STRONGLY CORRELATED ELECTRON SYSTEMS

(January to June 2000)

Report from the Organisers: D.M. Edwards (Imperial), A.C. Hewson (Imperial), P.B. Littlewood (Cambridge) and A.M. Tsvelik (Oxford).

Introduction

The aim of condensed matter theory is to understand the macroscopic behaviour of systems, in all their rich diversity, starting from a detailed description of the individual particles and the way they interact. This enterprise of relating the microscopic to the macroscopic has had some remarkable success stories, such as the understanding of phase transitions in the framework of the renormalization group, and the BCS theory of superconductivity. The general framework for understanding the behaviour of electrons in metals is that of Fermi-liquid theory (which has been established within a convergent perturbation theory) where the electrons are described in terms of renormalized quasi-particles, which are in one-to-one correspondence with the single particle excitations of the non-interacting systems, plus collective excitations which arise from the residual inter-particle interactions. However, in recent years an increasing number of metallic systems have been discovered where this framework does not provide a satisfactory description of their behaviour, and the quasi-particle picture appears to have broken down. This is the case in an important class of metallic systems, the high temperature (cuprate) superconductors. Though they were discovered experimentally more than ten years ago, there is no generally accepted theory of their superconductivity. Such a theory is unlikely to emerge without a prior understanding of how and why Fermi-liquid theory breaks down in the normal state of these materials, and this has become an important theoretical question to solve.
Apart from the high temperature superconductors, Fermi-liquid theory is known to break down in other types of metallic systems. It breaks down in one dimensional metals, and this is well understood. The Luttinger liquid framework replaces the Fermi-liquid one, and the low-lying excitations are purely collective ones, rather than quasi-electrons, which obey bose rather than fermi statistics. It has also been observed to breakdown in certain three dimensional metallic compounds under applied pressure, and in some alloys at particular concentrations, at the point at which long range magnetic order can no longer be sustained. This is known as quantum critical behaviour and may be relevant for an understanding of the cuprate superconductors.

Unusual excitations have also been observed in quantum Hall systems, which are two dimensional electron gases in which the motion of the electrons is further restrained by a strong magnetic field. They display anomalies in their conductivity, dependent on the number of electrons, which are known as the `integer' and `fractional quantum Hall effect'.

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The common feature of all these situations is the constrained motion of the electrons as a result of restricted dimensionality and/or the strong inter-electron interactions. These constraints induce complicated correlated motion in the motion of the electrons, and hence the term which is used to describe them collectively: *'Strongly Correlated Electron Systems'*.

Explicit mathematical models have been put forward to explain these various manifestations of strongly correlated electron behaviour. The simplest models proposed for an understanding of the breakdown of Fermi-liquid theory in the cuprate superconductors are the Hubbard and t-J models, which describe the motion of the electrons in the CuO_2 planes of these materials and the strong inter-electron interactions they experience at the Cu sites. Standard many-body techniques for predicting the behaviour of these models, such as perturbation theory and mean field theory are not applicable. Perturbation theory is inappropriate because the electron-electron interactions are very strong, and mean field theory takes no account of the subtle inter-electron correlations which are induced. Quantum Monte Carlo, and other numerical techniques, are restricted to small cluster sizes and are of limited value as the results cannot be used for comparison with experiment.

A great variety of non-perturbative techniques have been developed for tackling quantum many-body problems. These range from quantum field theory approaches, Bethe ansatz, conformal field theory, renormalization group, variational, dynamic mean field theories, slave bosons, 1/d and 1/N expansions (d-dimensionality, N-number of degrees of freedom), plus a range of purely numerical techniques. All these techniques have their strengths and limitations, and considerable progress has been made on many fronts. They have provided insights and quantitative descriptions of the behaviour of heavy fermions, metal-insulator transitions, transport in one dimensional conductors, integer and fractional quantum Hall systems, and many aspects of the behaviour of high temperature superconductors. However, some of the most important questions, such as `why are the cuprates superconductors?' remain to be answered. What is more there is no consensus as to what are the physically relevant models to provide a basis to answer this question. Quite a number of plausible `scenarios' have been proposed but a fully quantitative theory is lacking.

The aim of the workshop has been to tackle these problems by bringing into dialogue a wide range of experts in quantum many-body and condensed matter physics. No one technique is likely to provide the answers to all the questions we have about these complex systems, and their subtle and, at times, strange behaviour. However, we felt that by pooling our resources, we could clarify the issues, formulate the appropriate models, and develop the effective mathematical techniques for dealing with this class of many-body systems.

