Loewner evolution : from 2D critical interfaces to 2D turbulence*
C. Glattli: *Probing some Luttinger liquid properties of the Fractional Quantum Hall Effect and of SW Carbone Nanotubes*
J. Minahan: *The SU(2) sector in AdS/CFT*
C. Bender: *Ghost busting :Making sense of non-Hermitian Hamiltonians*
S. Alexandrov: *D branes in c=1 string theory*
J. Imbrie: *Dimensional Reduction, Then and Now*

C. Vafa: *Hartle-Hawking wave function in string theory*
N. Kitanine: *Correlation functions of the XXZ spin chain*
N. Read: *Minimum spanning trees*
G. Veneziano: *Fifty years of particle theory : a CERN-based retrospective*

Q.2.2 The Eleventh Itzykson Meeting: *Strongly Correlated Electrons* (June 21-23, 2006)

Organizers : O. Parcollet, C. Pépin (SPhT, Saclay)

A. Georges: *Two energy scales and the nodal/antinodal dichotomy in hole-doped superconducting cuprates*
G. Kotliar: *Dynamical RVB : Cluster Dynamical Mean Field Studies of Doped Mott Insulators*
A.M. Tremblay: *Insights into d-ware superconductivity from quantum-cluster approaches*
P. Coleman: *Quantum Criticality in Heavy Electron Systems*
I. Paul: *Quantum Criticality Near Kondo Breakdown Fixed Point*
D. Maslov: *Non-analytic behaviour of the spin susceptibility of Fermi- and non-Fermi liquid*
A.J. Schofield: *Metal to metal transitions*
A. Rosch: *Dephasing by Kondo impurities*
T. Giamarchi: *Deconfinement and cold atomic gases*
B. Altshuler: *Integrable Classical Dynamics of Quantum Condensates*
A. Chubukov: *Mass-shell singularities in a Fermi liquid and in a d-ware superconductor*
S. Sachdev: *Quantum theory of vortices in d-ware superconductors*
C. Varma: *Symmetry breaking in the Pseudogap state of the Cuprates and quantum critical fluctuations about it*
A. Tsvelik: *Finite temperature correlation function for 1D Quantum Ising model : regular expansion in the soliton density*
K. Le Hur : *Quantum Criticality in Kondo models : A Nano Perspective*
N. Andrei: *Dynamics of quantum impurities out of equilibrium*
A. Millis: *The spin-boson and the Ising ferromagnet : two steps towards a theory of nonequilibrium quantum phase transitions*
R. Moessner: *Ice, spin ice, and artificial ice*
M. Oshikawa: *Ferromagnetism and quantum statistics*
L. Balents: *Quantum and classical degeneracy breaking in some frustrated magnets*
G. Misguich: *Unconventional continuous phase transition in a three dimensional dimmer model*

Q.3 Other meetings organized at SPhT

Paul Bonche Symposium
June 27, 2005
Organizing Committee : T. Duguet (MSU), P.-H. Heenen (Bruxelles), J.-Y. Ollitrault, H. Orland (SPhT)

J.-B. Zuber is 60
June 1-2, 2006
Organizing Committee : Olivier Babelon (LPTHE, Paris), Michel Bauer (SPhT), Denis Bernard (ENS, Paris), Philippe Di Francesco (SPhT), Paul Zinn-Justin (LPTMS Orsay)

Robi is 60
November 24, 2006
Organizing Committee : Philippe Brax, Edmond Iancu (SPhT), Christophe Royon (DAPNIA), Samuel Wallon (LPT Orsay)

