Final Report,
STEP 2013 – Superconductivity. Theory, Experiments, and Phenomena

International Summer School, Cargèse, France,
August 5-17, 2013

Organizers:

Andrey V. Chubukov	University of Wisconsin
Dirk van der Marel	Université de Genève
Jörg Schmalian	Karlsruher Institut für Technologie
Henri Alloul	Université Paris Sud

1. Summary

The motivation for this summer school was that over the last decade the field of superconductivity witnessed a remarkable increase in its impact on modern society. Superconductivity plays a key role in high field magnets for medical applications, particle accelerators and thermonuclear reactors, while higher resolution magnetic resonance imaging furthers the development of improved high-Tc superconductor technology. Examples include: The discovery of the Higgs boson at LHC using a huge array of superconducting bending magnets, the International Thermonuclear Experimental Reactor, using 12 Tesla superconducting magnets for plasma confinement, the ongoing development of powerful new superconducting generators, wind turbines, cables and fault current limiters, and last but not least superconductor based magnetic levitation, such as the construction starting in 2014 of the Chuo Shinkansen Maglev line between Tokyo and Osaka by Central Japan Railway.
At the same time scientists worldwide are discovering a rapid succession of materials, where superconductivity is found in competition with other emergent behavior and on the theoretical front great progress has been made in understanding the superconducting behavior of materials such as cuprates, heavy-fermion, and organic superconductors, and Fe-pnictides or Fe-chalcogenides.

Given these exciting developments, we organized a summer school at the "Institut d'Études Scientifiques de Cargèse" in Corsica, France. The school was aimed at bringing to junior scientists, entering the correlated electron community, novel and exciting experiments, theory, and phenomenology of superconductors.

The school covered a wide variety of topics related to superconductivity, such as the phenomenology and symmetry aspects of superconductors, collective modes in superconductors, microscopic mechanisms of unconventional superconductivity, superconductivity in mesoscopic systems, numerous experimental end theoretical tools to investigate novel superconductors, and even an historical account of the theory of superconductivity. The school dealt with the most advanced theoretical methods for the study of these issues, along with a selection of different experimental approaches used to probe this new exciting physics.

The school was set in a format that allowed for longer pedagogical lectures, more recent research talks and contributions from the participants. We had intense discussion sessions (described in more detail in the next section) that allowed for a strong interactive participation of the school attendants. The majority of the school participants were PhD students and post-docs, coming mostly from European and North American countries.

2. Scientific content and discussions

Presentations at the school were given in different ways aiming at different perspectives. Here we report each kind of presentation, its purpose and its outcomes. Copies of the presentation slides are available at the school web site:

http://www.step-2013.org/

2.1. Lectures

Lecturers were allotted one 90 minutes slot and a second 60 minutes slot, each included 15 minutes for discussions at the end. In addition, approximately half-way during the 90 minutes lecture we stopped for another question/discussion session. This allowed students to “catch-up” with the lecture in case they could not follow certain details and gave the lecturers an early impression whether the presentation was adequate to the audience. These discussion sessions during the lecture turned out to be extremely efficient and were well received by all participants. We specifically asked for lectures to be pedagogical and at least 2/3 of the time to be used to present a broad overview of the field, not the individual research. The vast majority of the speakers followed these guidelines which lead to a large participation of the audience in the discussion portion of the lectures. In the following we describe the specific lectures presented at the school.

Here we summarize the content of the lectures. Speakers are ordered alphabetically. For the order of the talk during the school, please consult the program.

James Annett (University of Bristol) gave general overview of the concept unconventional superconductivity, starting with the basic symmetry principles and then developing simple models of unconventional pairing models relevant for a variety of different materials. Examples were taken from systems such as heavy fermion superconductors, high T_c cuprates, organic and pnictide systems among others. He also introduced the pairing states of superfluid helium-3 and its possible analogues in superconductivity such as the ruthenate Sr_2RuO_4.

Girsh Blumberg (Rutgers) gave an introduction into the collective modes in superconductors and how they can be measured using Raman spectroscopy. Examples were the Leggett mode in MgB_2 and the Bardasis-Schrieffer mode in cuprate superconductors. In addition, he presented Raman results for the iron based superconductors and showed that a significant increase of the response occurs near the structural phase transition of these systems.

Andrey Chubukov *Wisconsin) gave a pedagogical introduction to the microscopic origin of unconventional superconductivity. This lecture was added on short notice to substitute for the lectures that were scheduled to be delivered by Mohit Randeria. It started with the original Kohn-Luttinger instability and its relevance for unconventional superfluidity in liquid helium and went all the way to d-wave superconductivity in the cuprates and s+- superconductivity in the pnictides.

Daniel Esteve (CEA Saclay) introduced the local description of the superconducting order in terms of the Eilenberger and Usadel equations and demonstrated that superconductivity fits in the transmission channel picture ubiquitously used in mesoscopic physics. He then considered different mesoscopic situations of interest: What is the meaning of superconductivity in a small grain made of a superconducting material? When is the parity of the electron number relevant? What is the characteristic length-scale of proximity superconductivity? What is the density of states in a normal metal electrode close to a superconducting metal? What is the superconducting order in a superconducting atomic size contact with its electrodes at different phases?