Experimental techniques for probing strongly correlated electron materials, such as photemission, are developing rapidly and are providing new and more accurate information on the behaviour of these systems. These results are putting theories to a more severe tests, and revealing surprising new features, such as localization in the form of stripes in the cuprate superconductors. Many new materials are also being developed, in which the electrons are constrained in areas of mesoscopic dimensions, such as in quantum dots. These provide particularly good systems for testing theory against experiment as the parameters can be controlled and varied by applied voltages. Hence we felt it important to have some input from experimental work in the field at points within the programme.

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Organisation

The programme was planned by the organisers, David Edwards, Alex Hewson, Peter Littlewood and Alexei Tsvelik, who then shared the responsibilities for different parts of the programme. Apart from the conferences and workshops, there was a regular programme of seminars, running at the rate of three per week, which was arranged so as to give each participant an opportunity to talk about their work early on during their stay. We also had a few open discussion periods which focussed on specific controversial issues.

To convey the flavour of our programme to a wider mathematical audience A.M. Tsvelik and M. Stone gave Institute Seminars on 'Quantum Integrable Models' and 'Path Integrals for Spin: From Molecular Cluster to Holomorphic Line Bundles'. To reach a much more general audience D.M. Edwards gave a well-attended lecture during Science Week in which he explained why our work at the Newton Institute on strongly correlated electrons was interesting and important and how it fitted into the wider context of the History of the Universe.

Participation

We had 71 long-stay participants, with an average stay of six weeks, and 109 short-stay participants, from a total of 23 countries during the course of the programme. We were very grateful to the administrative staff at the Institute for making all this possible. Arrangements were made not only for these visits, but also for all the extra conferences and workshops, with remarkable efficiency and good humour. It lightened our task as organisers making it an enjoyable and rewarding experience.

As well as a significant UK participation in the programme, 47 in total, there was an encouraging amount of interaction between visitors and groups within the UK, and 35 seminars were given by our participants at venues outside the Institute. Many collaborations were initiated or continued during the workshop, and there was much appreciation expressed by participants of the layout and organisation at the Institute in creating a stimulating atmosphere and promoting informal discussions.

Interaction was encouraged between participants and the members of research groups in Cambridge, both theoretical and experimental, involved in similar work. Many from these groups attended our seminars, and several of them gave talks within our seminar programme.

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Conferences and Workshops

Newton Institute - ESF Conference: Non-Fermi Liquid Effects in Metallic Systems with Strong Electron Correlations

Organisers: David Edwards, Peter Littlewood and Hilbert von Löhneysen

This conference, held during the period 5-8 January, was an excellent way to start the programme. It was organised in conjunction with the European Science Foundation programme "Fermi-liquid instabilities in correlated metals" (FERLIN) which has a strong emphasis on experiment. The breakdown of Fermi liquid theory is perhaps the dominant central issue in strongly correlated electron systems and it was a good beginning to confront existing theory with new experimental data. The talks centred around four main topics: high temperature superconductors, heavy fermion materials near quantum critical points, fractional quantum Hall effect and low dimensional systems.

The speakers were: GG Lonzarich (Cambridge), F Steglich (Dresden), P Wölfle (Karlsruhe), O Stockert (Bristol), P Coleman (Rutgers), A Georges (ENS, Paris) SM Girvin (Indiana), JH Smet (Stuttgart), N Read (Yale), M Rozenberg (Buenos Aires), AO Gogolin (IC, London), J Nicholls (Cambridge), PM Chaikin (Princeton), AJ Millis (Rutgers), A Freimuth (Köln), A Chubukov (Wisconsin), BD Rainford (Southampton), Q Si (Rice), M Long (Birmingham) and M Zhitomirsky (ETH, Zürich). More than 80 people attended from 15 different countries and 18 of them contributed to a very successful poster session. This was preceded by an oral session in which each contributor had five minutes to advertise his poster.

Computational Many-body Physics

Organisers: Peter Littlewood and Philippe Monthoux
This Euroworkshop was held over the long weekend, 18-21 February. There were 21 invited speakers and the talks were spread out over four days. It was very much an international event with participants coming from Argentina, China, Japan and the United States, as well as many parts of Europe. Computational many-body methods constitute an important class of non-perturbational techniques for tackling problems involving strong correlation. The talks covered the main areas of activity in this field, renormalization group, quantum Monte Carlo, correlated wavefunctions, high temperature series, and Feynman diagram summation. There were of the order of 50-60 attending the talks. The general consensus was that it was very beneficial to be able to get together to concentrate on specifically computational approaches, to discuss their relative strengths and limitations, and to devise strategies for future work. Several of the participants were able to stay on for a longer period, so we were able to have more extended discussions, and additional seminars.

