INTERDISCIPLINARY
STATISTICAL AND FIELD THEORY APPROACHES TO NANOPHYSICS AND LOW DIMENSIONAL SYSTEMS
(INSTANS)

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Abstract:

We plan to develop a unique interdisciplinary research activity, which brings together expertise in condensed matter, quantum field theory and statistical physics. Our goal is to set up a new theoretical framework to answer the fundamental questions encountered in the modern physics of nanoscopic and low-dimensional systems.

This proposal concerns electronic systems, such as nanotubes, quantum dots and quantum Hall effect devices, as well as specific devices featuring cold atoms. These systems are dominated by quantum effects and strong interactions, which give rise to non-perturbative effects, like spin-charge separation or fractionally charged excitations. Moreover, interesting transport effects as well as other experimental probes often require non-equilibrium descriptions. These aspects make the standard theoretical approaches developed for systems at larger scales rather inadequate. Considerable progress in statistical field theory, in which Europe has played a leading role, has provided a new set of powerful non-perturbative theoretical methods, which are ideally suited for the challenges posed. Our purpose is to sharpen these tools and to address the fundamental problems in this rapidly evolving domain of physics.

Keywords: nanoscopic systems, transport properties, non-perturbative methods, low dimensional systems.

Status of the relevant research and scientific context

The field of nanophysics has been triggered by technological progress in microelectronics, resulting in incredibly small components, below one micrometer down to a few nanometers. A very important part of the research in this area is naturally concerned with practical applications, which have a considerable, widely publicized potential.

It is important to stress, however, that nanophysics addresses as well fundamental and difficult theoretical questions, whose answer may determine the fate of many technological possibilities. Some of the most important questions are concerned with transport phenomena. While classical and semi-classical physics had been sufficient to understand transport in standard electronic systems, at today's new scales, the electron coherence length is comparable to the dimensions of the devices and therefore transport exhibits new and often very strong quantum features. Some of the quantum effects in transport quantities have already been explored by the mesoscopic physics community, both experimentally and theoretically. Popular examples include universal conductance fluctuations, strong (Anderson) and weak localization, quantum shot noise, and conductance quantization in quantum point contacts or quantum Hall systems. Essentially all these phenomena have been theoretically described within effective single-particle theories, whose validity is often protected by Landau-Fermi liquid theory. However, as one proceeds to smaller and smaller length scales and enters the realm of nanoscopic transport, the quantum effects can be substantially modified by the presence of interactions and correlations.

Interactions at the nanoscale can be present either between the electrons or with the system environment. In their most spectacular form, such interactions are known to lead to strongly correlated states of matter like, for instance, the fractional quantum Hall fluids, where charge fractionalization, spin-charge separation, as well as other counter-intuitive and non-perturbative phenomena are common place. Handling these interactions and their quantum effects properly is a considerable theoretical challenge. It should be noted that the physics of interest arises in experiments and potential applications where transport is far from equilibrium. Under such circumstances, qualitatively new phenomena are expected to appear, which we are just beginning to discover, let alone to understand.

Exciting physics at the nanoscale is not restricted to electronic systems. An important area of research, where the experimental progress is very swift, is that of ultra-cold atomic matter. While in a standard Bose-Einstein condensate the effects of quantum fluctuations and interactions are in general small, many forms of strongly interacting atomic matter have been either realized or envisaged. Examples are nano-scale devices referred to as `atom chips' [1], atomic matter in (low-dimensional) optical lattices [2] and quantum Hall phases expected in a high-rotation limit[3] . Many of the issues discussed above for electronic systems have analogues and counterparts in atomic systems. At the same time, the experimental probes are entirely different, opening up the possibility for a different and novel perspective on quantum and interaction effects at the nanoscale and in low-dimensional systems. As a concrete example, it

[1] J. Reichel, W. Haensel and T.W. Haensch, Phys. Rev. Lett. 83, 3398 (1999).
[2] M. Greiner et al., Nature 415, 39 (2002).
[3] N.R. Cooper, N.K. Wilkin and J.M.F. Gunn, Phys. Rev. Lett. 87, 120405 (2001); J.W. Reijnders, F. van Lankvelt, N. Read and K. Schoutens, Phys. Rev. Lett. 89, 120401 (2002).

is worth mentioning various proposals for the observation and manipulation of fractional excitations in strongly correlated states of atomic matter [4].