Antoine Georges (Ecole Polytechnique) reviewed recent progress in the theoretical understanding of these properties, with a dynamical mean-field theory perspective. He discussed that the proximity of a Mott insulating state, and corresponding instabilities, is a defining feature of a number of such materials, will emphasize however that the Hund's rule coupling induces strong correlation effects in metallic compounds which are not close to a Mott insulator. This was shown to be especially relevant for oxides of 4d transition metals such as ruthenates, and also for iron-based superconductors. The Hund's rule coupling was then shown to have antagonistic effects on the Mott gap and on the quasi-particle coherence scale

Laura Greene (Urbana) gave an overview of quasi-particle scattering spectroscopy (QPS), also called point contact spectroscopy (PCS), a well-established spectroscopic tool for detecting phonons, magnons, and Kondo impurities. She demonstrated how in superconductors, details of the order parameter including the gap structure and symmetry are detected via Andreev scattering.

Peter Hirschfeld (Univ. of Florida) eviewed approaches to the investigation of superconductivity in the iron pnictides where he focused on pairing from spin and orbital fluctuations in the Fe 3-d states. He discussed how well random phase approximation based approaches allow us to understand current experiments on the superconducting state of various Fe-based systems. In the second part of his lectures, he focused on disorder effects on T_c and superconducting properties in these materials. He showed that they are richer than in one-band systems due to the need to separate intra- and interband scattering.

Daniel Loss (Basel) gave a pedagogical introduction into the physics of Majorana bound states in superconductors and quantum spin chains. He then reviewed the main experimental advances in the field. He demonstrated how to construct Majorana fermions in hybrid nanowires and showed how rotating magnetic fields can be used to generate ‘synthetic’ spin orbit interaction. Finally he discussed Majorana fermions in self-tunable RKKY-systems.

Dirk Van der Marel (Geneva) introduced the phenomenology of the electromagnetic field coupled to the matter in the normal and superconducting state. Examples of various superconducting materials (low and high T_c) were introduced and discussed. Furthermore an introduction was given in linear response theory of correlated electrons, and the concepts of sum-rules in relation to conservation principles and the average kinetic energy of a material.

Xavier Obradors (Barcelona) first presented the major past developments and the present existing bottlenecks towards successful manufacturing superconducting tapes based on $YBa_2Cu_3O_7$. Emphasis was made in describing the diverse nanostructuration opportunities to enhance vortex pinning based on cost-effective chemical deposition approaches. In addition he gave a review of the most outstanding and promising power applications, spanning from systems working under low field conditions (cables, Fault Current limiters, transformers) to high and ultra-high magnetic field devices (rotating machinery, magnets, etc.).

Joe Orenstein (Berkeley) gave an overview of the numerous optical techniques that allow the detection of broken symmetries. He demonstrated that optical properties are very powerful probes of the symmetries that define what is known as the point group – the set of operations that map the unit cell of a crystal into itself. He also described how the Berry phase helps to provide a physical picture of the optical response in several instances. Examples of broken symmetry states that were discussed include ferromagnets, antiferromagnets, and superconductors.

Sri Raghu (Stanford) described the mechanism of unconventional superconductivity in the Hubbard model in the limit of weak-coupling, where asymptotically exact solutions can be obtained. This presentation followed a detailed introduction of the renormalization group approach to fermions. He then considered the role of longer range (but finite) repulsive interactions and present explicit examples of ground states of unconventional superconductors in a variety of lattice systems obtained from this analysis

Subir Sachdev (Harvard) described the theory of symmetry-breaking quantum phase transitions in metals, especially in two spatial dimensions. The emphasis was given on transitions involving onset of spin density wave order that is relevant to the phase diagrams of numerous high temperature superconductors. He discussed the rich phenomenology of this transition, including its connection to superconductivity and charge ordering, and the emergence of pseudospin symmetry.

Joerg Schmalian (Karlsruhe) presented a lecture that summarized failed attempts to explain superconductivity prior to the BCS theory. More than 45 years passed between Kammerling-Onnes' discovery of superconductivity and the explanation of the phenomenon by Bardeen Cooper and Schrieffer. In the meantime, giants of theoretical physics like Einstein, Bohr, Landau, Heisenberg, or Feynman tried to formulate a microscopic theory of superconductivity. The lecture discussed these very interesting attempts to eluciate the innovative aspect of the BCS theory. It was the last lecture of the school.

Suchitra Sebastian (Cambridge) presented angle-resolved quantum oscillation and magnetoresistance measurements in underdoped YBCO, that resolve the electronic structure of the pseudogap as comprising a nodal twofold staggered Fermi surface in which the rotational symmetry has been transformed.

Jean Marc Triscone (Geneva) gave a general motivation for the search for novel properties at oxide interfaces; He discussed induced superconductivity obtained at oxide surfaces, described in detail the $LaAlO_3/SrTiO_3$ system in which the thickness of the electron gas is found to be a few nanometers at low temperatures. This electron gas with low electronic density, typically $5x10^{13}$ electrons/cm^2, and naturally sandwiched between two insulators is ideal for performing electric field effect experiments allowing the carrier density to be tuned. He discussed the origin of the electron gas; superconductivity; field effect experiments and the phase diagram of the system.

Chandra Varma (Riverside) gave an overview over the numerous collective modes in superconductors and focused his attention to the theoretical description and experimental observation of the amplitude mode (Higgs mode) of superconductivity in systems with charge density wave order. Here the density wave order-parameter served as a sensor of the Higgs mode. Varma concluded this lecture with a discussion whether particle physicists could develop an equally direct way to determine the Higgs boson

2.2. Topical talks

A second kind of presentations covered more cutting edge results and consisted of up-to-date scientific talks. Mostly, the speakers were given 60 minutes out of which 15 were allotted for discussions. These talks came in complement to the overview and more introductory presentations by the lecturers.