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New Theoretical Approaches to Strongly Correlated Systems

Organiser: Alexei Tsvelik
This EU workshop and Nato Advanced Study Institute was held during the period 10-20 April. Five broad areas of current activity in the theory of strongly correlated electron systems were covered in the ten days of the programme. These were: field theoretic methods, including conformal field theory, with particular application to one dimensional systems; problems relating to disorder and localization; dynamic mean field theory; systems with quantum critical points; doped Mott insulators and, in particular, problems relating to the high temperature superconductors. Some of the highlights were the outstanding lectures by Affleck on quantum field theory approaches, Saleur on conformal field theory and integrable systems, Cardy on problems with disorder, Kotliar and Georges on dynamic mean field theory and its applications, Sachdev on quantum critical points, Giamarchi on low dimensional systems and disorder, and Kivelson on theories of the cuprate superconductors.
Though the emphasis was on the theoretical methods for tackling this class of difficult many-body problems, there were discussions on relating theory to experiment in many of the talks, particularly those by Essler, Giamarchi, Kotliar, Georges and Kivelson. The whole programme conveyed a good picture of the theoretical problems in this field and the diversity of the approaches which are being used to tackle them.

Colossal Magnetoresistance

Organiser: Peter Littlewood

This two-day focussed meeting, which received financial support from the EU under the INTAS programme, was held 23-24 June, prior to the final meeting, with about 60 participants, many from countries in the former Soviet Union who are participants in this INTAS contract. Some strongly-correlated ferromagnets, particularly perovskite manganese oxides, exhibit a remarkable change in resistivity that can be influenced by modest magnetic fields -- so-called 'colossal' magnetoresistance. This meeting was an opportunity for theory and experiment to find themselves in rare agreement over many of the basic issues in the origin of the effect. Important talks included: manipulating materials chemistry to control physical properties (Attfield, Cambridge); theory and experiment on the surprising isotope effect on the transition (Yakubovskii, Moscow and Plakida, Dubna); topological excitations and the Hall effect(Majumdar, Allahabad); and charge-ordering and phase separation (Khomskii, Groningen).

Strongly Correlated Electron Systems - Novel Physics and New Materials

Organiser: Peter Littlewood

This final conference of the programme, which received financial support from the EU, was held 26-30 June, with more than 100 participants. In recent years, more and more systems have been discovered or constructed which have unusual properties due to strong correlations between the electrons. These include unusual alloys, such as those that display both magnetism and superconductivity, but also fabricated mesoscopic systems such as quantum dots and nanotubes. These have not only presented new problems but also different realizations of old ones, ones in which the parameters are easier to control and hence offer more scope for detailed comparison of theory and experiment. This conference was organised to focus on these developments and the future potential directions of strong correlation research.

Amongst the many stimulating and exciting talks were those by D. Cobden, S. De Franceschi and K.Matveev on experiment and theory on quantum dots and nanotubes, P. Johnson, H. Mook, M. Randeira, P. Horsch and S. Kivelson on recent experiment and theory for cuprate superconductors, and H.R. Ott, M. Aronson and T.M. Rice on the problems posed by the unusual behaviour observed in hexaborides.

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Achievements

Most major advances in condensed matter theory occur by piecing together insights from both phenomenological and microscopic models and, more recently, by complementing these with numerical approaches using the full power of modern computers. During the programme we succeeded in bringing people with these various starting-points together in one place so that such synthesis could begin more readily. It is too early to report on the longer term effects but the most immediate developments along these lines were between groups of people all concerned with a particular type of problem but coming from different backgrounds. For example this occurred amongst the experts on integrable models. Those more concerned with the application to models describing experimental systems, such as F.H.L. Essler, N. Andrei and A.M. Tsvelik, had important discussions with people like S. Lukyanov whose approach is more formal. Lukyanov and Essler collaborated on a renormalization group treatment of the short-distance behaviour of correlation functions in the integrable Sine-Gordon model. This complemented the form-factor approach to the long-distance behaviour used by Essler and Tsvelik in their paper, completed during the programme, on optical conductivity of one-dimensional Mott insulators. Such systems, which may apply to some quasi-one-dimensional organic conductors, can be described by the integrable Sine-Gordon model within the framework of a low energy effective field theory. Tsvelik also collaborated with A. Schofield and T.M. Rice on non-linear optical properties of Mott insulators. The exact calculation of correlation functions in an integrable model is a formidable problem. As a possible first step F.D.M. Haldane worked on the identification of the generators of the Yangian SO(4) quantum symmetry of the integrable single-impurity Anderson model. Haldane also had discussions with N. Andrei and M. Lavagna on new integrable models in the context of the multichannel Kondo model.