Q.4 Organization of workshops and conferences

Organizers	**Conference**	**Date**
Francis Bernardeau Christophe Grojean	Les Houches summer school, 86th session: *Particle physics and cosmology: the fabric of spacetime*	July 31 - August 25, 2006
Francis Bernardeau	XXIIIrd IAP Colloquium : *From giant arcs to CMB lensing: 20 years of gravitational distortion*	July 2–7, 2007
François David	ENRAGE Network School on *Random Matrices and Random Geometry*, Barcelona, Spain	April 16–20, 2007
Bertrand Duplantier Vincent Pasquier	Séminaire Poincaré: Quantum Decoherence	November 17, 2005
Bertrand Duplantier Vincent Pasquier	Séminaire Poincaré: Gravitation and Experiment	October 28, 2006
Bertrand Duplantier Vincent Pasquier	Séminaire Poincaré: Quantum Spaces	April 28, 2007
Christophe Grojean	SUSY'05, convener of the New Physics session, Durham, England	July 2005
Christophe Grojean Stéphane Lavignac Géraldine Servant	Planck'06: *from the Planck scale to the electroweak scale*, Carré des Sciences, Paris	May 29 – June 2, 2006
Christophe Grojean	SUSY'06, convener of the New Physics session, New Port Beach, CA, USA	June 2006
Edmond Iancu	*Low-x meeting*, Sinaia, Romania	June 29 – July 2, 2005
François Gelis Edmond Iancu	*High-energy QCD: From RHIC to LHC*, ECT* Trento (Italy)	January 9–13, 2007
Stéphane Lavignac	Ecole de Gif (French summer school on theoretical particle physics)	since 2001
Stéphane Lavignac	Les Houches summer school 84^{th} session, *Particle Physics Beyond the Standard Model*	August 1–26, 2005
Jean-Marc Luck	Rencontres de physique statistique, ESPCI, Paris	January, 2006 and 2007
Géraldine Servant	Co-organiser of the ENTApP Dark Matter Visitor Program, CERN, Geneva	March 5–9, 2007
Géraldine Servant	Convener of the Dark Matter parallel session of the Kavli Institute Symposium in honor of David Schramm, *New views of the universe*, Chicago	December 8–13, 2005
Pierre Vanhove	Cargese summer school *Strings and Branes:The present paradigm for gauge interactions and cosmology*	June 2006
André Voros	Ecole thématique du CNRS *Resonances and periodic orbits: spectrum and zeta functions in quantum and classical chaos* (part of the thematic programme *Time at Work*, Institut Henri Poincaré, Paris)	June 27 – July 5, 2005

CHAPTER R

Research administration

Who	Assignment	Institution
Roger Balian	Member of the scientific committee	CEA, CEA/DAM
Roger Balian	Member of the ethics committee	AREVA
Roger Balian	Member of the management committee	Leon Brillouin Laboratory (LLB), CEA Saclay
Roger Balian	Member of the advisory committee	Spiral II, GANIL
Francis Bernardeau	Board member	CNRS, section 47 (astroparticles).
Francis Bernardeau	Scientific Committee (CSTS)	Astrophysics Department, Saclay (DAPNIA/SAP)
Francis Bernardeau	President of the scientific committee	National cosmology program
Alain Billoire	Coordinator of call projects in mathematics, physics, and communication technologies	Région Rhône-Alpes
Giulio Biroli	Commission de spécialistes	ENS Lyon
François David	Member of Panel	European Research Council
François David	Member of the programme committee	Institut Henri Poincaré, Paris
Christophe Grojean	Member of the scientific committee	CNRS, sections 02 (theoretical physics) and 47 (astroparticles)
Christophe Grojean	Member of the scientific committee	Particle physics department, Saclay (DAPNIA/SPP)
Stéphane Lavignac	Member of the scientific committee (CSTS)	Particle physics department, Saclay (DAPNIA/SPP)
Jean-Marc Luck	Member of the scientific committee	CNRS, section 02 (theoretical physics)
Jean-Marc Luck	Member of the scientific committee	RTRA Triangle de la Physique
Jean-Yves Ollitrault	Member of the scientific committee	Subatech, Nantes
Jean-Yves Ollitrault	Commission de spécialistes	Université de Nantes
Henri Orland	Scientific Committee	ECT*[1], Trento, Italy
Henri Orland	Member of the Steering Committee	IUPAP[2], Section C3 (statistical physics)
André Voros	Member of the scientific committee	Agence Nationale de la Recherche, Mathematics division

[1] European centre for theoretical studies in nuclear physics and related areas
[2] International union of pure and applied physics