David Le Boeuf (Univ. Paris-Sud) discussed recent measurements of the sound velocity in unconventional superconductors and more specifically in the hole-doped high-Tc cuprate superconductor $YBa_2Cu_3O_y$. Sound velocity measurements in this material were used lately to establish remarkable phase boundaries, such as the boundary of static charge order in the magnetic field - temperature phase diagram.

Andrey Chubukov gave a warm-up presentation on basic concepts of superconductivity from repulsion, starting from the Kohn-Luttinger prediction of p-wave pairing below 1 mK in He3. The conditions were introduced for which the notion of a pairing glue becomes applicable, and the role of competing order in hole-doped cuprates and its interplay with superconductivity was explained.

Catherine Pepin (CEA-Saclay) re-visited the problem of the anti-ferromagnetic quantum critical point in two dimensions. Exploiting an analogy with the Anderson localization two dimensional disordered metals, she described the emergence of two types of bosonic modes at the QCP ; a "diffuson"-like mode and a "Cooperon"-like mode. Those modes are related by an intrinsic SU(2) symmetry, forming a composite order parameter, which condenses in the quantum critical region, creating a pseudo-gap.

Francoise Rullier-Albenque (CEA Saclay) gave a pedagodical review of the different fluctuation effects that occur in the vicinity of a superconducting phase transition and demonstrated and how they manifest themselves in the physical properties: conductivity, magnetization, and Nernst effect. These insights were then applied to investigate the role of fluctuations in cuprate superconductors, a work in which large pulsed magnetic fields were used to detect the fluctuation contributions contribution to the in-plane conductivity versus temperature and magnetic field.

Alan Sacuto (Université Paris VII) introduced electronic Raman scattering and showed that it is a very powerful technique to explore superconductors in general and the cuprates phase diagram in particular. He discussed that superconducting and the pseudogap phases affect distinct parts of the Fermi surface and showed how superconductivity and the critical temperature T_c are affected by Fermi surface disturbances related to the pseudogap.

Yvan Sidis (Lab. Laue-Langevin) demonstrated that in condensed matter physics, neutron scattering technique is widely used to probe static and dynamical magnetic properties in a large range of energy and momentum. He then showed that in copper oxide superconductors, a large number of neutron scattering studies suggests the existence of different types of competing instabilities, whose interplay with superconductivity remains to be understood. He gave an overview of the most salient results obtained over the last two decades

Jörg Schmalian gave a lecture on the theoretical ideas about superconductivity predating the BCS theory. Several original ideas, including those of the sharpest minds like Landau, Einstein,Bloch, Bohr, Heisenberg, Kronig etc., did not resist confrontation with experimental facts of superconductors. Yet, more often than not these ideas turned out to be useful in a different context. Conclusion: Explore the unbeaten path.

2.1. Contributed talks

We also reserved time in the program for contributed talks from the school participants. These talks were chosen during the school from the posters presented. There were three contributed talks during this session each with three 20 minutes presentations.

2.2. Meeting with speakers sessions

In order to promote a large participation of all school attendants we reserved, in addition to the ample discussion time discussed earlier six time slots for sessions where speakers met with students to discuss the topics of the talk or simply ask general questions related to the school. Luckily we decided not to organize these discussions via a wiki session, as was done previously during Cargese workshops, as a major thunderstorm in Corsica paralyzed the access to the internet for about half the summer school. Instead we asked students to chair these sessions and to collect questions from the participants if they prefer to ask those questions anonymously. Overall these sessions were a success, as they allowed for yet another reflection on the material presented during the lectures.

3. Assessment of the results

As a whole the vast majority of the lecturers made a large effort to follow the school guidelines. The presentations were very clear and pedagogical. The long discussion times, in particular those in the middle of the lectures, turned out to be extremely useful. They allowed that students could follow not only the first half of each talk, but often get a good understanding of the topics all the way to the end of the presentations. This was also a consequence of lectures prepared with a proper amount of introductory material and overview of the field. Most lecturers made a large effort to avoid presenting her/his results alone and really covered a big picture in their respective fields.

Virtually all school attendants presented a poster which was discussed over two afternoon sessions. These poster sessions were the basis for the choice of contributed talks. These contributed speakers were chosen with a very short notice (24 hours before the contributed session). Nevertheless, the attendants took up the challenge and gave terrific presentations on their respective works.

The meeting with the speakers sessions turned out to work reasonably well. The attendants who hosted the sessions did a wonderful job in addressing the questions asked and promoting a large discussion during the session. The possibility of asking anonymous questions through the student-chairs of the sessions was also appreciated. It allowed for the participation of attendants who did not feel comfortable asking a question during a lecture or a talk.

Let us close this report with some administrative remarks.

The school was attended by 77 participants (29 female, 48 male). Of those 77 participants 56 came from Europe, 3 from Israel, 16 from North America and 2 from Asia. The total number of applicants was 210, making the selection process a major challenge. In the end, the quality of the students who were selected was exceptionel, contributing significantly to the success of the school. In our selection process we also paid attention to admit a group of students who were at a comparable state of their education, fostering the discussion among the students significantly. In addition to the students there were 19 speakers and lecturers (out of which 12 are from Europe and 7 from North America) as well as the 4 organizers. Unfortunately, Mohit Randeria (Ohio State University), who had agreed to lecture on BEC-BCS crossover phenomena and related topics, was unable to attend the school due to problems with getting a visa issued. The organizing committee decided to give minimum travel support and cover the local expenses for almost all the participants. This allowed us to have a large number of young researchers attending the school.