A lot of theoretical activity has of course already taken place in this wide domain. Yet, a lot of very interesting, old and new, questions remain to be answered. One reason is that, on the one hand, the approaches used so far are few, and mostly perturbative or of mean-field type - hence not reliable in the strongly interacting and strongly fluctuating cases of interest. Numerical techniques could a priori be expected to do better. However, such computations typically introduce approximations, like density functional theory or dynamical mean-field theory, and rarely permit direct access to transport quantities, especially out of equilibrium. The powerful path-integral Monte Carlo techniques sometimes permit to make progress, but, owing to the well-known sign problem arising in a real-time path integral simulation, have been of limited use so far. Numerical approaches for handling transport on the nanoscale in an exact way, and possibly out of equilibrium, therefore appear (for the moment) to be out of reach. This state of affairs is rather frustrating since, on the other hand, experimental results are many.

Scientific objectives and scope of the Programme

The main objective of this proposal is to develop new methods to tackle the above strongly correlated problems, with a particular emphasis on the study of out-of-equilibrium and non-perturbative features. The interesting new phenomena at the nanoscale occur in particular because of the low dimensionality of the systems. This low dimensionality invalidates many of the standard approaches of solid state physics, such as the Fermi liquid paradigm. At the same time, it opens the way to the use of other techniques, which have been pioneered in different fields like mathematical physics and string theory, and that can find now applications of experimental relevance. Among these techniques, we would like to mention, for instance: (a) the two-dimensional conformal field theories, proving a vast scenario of exactly solvable models with interacting massless excitations; (b) the massive integrable field theories, that can be solved by the exact Scattering matrix approach and the associated form-factor expansion of correlation functions; (c) the thermodynamic Bethe Ansatz for computing thermodynamic quantities at and outside equilibrium; (d) the integrable modes on the lattice, like spin chains and networks, and their interpretation as statistical sums of geometrical objects like loop gases and polymers. Of course, cross fertilization between condensed matter physics and other fields has taken place in the past already, but usually on a much smaller scale.

The success of the kind of interdisciplinary approach we have in mind has been demonstrated over the last decade, when several problems involving transport and strong interactions have been tackled by a combination of field theory and Bethe ansatz techniques, supplemented by generalizations of the Landauer-Buettiker approach. The most spectacular example has been the tunneling between edge states in the fractional quantum Hall effect, where fractional charges were observed experimentally for the first time [5], and exact calculations for quantities such as the conductance out of equilibrium and the shot noise were carried out and quantitatively compared with experiments [6]. Other examples include transport through quantum

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[4] B. Paredes et al., Phys. Rev. Lett. 87, 010402 (2001); J. Javanainen and J. Ruostekoski, Phys. Rev. Lett. 91, 150404 (2003).

[5] L. Saminadayar et al., Phys. Rev. Lett. 79, 2526 (1997); R. de Picciotto et al., Nature 389, 162 (1997).

[6] P. Fendley, A.W.W. Ludwig and H. Saleur, Phys. Rev. Lett. 74, 3005 (1995); Phys. Rev. Lett. 75, 2196 (1995).

dots [7], charge transport through carbon nanotubes [8], or through interacting wires in one dimension [9]. We can also mention the studies of dissipation and quantum fluctuations on small Josephson junctions and single electron transistors and the field theory of superconductivity in carbon nanotube ropes [10].

Yet numerous experimental results await theoretical explanation, sometimes even at a qualitative level. Well-known examples include strange properties of Laughlin quasiparticles [11], out-of-equilibrium transport through quantum dots in the Kondo regime, and the puzzling fractional conductance plateau in quantum point contacts [12]. Another fundamental problem is the mixture of superconductivity and the Kondo effect in the context of carbon nanotube dots in the presence of superconducting leads [13], where anomalously high proximity effects [14] still await the beginning of a theoretical explanation.