Many participants came from a physics background but were working on highly mathematical problems like those mentioned above. Others like Y.Y. Lobanov and G.S. Tian, each of whom produced a Newton Institute preprint, were more explicitly mathematical in outlook. Lobanov developed a new technique for numerical functional integration which can be applied to open quantum systems. Tian proved two theorems stating inequalities between charge and spin excitation gaps for some models of strongly correlated systems.

There was naturally much activity on various aspects of high temperature superconductors and it became clear that experiment and theory are combining to sharpen the points of controversy. T. Xiang and Tai-kai Ng wrote a paper showing how current noise spectra of a tunnel junction between an underdoped and optimally doped cuprate superconductor can probe pair fluctuations in the underdoped material above its transition temperature. It is concluded that a suitable experimental study might settle the question of whether or not the famous observed pseudo-gap is an incipient pairing gap. C. Nayak and P. Fendley initiated a collaboration during the Nato ASI which has resulted in a paper on tunneling between Luttinger liquids. They map the problem of coupled Luttinger liquids on to the 4-state chiral clock model and draw conclusions which challenge some of P.W. Anderson's ideas on high T_c cuprates. T.V. Ramakrishnan, who was a Rothschild professor during his two-month stay, was strongly involved in discussions on high T_c which included people from the strong Cambridge experimental group. He wrote two papers on the subject including one on transport properties in a magnetic field. A seminar by T.M. Rice, reporting very recent work in his group, made a strong impression. An "N-patch" renormalization group analysis of the two-dimensional Hubbard model shows the viability of a new scenario for the breakdown of a Fermi liquid which may relate to the high-T_c cuprates. On the path from a Fermi liquid to a Mott insulator, with increasing electron density, a precursor of the Mott gap opens on the parts of the Fermi surface susceptible to umklapp scattering.

The quantum Hall effect occupied a central place in the programme. In the fractional quantum Hall regime electrons are in the limit of extreme correlation where the low energy properties are determined entirely by electron-electron interactions and perturbation theory fails completely. During the programme V.I. Falko announced the solution of an outstanding problem in the theory of quantum Hall ferromagnets. The gap in the excitation spectrum is generally believed to be the activation energy of a skyrmion-antiskyrmion pair, but this is larger than the gap which is observed. Dropping the assumption of particle-hole symmetry implicit in previous work Falko and Iodanski show that a much smaller activation energy exists due to the creation of a bare electron and an antiskyrmion. Yong Baek Kim wrote a paper investigating the limitations of the Chern-Simons composite fermion theory of the fractional quantum Hall effect for the important case of a half-filled Landau level. He did this by considering the frictional drag between two two-dimensional electron gases in a double-well potential structure, and recently followed this up with a further paper using a more microscopic dipolar composite fermion approach. J.J. Betouras and J.T. Chalker completed a paper on the effects of interactions and disorder on mesoscopic conductance fluctuations in the two-dimensional chiral metal formed by edge states in a multilayer quantum Hall system. N. d'Ambrumenil worked on edge modes in fractional quantum Hall systems and N.R. Cooper pushed forward his work on interlayer conductance of bilayer quantum Hall systems.

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Dynamic mean field theory has provided a way of studying the Mott metal-insulator transition in strong correlation models, such as the Hubbard model. The numerical calculations are difficult, however, to carry out particularly in the immediate region of the transition. Y. Ono, R. Bulla and A.C. Hewson applied a linearized form of this theory to the two-band Hubbard model. Their approach gives analytic results which generate the complete metal insulator phase diagram for this model, and they have shown that it is in excellent agreement with numerical results. This approach should be useful for studying the metal-insulator transition in other models.