The financial support for the school came from ICAM, Intelbiomat and Triangle de la Physique. The CNRS support the school through the work and logistic provided at l'Institut d'Études Scientifiques de Cargèse (IESC).

STEP-2013: International Summer School on Superconductivity – Theory, Experiments, and Phenomena

August 5 - 17, 2013

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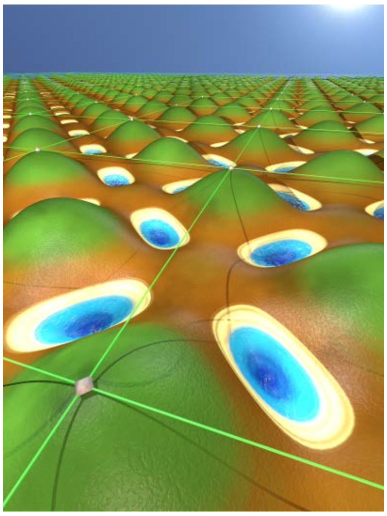

CNRS

ICAM-I2CAM Institute for Complex Adaptive Matter

European Science Foundation — Setting Science Agendas for Europe

Triangle de la Physique

The school will bring together both experts and young researchers, both theorists and experimentalists, working in the field of superconductivity. The program will feature lectures (at least six hours for each subfield) and scientific talks. Most of lecturers will stay in Cargèse for at least a week to have enough time to communicate with the students and other participants. We encourage students, postdocs, and senior researchers from all around the world to attend.

Main Topics:

- Phenomenology of superconductivity and pairing symmetries,
- Mechanisms of superconductivity,
- Mesoscopic aspects of superconductivity and topological superconductivity,
- The search for new superconductors and applications of superconductivity.

Invited Speakers:

James Annett, University of Bristol (Bristol UK),
Girsh Blumberg, State University of New Jersey (Rutgers NJ),
Daniel Esteve, CEA IRAMIS SPEC (Saclay FR),
Laura H. Greene, University of Illinois (Urbana-Champaign IL),
Antoine Georges, École Polytechnique (Palaiseau FR) ,
Peter Hirschfeld, University of Florida (Gainesville FL),
David LeBoeuf, University Paris- Sud (Orsay FR),
Daniel Loss, University of Basel (Basel CH),
Xavier Obradors, ICMAS-CSIC Institut Materials Science Barcelona (Barcelona SP),
Joseph W. Orenstein, University of Berkeley (Berkeley CA),
Catherine Pépin, CEA IPhT (Saclay FR),
Srinivas Raghu, Standford University (Stanford CA),
Mohit Randeria, Ohio State University (Columbus OH),
Florence Rullier-Albenque, CEA IRAMIS SPEC (Saclay FR),
Subir Sachdev, Harvard University (Cambridge, MA),
Alain Sacuto, Université Paris VII (Paris FR),
Suchitra E. Sebastian, University of Cambridge (Cambridge UK),
Yvan Sidis, LLB (Saclay FR),
Jean-Marc Triscone, Université de Genève (Geneva CH)
Chandra M. Varma, University of California (Riverside CA),

Organization Committee:

Andrey V. Chubukov, University of Wisconsin (Madison WI)
Dirk van der Marel, Université de Genève (Geneva CH)
Jörg Schmalian, Karlsruhe Institute of Technology (Karlsruhe DE)
Henri Alloul , Université Paris-Sud (Orsay FR)

Application and registration:

http://www.step-2013.org/
For questions please contact: Nadine Mehl mehl@lps.u-psud.fr

The school will be held at the Institut d'Etudes Scientifiques de Cargèse, Corsica, France August 5-17, 2013

SCOPE OF THE SCHOOL

The school will bring together both experts and young researchers, both theorists and experimentalists, working in the field of superconductivity. The program will feature lectures (at least six hours for each subfield) and scientific talks. Most of lecturers will stay in Cargèse for at least a week to have enough time to communicate with the students and other participants. We encourage students, postdocs, and senior researchers from all around the world to attend.

MAIN TOPICS

- Phenomenology of superconductivity and pairing symmetries,
- Mechanisms of superconductivity,
- Mesoscopic aspects of superconductivity and topological superconductivity,
- The search for new superconductors and applications of superconductivity.

INVITED SPEAKERS:

James Annett, University of Bristol (Bristol UK),
Girsh Blumberg, State University of New Jersey (Rutgers NJ),
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Yvan Sidis, LLB (Saclay FR),
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Chandra M. Varma, University of California (Riverside CA),

ORGANIZATION COMMITTEE:

Andrey V. Chubukov, University of Wisconsin (Madison WI)
Dirk van der Marel, Université de Genève (Geneva CH)
Jörg Schmalian, Karlsruhe Institute of Technology (Karlsruhe DE)
Henri Alloul , Université Paris-Sud (Orsay FR)

The workshop is sponsored by:

ICAM, the Institute for Complex Adaptative Matter (http://www.i2cam.org/).