The foregoing examples and many others show that there are numerous problems of experimental importance in nanophysics which are amenable to exact solution. An important goal of this proposal is to understand in depth why this is the case and to develop further the use of exact solutions, together with the techniques necessary to transform such solutions into useful predictions, in particular for transport properties. The latter aspect is by far the most challenging, and goes well beyond the calculation of equilibrium thermal properties - the stage where solutions of the earlier models usually stopped. Progress will involve further developments in the theory of form factors, quantum field theories at finite temperature and volume[15], and renormalization group approaches to the Keldysh formalism. For systems where fractional excitations have been identified, it will be natural to base computational schemes directly on such entities, rather than following indirect schemes like bosonization [16].

Another, different and yet deeply related, topic addressed by this proposal is the study of phase transitions in disordered electronic systems, such as the transition between plateaus in the integer quantum Hall effect. Experimental and numerical data are available for critical exponents in such transitions, but no convincing theoretical prediction exists to this day. While the methods of conformal field theory in principle are applicable here and should lead to such predictions, considerable difficulties have been encountered for many years. One of the problems is the non-unitarity of the candidate conformal field theories, which leads to a whole class of new, ill-understood behaviors, involving the absence of a ground state, logarithmic correlators and dense sets of critical exponents [17]. Here again, great benefits could be reaped from cross fertilization with other fields: the kind of field theory one is after bears a lot of resemblance to Liouville and AdS3 theories that have been studied recently in string theory [18].

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Our more specific goal for this topic would be to make progress on sigma models on super and non compact manifolds, and on network models, in particular their geometrical reformulations, which could benefit from recent tremendous progress in the study of stochastic Loewner equation (SLE) [19].

Proposed scientific research by major headings

The proposed research would concentrate on the following themes.

A. Methodological and fundamental developments in transport

A strong effort will be required to connect exact solvability with experiments involving transport out of equilibrium. In fact, the Keldysh formalism (which is a convenient and sophisticated formulation of quantum mechanics out of equilibrium, widely used in perturbative calculations), has not been thoroughly discussed from a field theoretic point of view. In this context, we plan to study further general issues such as the renormalization group, universality and fixed points. The next stage will be to consider integrability with the Keldysh formalism, and to see, in particular, how the conserved quantities appear, and in what sense the problem out of equilibrium is integrable. An alternative direction here will be to understand and generalize scattered observations of problems where quantities out of equilibrium in a certain theory turned out to be related with quantities in equilibrium in other, more complicated theories. Finally, we plan to justify further the generalization of the Landauer Buettiker formalism which has been used so far to short circuit these difficulties. This will involve more comparison with perturbative Keldysh computations, as well as attempts to diagonalize systems in the presence of reservoirs. A related direction of attack will be to study further quantum field theories at finite temperature or in finite volume, in the presence of chemical potentials, and, in particular, to develop further the form-factors approach in this situation. Still from a methodological point of view, exact solutions are often based on finding an appropriate basis of excitations, which constitutes therefore another theme of research in this area.

Leaving methodology aside and turning to fundamental questions, a fascinating field that is emerging from recent experiments concerns the dynamics of Laughlin quasiparticles. Here, very basic questions, such as what these quasiparticles are, how they are obtained, how they interact and how they get across barriers, have to be much better defined theoretically, and answered. All the non-perturbative processes related to the existence of these quasiparticles are in fact little understood. To make progress here, we plan to study further the dynamics leading to the `decomposition of electrons into Laughlin quasiparticles' at the contact between Fermi and Luttinger liquids, and calculate in particular the relative amplitudes of the different physical processes taking place there.

Aside from `diluted beams' experiments, one of the main probes to study quasiparticles has been the measurement of shot noise. We plan to study further the properties of this noise, its dependence on temperature and on the environment, in order to perform better comparisons with tunneling experiments in the fractional quantum Hall effect. The possibility of measuring the third cumulant of the noise has been recently raised. We also plan to adapt the exact

19 see, e.g. W. Kager and B. Nienhuis, ``A Guide to Stochastic Loewner Evolution and its Applications", math-ph/0312056, in press in J.Stat.Phys.

formalism to calculate this cumulant at finite temperature, and explore the additional information it may contain.