CHAPTER S

Scientific editing

Who	Role	Journal
Roger Balian	Advisory panel	Journal of Physics A
Roger Balian	Comité de rédaction	Lettre de l'Académie des Sciences
Bertrand Duplantier	Editor	Nuclear Physics B
Bertrand Duplantier	Editor	Geometry and Functional Analysis
Bertrand Duplantier	Editor	Journal of Statistical Physics
Bertrand Duplantier	Editor	La gazette des mathématiciens (SMF)[t05/186]
Bertrand Duplantier	Member of the Executive committee	Annales Henri Poincaré
Bertrand Duplantier	Editor-in-Chief	*Poincaré Seminar Series* in Progress in Mathematical Physics, Birkhäuser [t05/228, t05/229, t06/014, t06/209, t06/253, t06/254, t07/131, t07/132]
Bertrand Eynard	Editor	JSTAT (Journal of statistical mechanics: theory and experiment)
Jean-Marc Luck	Member of the advisory panel	Journal of Physics A
Stéphane Lavignac	Editor	Proceedings of Les Houches Summer School [t06/194]
Stéphane Nonnenmacher	Editor	Nonlinearity
Stéphane Nonnenmacher	Editor	European Physical Journal B.
Henri Orland	Editor	Physics Reports
Vincent Pasquier	Associate editor	Annales Henri Poincaré
Didina Serban	Editor	JSTAT (Journal of statistical mechanics: theory and experiment)
Pierre Vanhove	Editor	Proceedings of the Cargese summer school [t07/058]
Pierre Vanhove	Editor	Frontiers in Number Theory, Physics, and Geometry, Springer [t06/129]

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[t05/229] B. Douçot, B. Duplantier, V. Pasquier, and V. Rivasseau. *Poincaré Seminar 2004: The Quantum Hall Effect*, volume 45. Birkhaeuser Verlag, Basel, (2005).

[t06/014] T. Damour, O. Darrigol, B. Duplantier, and V. Rivasseau. *Poincaré Seminar 2005: Einstein, 1905-2005*, volume 47. Birkhäuser Verlag, Basel, (2006).

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[t06/209] B. Duplantier, J.-M. Raimond, and V. Rivasseau. *Poincaré Seminar 2005: Quantum Decoherence*, volume 48. Birkhaeuser Verlag, Basel, (2007).

[t06/253] T. Damour, B. Duplantier, and V. Rivasseau. *Gravitation et expérience*. (2006). Séminaire Poincaré, 28 octobre 2006, Institut Henri Poincaré, 114 pages.

[t06/254] B. Duplantier and V. Rivasseau. *Poincaré Seminar 2006: Gravitation and Experiment*, volume 52. Birkaeuser Verlag, Basel.

[t07/058] P. Vanhove. *Edition des actes de l'Ecole de Cargèse*. *Nucl. Phys. B (Proc. Suppl.) (to appear)*, (2007). Proceedings of the Cargese School on String Theory (Strings and Branes: The present paradigm for gauge interactions and cosmology) , Cargèse, Corsica, France , 2006-05-22/2006-06-03.

[t07/131] B. Duplantier and V. Rivasseau. *Espaces quantiques*, (2007). Séminaire Poincaré, 28 avril 2007, Institut Henri Poincaré, Paris, 202 pages.

[t07/132] B. Duplantier and V. Rivasseau. *Poincaré Seminar 2007: Quantum Spaces*, volume 53. Birkaeuser Verlag, Basel, (2007).

CHAPTER T

Internal organization

T.1 Affiliation, Direction

The SPhT (Service de physique théorique) is a department of DSM (Direction des sciences de la matière), the Physics division of CEA (Commissariat à l'énergie atomique). SPhT is also affiliated with the national research center, CNRS, under the name URA D2306. Since September 2004, the Head of the department is Henri Orland. He is assisted by two deputies, Anne Capdepon (who replaced Michel Bauer in January 2007), and Jean-Yves Ollitrault (since October 2004). The department is informally divided into three groups:
Models and structures: mathematical physics
Cosmology and particle physics
Statistical physics and condensed matter physics.