ESF, European Science Foundation (http://www.esf.org/)

RTRA, Triangle de la Physique (www.triangledelaphysique.fr)

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Summer School Cargèse, STEP 2013, 5 – 17/08/2013: program

Registration open from 8:00 on Tuesday 06

	Tuesday 06/08	Wednesday 07/08	Thursday 08/08	Friday 09/08	Saturday 10/08	Sunday 11/08
9h00 – 10h45	J. Annett	D. Esteve	J. Orenstein	X. Obradors	J. Orenstein	Free day + Excursions
10h45 – 11h15	Coffee break	Coffee break	Coffee break	Coffee break	Coffee break	
11h15 – 12h15	C. Varma	F. Rullier-Albenque	S. Sebastian	L. Greene	A. Chubukov	
12h15 – 14h15	Lunch	Lunch	Lunch	Lunch	Lunch	
14h15 – 16h00	D. van der Marel	J. Annett	Y. Sidis	D. Esteve	X. Obradors	
16h00 – 16h30	Coffee break	Coffee break	Coffee break	Coffee break	Coffee break	
16h30 – 17h30	A. Sacuto	C. Varma	G. Blumberg	S. Sebastian	L. Greene	
17h30 – 19h00	Free time	Meeting with speakers	Free time	Posters Session	Meeting with speakers	

Summer School Cargèse, STEP 2013, 5 – 17/08/2013: program						
	Monday 12/08	**Tuesday 13/08**	**Wednesday 14/08**	**Thursday 15/08**	**Friday 16/08**	**Saturday 17/08**
9h00 – 10h45	P. Hirschfeld	S. Raghu	J.-M. Triscone	S. Raghu	J.-M. Triscone	Departure day
10h45 – 11h15	Coffee break	Coffee break	Coffee break	Coffee break	Coffee break	
11h15 – 12h15	S. Sachdev	D. Loss	D. Le Boeuf	A. Georges	J. Schmalian	
12h15 – 14h15	Lunch	Lunch	Lunch	Lunch	Lunch	
14h15 – 16h00	D. Loss	P. Hirschfeld	D. Van der Marel	Participant talks	Free time	
16h00 – 16h30	Coffee break	Coffee break	Coffee break	Coffee break	Free time	
16h30 – 17h30	G. Blumberg	S. Sachdev	C. Pepin	A. Georges	Free time	
17h30 – 19h00	Posters Session	Meeting with speakers	Free time	Meeting with speakers	Free time	
19h30	Free time	Free time	Banquet	Free time	Free time	

International Summer School on Superconductivity – Theory, Experiments, and Phenomena
August 5 - 17, 2013
List of Invited Speakers, Directors[4] and Co-Directors[1,19,23]

	Civility	NAME First Name	email	Institution
1	M	**ALLOUL Henri**	henri.alloul@u-psud.fr	Université Paris-Sud (Orsay, FR)
2	M	ANNETT James	james.annett@bristol.ac.uk	University of Bristol (Bristol, UK)
3	M	BLUMBERG Girsh	girsh@physics.rutgers.edu	State University of New Jersey (Rutgers, NJ)
4	M	**CHUBUKOV Andrey V.**	chubukov@physics.wisc.edu	University of Wisconsin (Madison, WI)
5	M	ESTEVE Daniel	daniel.esteve@cea.fr	CEA IRAMIS SPEC (Saclay, FR)
6	M	GEORGES Antoine	Antoine.Georges@cpht.polytechnique.fr	École Polytechnique (Palaiseau, FR)
7	MRS	GREENE Laura	lhgreene@illinois.edu	University of Illinois (Urbana-Champaign, IL)
8	M	HIRSCHFELD Peter	pjh@phys.ufl.edu	University of Florida (Gainesville, FL)
9	M	LEBOEUF David	david.le-boeuf@u-psud.fr	University Paris- Sud (Orsay, FR)
10	M	LOSS Daniel	daniel.loss@unibas.ch	University of Basel (Basel, CH)
11	M	OBRADORS Xavier	xavier.obradors@icmab.es	ICMAS-SCIC Institut Materials Science Barcelona (Barcelona, SP)
12	M	OREINSTEIN Joseph W.	jworenstein@lbl.gov	University of Berkeley (Berkeley, CA)
13	MRS	PEPIN Catherine	catherine.pepin@cea.fr	CEA IPhT (Saclay, FR)
14	M	RAGHU Srinivas	sraghu@stanford.edu	Standford University (Stanford, CA)
15	M	RANDERIA Mohit	mohitranderia@gmail.com	Ohio State University (Columbus, OH)
16	MRS	RULLIER-ALBENQUE Florence	florence.albenque-rullier@cea.fr	CEA IRAMIS SPEC (Saclay, FR)
17	M	SACHDEV Subir	sachdev@g.harvard.edu	Harvard University (Cambridge, MA)
18	M	SACUTO Alain	alain.sacuto@univ-paris-diderot.fr	Université Paris VII (Paris, FR)
19	M	**SCHMALIAN Jörg**	joerg.schmalian@kit.edu	Karlsruhe Institute of Technology (Karlsruhe, DE)
20	MRS	SEBASTIAN Suchitra	ses59@cam.ac.uk	University of Cambridge (Cambridge, UK)
21	M	SIDIS Yvan	yvan.sidis@cea.fr	LLB (Saclay, FR)
22	M	TRISCONE Jean-Marc	Jean-Marc.Triscone@unige.ch	Université de Genève (Geneva, CH)
23	M	**VAN DER MAREL Dirk**	dirk.vandermarel@unige.ch	Université de Genève (Genova, CH)
24	M	VARMA Chandra	chandra.varma@ucr.edu	University of California (Riverside, CA)

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19h30	Free time	Free time	Banquet	Free time	Free time	