Renormalization group techniques have proved to be a very effective in tackling strong correlation impurity problems and have recently been combined with dynamic mean field theory for calculations for Hubbard and periodic Anderson models. S. Bradley, A.C. Hewson, R. Bulla and Y. Ono combined resources to apply this approach to study the interplay of phonons and strong electron correlation. The first stage, the calculations for impurity models have been completed and the work is being extended to include the dynamic mean field theory to study the behaviour of lattice models.

It was shown by A.C. Hewson, a few years ago, that another renormalization group technique, renormalized perturbation theory, is a very effective way of calculating the energy behaviour of a number of strong correlation impurity and lattice models. In particular, he demonstrated that, when carried out to second order for the impurity Anderson model, it gives asymptotically exact results for the leading low temperature conductivity and thermodynamic behaviour. Using an entirely different approach based on conformal field theory, H. Saleur has derived exact expressions for the next leading order low temperature terms in the conductivity using boundary conformal field theory. The renormalized perturbation approach taken up to fourth order would generate similar terms. It is of some interest, therefore, as the renormalized perturbation theory is a more generally applicable technique, to see whether it gives these next leading correction terms exactly if taken to fourth order. These calculations are well under way and Hewson expects to be able to answer this question in the near future.

Rather than working on generic models, such as the Hubbard model, M.W. Long developed models for some specific materials, oxides of vanadium. The symmetry of different vanadium d-orbitals is regarded of prime importance and a new theory of the metal-insulator transition in V_2O_3, in terms of orbital ordering, was written up. Long's incisive questioning during seminars was a notable and welcome feature of his two-month stay. In the same spirit G.A. Gehring was developing a new theory of the charge ordering in magnetite, the oldest known magnetic material (lodestone). Once again the nature of the atomic orbitals is crucial.

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Electrons confined in mesoscopic structures such as quantum dots and nanotubes inevitably exhibit strong correlation and these new materials featured strongly in the final conference. During the programme K.A. Matveev completed work with A.V. Andreev on the thermoelectric properties of quantum dots in the Coulomb blockade regime. A particular interest of this work is the possible application of such small devices as micro-refrigerators. J. von Delft was concerned with Kondo effects in quantum dots and had much useful discussion with the Kondo experts.

There was a certain amount of activity on spin chains which are in the extreme limit of strong correlation where an integral number of electrons sit on each site and only spin degrees of freedom remain. Tai-Kai Ng finished a paper on topological effects in short antiferromagnetic Heisenberg spin chains. He gives numerical evidence, using the density matrix renormalization group technique, that the topological effect which is responsible for the difference between integer and half-integer spin infinite chains (Haldane conjecture) also manifests itself as end-states which exist even for short chains where the Haldane gap is unobservable. T. Xiang completed a paper in which he and his co-authors used the transfer matrix renormalization group method to calculate numerically the magnetic susceptibility and specific heat of the spin 1 Heisenberg chain with linear and biquadratic exchange. T. Giamarchi was at the centre of discussions over a wide range of topics. However he completed a long paper on a general renormalization group analysis of creep and pinning in disordered media. In the context of the present programme this relates to charge density waves, Wigner crystals and vortex lattices.

During the programme many people became aware for the first time of the theoretical problem posed by an apparently new type of itinerant electron ferromagnetism recently observed in alkaline earth hexaborides doped with small amounts of lanthanum. Although the magnetic moment is very small the Curie temperature is extraordinarily high. These new materials featured strongly in two of the conferences and in several seminars. A special discussion session was held in which T.M. Rice expounded the doped excitonic insulator theory and D.M Edwards put forward some different ideas he is developing.

A different class of problems involving strong correlation physics arises with nonlinear optical excitation in semiconductors. Littlewood finished calculations on the thermodynamic properties of a model exhibiting a Bose-condensed ground state of excitons, which also relates to the recent proposals of Rice and coworkers on the hexaborides mentioned above.

Quantum critical fluctuations occur near a phase transition at zero temperature, typically between a paramagnet and a magnetically ordered state. They are believed to play an important role in the superconductivity of many heavy fermion compounds and both spin and charge fluctuations are invoked in various theories of the high-T_c cuprates. Fermi liquid theory is found to break down near a quantum critical point. Quantum critical behaviour was therefore a recurring theme during the conferences and discussions but the theory is still at the phenomenological stage, as stressed by P. Coleman in his seminar. Inelastic neutron scattering measurements on many systems indicate non-analytic behaviour of the magnetic response which departs markedly from the mean- field theory of Hertz and Millis. The theory of quantum phase transitions is still in its infancy and should make an excellent topic for a Newton Institute programme in two or three years time.

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