T.2 Committees

T.2.1 Evaluation

Our activity is reviewed on a regular basis by an evaluation committee *(Conseil scientifique extérieur)*. The present report is meant to serve as a written basis for the next evaluation. The committee will visit our department on Dec. 4-5, 2007. The members are: Eugène Bogomolny (LPTMS, Orsay, France), Robbert Dijkgraaf ((KdV Institute, Amsterdam, NL), Hendrik-Jan Hilhorst (LPT, Orsay, France), Mehran Kardar (MIT, USA), Antti Kupiainen (Helsinki, Finland), Patricio Leboeuf (LPTMS, Orsay and MPPU, CNRS), Giuseppe Marchesini (Milan, Italy), Andrew Millis (Columbia, USA), Michael Moore (Manchester, UK), Alfred Mueller (Columbia, USA), André Neveu (AERES), Graham Ross (Oxford, UK), Joseph Silk (Oxford, UK).

T.2.2 Local scientific committee *(Conseil scientifique)*

A local scientific committee is elected every second year among the permanent physicists of the department. It assists the Head of the department with scientific decisions, in particular hirings. The present members are (since December 2005) : Giulio Biroli (Secretary), Philippe Brax, Bertrand Eynard, Edmond Iancu, Hubert Saleur.

T.2.3 Department committee *(Conseil de laboratoire)*

The Department committee is in charge of practical matters. It aims at facilitating everyday life. It consists of eight members, who are elected for two years: three permanent physicists, two administrative staff, one emeritus physicist, one PhD student, and one postdoc. It normally meets three times per year. The present members are (since December 2005) : François David, Bertrand Duplantier, Michele Frigerio, André Morel, Nicolas Orantin, Olivier Parcollet, Christian Perez (until March 2007), Laure Sauboy (Secretary). The minutes of meetings can be downloaded from the Intranet webpage.

T.3 Support

T.3.1 Administrative secretaries

The Department has three secretaries, for a total of roughly 90 people.

Sylvie Zaffanella is the Secretary of the Head of the Department. She is also in charge of human resources management, equipment purchase, and travel (to conferences, etc.). Most of our accounting is managed by a different department, the DRECAM, for historical reasons. However, CNRS money is managed locally by S. Zaffanella using a dedicated software, XLAB.

Catherine Cataldi replaced Anne-Marie Arnold in 2006. She is in charge of PhD students, postdocs, and long-term (> 1 month) visitors.

Laure Sauboy has the responsibility of short-term visitors, whose number is continuously increasing. She also keeps track of fundings and grants (Marie-Curie, ANR, etc.).

T.3.2 Library and Electronic resources

Our local library owns as many as 11000 books and 120 journals. It is shared with the neighbouring Condensed Matter Physics Department (SPEC). It is expected to undergo a profound mutation in the next few years, due to the spread of electronic publishing.

Our Web was rewritten by François David, using the Phocea product Co-developed by SPhT, DRECAM and DAPNIA. We maintain a local database of our publications. In 2007, this database was migrated to a standard mysql database. Olivier Parcollet and François David are taking an active part in this project.

Bruno Savelli is in charge of maintaining the library, and of repair works. Loïc Bervas, our scientific secretary, is in charge of updating the local publication databases of SPhT and SPEC. He is also responsible for seminar announcements and for the purchase of computer equipment. Marc Gingold, the head of the Library, will retire in October 2007. He was helping in the organization of events, and in managing applications for jobs (permanent and postdoc).

T.3.3 The computer team

The management of the computer system is shared with the DRECAM (Department of research on Condensed Matter, Atoms and Molecules). The group is composed of 8 people, under the direction of Jean-Louis Greco (DRECAM).

The local team at Orme des Merisiers, which is mostly in charge of Unix and Linux machines, is composed of 4 people: Pascale Beurtey (DRECAM) is in charge of the team. She joined the group in 2007, and replaced Anne Capdepon. Philippe Caresmel (DRECAM) was hired in July 2007 to replace Olivier Croquin, who left in March. Similarly, Laurent Sengmanivanh (SPhT) will be hired in November 2007 to replace Christian Perez, who left in April. Finally, Patrick Berthelot (SPhT) is in charge of maintaining local Windows machines and the wireless network.