LIST OF ABSTRACTS		
A1	Unconventional Superconductivity	James Annett, University of Bristol (Bristol UK),
A2	Higgs Bosons and some other Collective Modes in Superconductors.	Chandra Varma, University of California (Riverside CA),
A3	D-Wave Superconductivity by Exchange of Electronic Fluctuations	Chandra Varma, University of California (Riverside CA),
A4	Optical probes of symmetry breaking	Joseph W. Orenstein, University of Berkeley (Berkeley CA),
A5	New insights into the phase diagram of the copper oxide superconductors from electronic Raman scattering	Alain Sacuto, Université Paris VII (Paris FR),
A6	Mesoscopic superconductivity	Daniel Esteve, CEA IRAMIS SPEC (Saclay FR),
A7	Superconducting fluctuations in high-Tc cuprates	Florence Rullier-Albenque, CEA IRAMIS SPEC (Saclay FR),
A8	Fermi surface of the pseudogap state in underdoped cuprate superconductors	Suchitra Sebastian, University of Cambridge (Cambridge UK),
A9	High Tc superconductivity in cuprates	Mohit Randeria, Ohio State University (Columbus OH),
A10	Raman spectroscopy of multiband superconductors and pnictide phase diagram	Girsh Blumberg, State University of New Jersey (Rutgers NJ),
A11	High current nanostructured superconductors: materials challenges for large scale applications	Xavier Obradors, ICMAS-SCIC Institut Materials Science Barcelona (Barcelona SP),
A12	Detecting strong electron correlations with quasiparticle scattering spectroscopy: Electron matter in Fe-pnictides, Fe-chalcogenides, and heavy fermions	Laura Greene, University of Illinois (Urbana-Champaign IL),
A13	High-T_c superconducting cuprates: the neutron scattering legacy	Yvan Sidis, LLB (Saclay FR),
A14	Spin Fluctuaction Theory of FE-based Superconductivity	Peter Hirschfeld, University of Florida (Gainesville FL),
A15	Quantum criticality in metals	Subir Sachdev, Harvard University (Cambridge, MA),
A16	Exotic Spin Physics in Low Dimensions: From Majorana Fermions to Spin Qubits	Daniel Loss, University of Basel (Basel CH),
A17	Weak-coupling theories of unconventional superconductivity	Srinivas Raghu, Standford University (Stanford CA),
A18	Wilsonian theories of quantum critical metals and their instabilities	Srinivas Raghu, Standford University (Stanford CA),
A19	Superconductivity at oxide surfaces, in oxide heterostructures, and at the LaAlO3/SrTiO3 interface.	Jean-Marc Triscone (Geneva CH)
A20	Static charge order in underdoped YBCO measured by sound velocity	David LeBoeuf, University Paris- Sud (Orsay FR)
A21	Optical properties of Superconductors	Dirk van der Marel, Université de Genève (Genvève CH)
A22	Pseudo-gap state from quantum criticality	Catherine Pépin, CEA IPhT (Saclay FR),
A23	Understanding and Controlling the Electronic Properties of Materials with Strong Correlations	Antoine Georges, École Polytechnique (Palaiseau FR) ,

Unconventional Superconductivity

James F. Annett

University of Bristol

Unconventional superconductivity is usually defined as superconductivity in which the condensate of Cooper pairs occurs in a channel other than the usual s-wave spin singlet channel of the original Bardeen Cooper Schrieffer, BCS, theory[1,2]. This typically means that there are clear symmetry related features in the pairing, such as the presence of line or point node in the superconducting gap function, as shown below. Specifically this is usually (but not always) a signature of spontaneously broken symmetries at T_c in addition to the usual U(1) gauge symmetry breaking which is common to all superconductors. Such broken symmetries would also strongly suggest that novel types of pairing mechanisms are in operation, beyond the usual BCS electron-phonon interaction.

In these lectures we shall provide a general overview of these concepts, starting with the basic symmetry principles and then developing simple models of unconventional pairing models relevant for a variety of different materials. Examples will be taken from systems such as heavy fermion superconductors, high Tc cuprates, organic and pnictide systems among others. We shall also introduce the pairing states of superfluid helium-3 and its possible analogues in superconductivty such as the ruthenate Sr_2RuO_4. We shall also examine the influence of unconventional pairing symmetry on measurable physical properties of superconductors, including gap nodal states, novel topological defects (such as half-flux vortices), and sensitivity to disorder.

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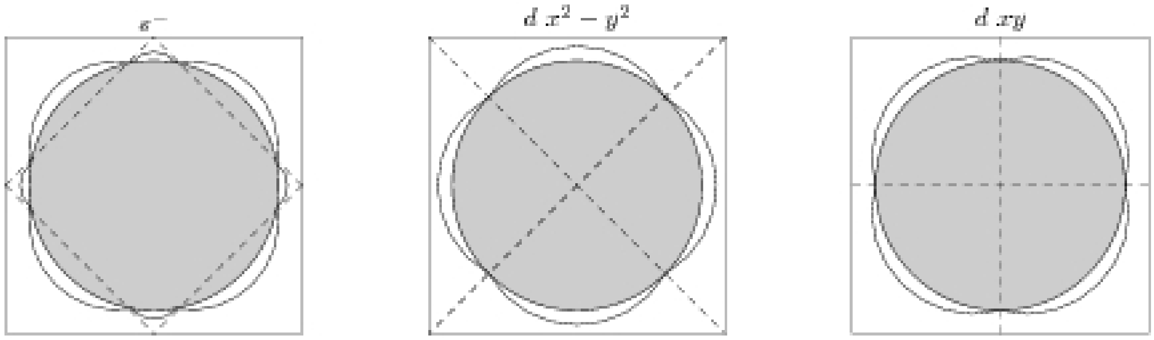

Higgs Bosons and some other Collective Modes in Superconductors.