B. Applications to recently observed phenomena

In the area of nanophysics, there is a wealth of physical phenomena for which proper and profound theoretical understanding is still missing. Here the methods discussed in this proposal may lead to new insights. Many of the questions of interest are motivated by experimental results obtained on carbon nanotubes. Using short nanotubes, transport through quantum dots in the presence of normal and/or superconducting leads can be studied, where the nanotube can be well described as an Anderson impurity.

We plan to investigate the fate of the Kondo effect in gapped systems in general, with specific application to the Josephson and quasiparticle current through a correlated nanotube dot, where experimental data are readily available to compare with. In addition, the conductance through a Kondo dot contacted by normal leads in the far-from-equilibrium regime is one of the outstanding open problems in this field.

The proximity-induced current through a single-wall nanotube has been experimentally found to exceed the non interacting value by two orders of magnitude, and it is likely that correlations are needed to explain this effect. We plan to study this problem in detail.

Another question is related to intrinsic superconductivity in nanotube ropes, which are thin wires with a few ten to one hundred channels only. This effect was recently observed in Orsay. Quantum Ginzburg Landau models are able to explain the observed resistance below the transition point very well, and lead to interacting multiboson theories. Such theories permit to also capture the Meissner effect and could provide a unified description of one-dimensional superconductivity. For only a few channels, such models can be integrable and allow for exact solutions. In addition, disorder can play an important role and has to be considered.

A related setup in single-wall nanotubes concerns transport through a double barrier. Recently a debate started about the mechanisms of tunneling, triggered by unconventional power law scalings observed by the Delft experimental group. The question of shot noise in such systems also deserves a closer look. A non-perturbative approach to this difficult problem can proceed by first mapping it to spin-boson-type three state (i.e. spin 1) model, which then permits to reach an exact solution in the scaling limit, similar to the previous solution of the two-state problem[20]

Finally, disorder and interaction both play a role in multi-wall nanotubes. Experimentally, a wealth of data is available for the tunneling density of states, and one can in particular probe the full crossover from the ballistic to the diffusive and on to the localized regime. The development of a field theory for this situation is particularly urgent, and sigma models are likely to allow for progress.

In the near future, relevant experimental results on nanoscopic devices for cold atoms (such as atom chips) are expected. In many ways these will be complementary to results for carbon-nanotubes and they are bound to pose further challenges to the theoretical framework.

C. Fundamental developments in field theories for disordered systems

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[20] F. Lesage and H. Saleur, Phys. Rev. Lett. 80, 4370 (1998).

There is at the present time no a clear idea about the type of conformal field theory that may describe critical disordered electronic systems, such as the transitions between plateaus in the Integer quantum Hall effect. Earlier proposals were based on replica approaches or supersymmetric reformulations, and assumed the conformal field theory to be a Wess Zumino model, maybe properly gauged. Back then, too little was known about such theories in the case of non compact groups and supergroups to entirely justify or invalidate the various proposals. In the past few years, however, there has been tremendous progress on non compact conformal field theories coming from string theory. Models such as the Liouville theory or the SL(2,R) Wess Zumino models are by now much better understood. We feel it is time to reexamine under the light of these solutions the possible theories describing critical disordered electronic systems. This will involve building properly theories such as the OSP(2N | 2N) and SL(N | N) Wess Zumino models, by studying systematically the correlation functions and modular invariants, and investigating in particular the role of normalizable versus non-normalizable operators, spectral flow, operators with arbitrarily large negative dimension, and the presence of logarithmic structures.

There is however growing suspicion that the theories one is looking for are of another type altogether, and that the current symmetry is broken by anomalous logarithmic terms in the operator product expansions. Examples of such `logarithmic current theories' have been explored in Ref.[17] and were found to exhibit a complex structure, with dense sets of conformal weights, and symmetries that are reminiscent of, but differ from, Yangian symmetries. Another of our goals is to study these theories - such as the super CP(n | m) model with topological angle or the critical OSP(N | 2M) - in more details. This will be done by understanding better the symmetries in the lattice formulation, and building a general formalism to define and classify logarithmic current algebras. Another promising direction is to use the exact S matrix approach, and try for non perturbative solutions of the sigma models at intermediate couplings. Such calculations would become essential in future applications.