A committee composed of four physicists (currently: Michel Bauer, François David, Gregoire Misguich (secretary) and Olivier Parcollet) and the local computer team decides the future orientations of our computer system, makes purchase decisions and informs the physicists about changes. The minutes of this committee can be downloaded from our intranet webpage.

Thanks to the implication of Jean-Marie Normand, a Hotspot wireless is now accessible to our visitors in the whole department, and in the Claude Bloch auditorium for conferences and events. This is the first such network at CEA. This successful premiere has already been followed by many similar implementations in other buildings in Saclay.

T.3.4 SPhT and scientific computing at CEA

CEA has shared supercomputer resources, which are among the largest in France and even Europe. They are managed by the CCRT (Centre de Calcul Recherche et Technologie, Research and Technology Computing Centre). The Physics Division of CEA, DSM, contributes about 25% to CCRT. Scientific projects requiring large computer resources are submitted to a scientific committee, which distributes computer time. Since created in 1994, the head of this committee is the head of our Department. The secretary of the committee, who does most of the work, is also a physicist of our Department, Olivier Golinelli.

CHAPTER U

Permanent Members of SPhT

U.1 Physicists, CEA

Michel BAUER
Iosif BENA (since 2006)
Francis BERNARDEAU
Alain BILLOIRE
Giulio BIROLI
Jérémie BOUTTIER (since 2006)
Philippe BRAX
Philippe DI FRANCESCO
Jean-Michel DROUFFE (until 2006)
Bertrand DUPLANTIER
Bertrand EYNARD
François GELIS (at CERN since 1/1/2007)
Claude GODRECHE (since 2006)
Olivier GOLINELLI
Mariana GRANA (since 2005)
Christophe GROJEAN (at CERN since 2006)
Riccardo GUIDA
Emmanuel GUITTER
David KOSOWER
Jean-Marc LUCK
Kirone MALLICK
Grégoire MISGUICH
Stéphane NONNENMACHER
Jean-Marie NORMAND
Henri ORLAND
Olivier PARCOLLET
Vincent PASQUIER
Catherine PEPIN
Robi PESCHANSKI (until 2006)
Hubert SALEUR
Didina SERBAN
Géraldine SERVANT (at CERN since 2006)
Jean-Louis SIKORAV (since 2006)
Patrick VALAGEAS
Pierre VANHOVE
André VOROS

U.2 Physicists, CNRS

Michel BERGERE
Denis BERNARD (at ENS since 2006)
Jean-Paul BLAIZOT (at ECT*, Trento since 2004)
Marc CHEMTOB
François DAVID
Thomas GAREL
Jérôme HOUDAYER
Edmond IANCU
Ivan KOSTOV
Robert LACAZE (until 2006)
Stéphane LAVIGNAC
Alexandre LEFEVRE
Ruben MINASIAN (since 2006)
Cécile MONTHUS
Christiane NORMAND
Jean-Yves OLLITRAULT
Carlos SAVOY

U.3 Emeritus

Roger BALIAN
Paul BONCHE (deceased in 2006)
Bertrand GIRAUD
André MOREL
Pierre MOUSSA
Robi PESCHANSKI (since 2006)
Manque RHO
Richard SCHAEFFER
Jean-Bernard ZUBER

U.4 Association "Pour la science"

Jacques BROS
Henri CORNILLE
Cirano DE DOMINICIS
Madan Lal MEHTA (deceased in 2006)
Georges RIPKA
Edgar SOULIE

U.5 Support

Anne-Marie ARNOLD (until 2006)
Patrick BERTHELOT
Loïc BERVAS
Anne CAPDEPON (since 2007)
Catherine CATALDI (since 2006)
Marc GINGOLD
Christian PEREZ (until 2007)
Laure SAUBOY
Bruno SAVELLI
Claudine VERNEYRE (until 2007)
Sylvie ZAFFANELLA