Chandra M. Varma

University of California, Riverside CA

Spurred by some strange experimental observations in some superconductors, the theory of a new collective mode[1] in superconductors and how it can be experimentally found very easily under certain circumstances was provided in 1981. It was called the "Amplitude Mode" to distinguish it from the "Phase Modes" which provide Josephson effects and which in homogeneous superconductors are coupled to charge density fluctuations and are at the energies of the plasmons. More generally[2], this mode is the amplitude mode of a particle-hole symmetric U(1) field, i.e the model treated by Higgs and others in the1960's whose generalizations have played an important role in the standard model of particle physics. Recently the amplitude or Higgs mode for d-wave superconductors have also beendiscussed[3], where its various cousins may also be found.

I will tell the story of the above and why such modes were missed in the theory of superconductivity for so long and the applications of the ideas about such modes for cold bosons and fermions in optical lattices. I will also comment, as a very interested outsider and an enthusiast, on the Higgs in particle physics being discovered at LHC from the pointof view of the theory of superconductivity.

[1] P.B. Littlewood and C.M. Varma, Phys. Rev. Lett. **47**, 811 (1981); Phys. Rev. B **26**, 4883 (1982).

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D-Wave Superconductivity by Exchange of Electronic Fluctuations

Chandra M. Varma

University of California, Riverside

I will review the necessary requirements for D-wave superconductivity and the conditions on Antiferromagnetic Fluctuations that determine the transitions temperature. The recently measured spin-fluctuation spectrum near the Anti-ferromagnetic quantum-critical point in $CeCu_2Si_2$ is used to calculate T_c and the temperature dependence and the coefficient of resistivity to substantiate the conclusions. Similar calculations show that the measured spin-fluctuation spectrum in the cuprate high temperature superconductors cannot be responsible for their superconductivity or normal state anomalies.

The phase diagram of the cuprates is reviewed pointing out the region of quantum-critical fluctuations and the order necessary in under-doped cuprates to generate them. The theory of such an order, its quantum-critical fluctuations and the coupling of such fluctuations to fermions to generate the normal state anomalies and D-wave will be briefly described. The deduction of the fluctuation spectrum from inversion of Angle-Resolved Photoemission is also demonstrated.

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Optical probes of symmetry breaking

Joseph W. Orenstein

University of California, Berkeley

Symmetry plays a key role in our understanding of the properties of condensed matter. In the study of strongly correlated systems, interactions lead to a cascade of broken symmetries with lowering of temperature or application of magnetic field or pressure. Each of these states is characterized by a set of operations that leave the solid unchanged. Optical properties are very powerful probes of the symmetries that define what is known as the point group – the set of operations that map the unit cell of a crystal into itself. The possible symmetry operations include rotations, mirror reflections, inversion, and time-reversal. In this lecture I will describe how various optical measurements allow one to determine which symmetries are broken upon entering a new phase. I will also describe how the Berry phase helps to provide a physical picture of the optical response in several instances. Examples of broken symmetry states that will be discussed include ferromagnets, antiferromagnets, and superconductors.

New insights into the phase diagram of the copper oxide superconductors from electronic Raman scattering

Alain Sacuto

Université Paris VII - France

We introduce electronic Raman scattering and shows it is a very powerful technique for exploring the cuprates phase diagram. In particular, we study the superconducting and the pseudogap phases in distinct parts of the Fermi surface and show how superconductivity and critical temperature Tc are affected by Fermi surface disturbances related to the pseudogap.

Reference: A. Sacuto et al 2013 Rep. Prog. Phys. **76** 022502

Mesoscopic superconductivity

Daniel Esteve

Quantronics, SPEC, CEA Saclay

Superconductivity involves numerous length-scales relevant for mesoscopic physics. After having introduced a local description of the superconducting order, I will discuss how superconductivity fits in the transmission channel picture ubiquitously used in mesoscopic physics. I will then consider different mesoscopic situations of interest: What is the meaning of superconductivity in a small grain made of a superconducting material? When is the parity of the electron number relevant? What is the characteristic length-scale of proximity superconductivity? What is the density of states in a normal metal electrode close to a superconducting metal? What is the superconducting order in a superconducting atomic size contact with its electrodes at different phases? And other ones if time allows.

Superconducting Fluctuations in High-T_c Cuprates

F. Rullier-Albenque[1], H. Alloul[2]

[1] *Service de Physique de l'Etat Condensé, IRAMIS, CNRS URA 2464, CEA Saclay, 91191 Gif-sur-Yvette cedex, France.*

[2] *Laboratoire de Physique des Solides, UMR CNRS 8502, Université Paris Sud, 91405 Orsay cedex, France.*

The effects of superconducting fluctuations (SCFs) which are generally quite small in conventional superconductors turn out to be strongly enhanced in high-T_c cuprates, due to the interplay of different factors: high temperatures, short coherence length and quasi-two dimensionality. This results in a large magnitude and an extended temperature range of SCF effects, which has renewed interest to study the dependence of SCFs on temperature and magnetic field. Moreover, in high-T_c cuprates a lot of attention has been recently focused on the temperature range of SCFs above the critical temperature T_c, as this can provide some hints to understand the nature of the superconductivity and its relation with the pseudogap phase.