Beside the pure field theory approach, another way to tackle critical disordered electronic systems is to use network models and the related quantum spin chains. An open problem concerns what the continuum limit of spin chains (integrable or not) with supergroup symmetries might be. Examples include Wess Zumino models as well as Goldstone phases. Another one of our goals is to clarify this question and try to gain some systematic understanding of the possibilities, first in the compact cases of OSP(1 | 2) and SL(2 | 1), then in non-compact cases (where the spin space is infinite at each site). This understanding would be gained by a mix of techniques like numerical diagonalization and study of zeroes of partition functions to Bethe ansatz calculations.

Network models also have a natural geometrical description, in terms of averages of sums over Feynman paths. This suggests that they may map onto lattice models of random walks of various kinds. For a certain class of such models, called Class C, it is already known how to do this: the corresponding geometrical objects are then amenable to the powerful new methods of Schramm-Loewner evolution. A promising avenue is to extend these ideas to cover more general network models, including that of the integer quantum Hall plateau transition.

Expected benefit from European collaboration and European context

Europe is presently a center of tradition and excellence in the study of integrable systems and quantum field theory. European scientists have played leading roles in several major developments in these areas. Many of these scientists participate in the activities of the European network EUCLID, devoted to integrable models and applications. European groups are also building strength very quickly in string theory. However, it is fair to say that little of the theoretical excellence has been turned towards applications in experimental physics. This is especially regrettable since Europe excels as well in experiments on nanoscopic and low-dimensional systems.

It is a major goal of our proposed programme to change this situation. One way to do this will be to foster interactions between the more formal and more applied researchers who usually, due to the specialized nature of funding and conferences, have few opportunities to meet. Integration in a single European programme, where already many collaborations and relationships within different specialities exist, will no doubt be of considerable help. In this respect, we have in mind to organize interdisciplinary conferences and schools, providing opportunities for productive encounters between members of our programme and other experts (experimentalists and other theorists in condensed matter physics, field and string theorists, etc.). In addition, we will stimulate the mobility of young researchers between the different nodes in Europe and widely publicize the activities related to this programme.

In this way, we think it is possible to build on our considerable but slightly scattered scientific resources to develop a unique programme of research, aiming at the development of new theoretical paradigms of potential importance in experimental physics, and thus bridging advanced theory with advanced experimental applications. A programme of this type would have tremendous difficulties being developed in the US where funding in physics is much compartmented. It is thus natural to hope that success in this activity should lead to European leadership in this very exciting area of physics.

Proposed activities and budget

The duration of the programme is 5 years. We plan to run several activities, including the organization of conferences and schools, the setting up of a website, and the publications of volumes of lecture notes and proceedings, grants for graduate students, postdocs and senior scientists.

The estimate budget of the programme is in average 180000 E/y, for a total of 900000 Euro.

More specifically, we plan to organize in the first, third and fifth year of the programme

(a) a conference of 4 days, with about 60 participants, followed by

(b) a meeting of the steering committee.

The estimated cost of each of these activities is 60000 Euro, for a total of 1800000 Euro

Moreover, we plan to organize in the second and in the fourth year of the programme

(c) a school of one week, with about 50 participants (mainly graduate students) followed by

(d) a meeting of the steering committee.

The estimated cost of each of these activities is 120000 Euro, for a total of 240000 Euro.

400000 Euro are devoted to short visits and exchange grants for collaborations among the scientists of the different European groups in the 5 years of the programme running.

The remaining 80000 Euro should cover the cost of: (a) publicity, website, publications and other communication activities (45000 E); (b) secretarial help and running expenses of Chair's institute (25000 E); (c) a programme coordinator (10000 E)

In view of the many other academic duties of the Chair, the programme coordinator will be of considerable help in assisting the Chair in achieving the Programme aims and in updating the relevant documentation. The proposed person is Dr. Davide Controzzi, a post-doctoral fellow of SISSA, in Trieste.

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5 most relevant publications since 1998
F. Lesage, H. Saleur, Strong coupling resistivity in the Kondo model, Phys. Rev. Lett. 82 (1999), 4540--4543
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