In the first part of the talk, I will briefly review the different fluctuation effects and how they manifest themselves in the physical properties: conductivity, magnetization, Nernst effect,… In a second part, I will present our work in which large pulsed magnetic fields were used to detect the SCF contribution to the in-plane conductivity versus temperature and magnetic field in a series of $YBa_2Cu_3O_{6+x}$ single crystals [1-3].

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[2] H. Alloul et al., Europhys. Lett. **91**, 37005 (2010).
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Fermi surface of the pseudogap state in underdoped cuprate superconductors

<u>Suchitra Sebastian</u>, Gil Lonzarich *(University of Cambridge),*

Neil Harrison, Fedor Balakirev, Brad Ramshaw, Moaz Altarawneh, Chuck Mielke, Jon Betts *(National High Magnetic Field Laboratory, Los Alamos),*

Ruixing Liang, Doug Bonn, Walter Hardy *(University of British Columbia)*

The electronic structure of the pseudogap state in the cuprates is crucial to a comprehensive understanding of high temperature superconductivity. I will present angle-resolved quantum oscillation and magnetoresistance measurements in underdoped YBCO, that resolve the electronic structure of the pseudogap as comprising a nodal twofold staggered Fermi surface in which the rotational symmetry has been transformed. This Fermi surface geometry can explain key signatures of the pseudogap such as gapless fermionic quasiparticles seen by photoemission to lie on arcs near the nodal Brillouin zone regions, a negative Hall effect and strongly enhanced interlayer transport anisotropy, and has a natural origin in a staggered biaxial charge density wave instability.

High Tc superconductivity in cuprates

Mohit Randeria

Ohio State University, Columbus

In the first part of my lectures I will give a pedagogical summary of experiments, with an emphasis on angle-resolved photoemission spectroscopy (ARPES), that show us that the high Tc cuprates challenge three paradigms of 20^{th} century condensed matter physics. (i) The parent Mott insulator cannot be understood within band theory; (ii) the superconducting state and phase transition force us to go beyond a BCS mean-field description; and (iii) the high temperature "normal" metallic state cannot be described within Landau Fermi liquid theory.

In the second part of my lectures, I will describe some of the success in theoretically understanding aspects of the strongly correlated superconducting state in doped Mott insulators. I will also describe recent work on reconciling quantum oscillations with the pseudogap in underdoped cuprates.

Raman spectroscopy of multiband superconductors and pnictide phase diagram

Girsh Blumberg

Rutgers, The State University of New Jersey (Rutgers NJ),

Most pnictide compounds share a common phase diagram which in the underdoped region is marked by a structural transition from tetragonal to orthorhombic phase (T_s) followed by an spin-density-wave transition (T_SDW). The orthorhombic distortion at T_s breaks C_4 rotational symmetry while the antiferromagnetic structure formed at T_SDW breaks translational symmetry. The symmetry-breaking nature of these phases in proximity to the superconducting (SC) phase provides an exceptional setting to study coexistence and/or competition between SC and a SDW phase, the pairing mechanism and its relation to magnetism, the pairing symmetry, and the role of quantum critical fluctuations. In multiband superconductors pair-breaking excitations at multiple gap energies as well as a rich spectrum of collective modes can be observed using optical techniques. Examples include relative phase fluctuation between weakly coupled order parameters (Leggett mode), in-gap excitons arising from pairing in the symmetry channels different from those of the ground state (Bardasis-Schrieffer excitons), and others. I will discuss examples of experimental observations in several families of the multiband superconductors.

The work is done in collaboration with V.K. Thorsmolle, A. Ignatov, A. Mialitsin, C. Zhang, P. Dai, J. Paglione, N.L. Wang. Research at Rutgers was supported by U.S. DOE, Office of BES, Award DE-SC0005463 and by NSF DMR-1104884.

High current nanostructured superconductors: materials challenges for large scale applications*

Xavier Obradors

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During 25 years, after the discovery of High Temperature Superconductivity, a huge progress has been made in basic science, materials preparation and technological developments. Achieving high current superconducting wires for large scale applications has been one of the most challenging objectives during all the HTS era. Extraordinary new ideas and materials developments have been demonstrated and second generation $YBa_2Cu_3O_7$ conductors (coated conductors) have emerged as the most attractive opportunity to reduce the cost/performance ratio down to the levels required for energy applications. These quasi-epitaxial multilayered films are deposited on flexible metallic substrates in long lengths without the detrimental influence of grain boundaries. Additionally, they can be accurately nanostructured to achieve very high vortex pinning strengths. Their current-carrying capability is at least a factor 5 above copper for the same cross section and they can stand large currents under very high magnetic fields. All these features make coated conductors very appealing to achieve the challenge of building up a sustainable electrical grid system.

In these talks I will first present the major past developments and the present existing bottlenecks towards successful manufacturing of these advanced nanostructured materials. Emphasis will be made in describing the diverse nanostructuration opportunities to enhance vortex pinning based on cost-effective chemical deposition approaches. I will report as well about the research progress in CC development in Europe, particularly in the scope of the European research program EUROTAPES (www.eurotapes.eu).

On the other hand, a review of the most outstanding and promising power applications will be presented, spanning from systems working under low field conditions (cables, Fault Current limiters, transformers) to high and ultra-high magnetic field devices (rotating machinery, magnets, etc.).

* Research funded from EU-FP7 NMP-LA-2012-280432 EUROTAPES project

Detecting strong electron correlations with quasiparticle scattering spectroscopy: Electron matter in Fe-pnictides, Fe-chalcogenides, and heavy fermions.

Laura H. Greene

Department of Physics, Materials Research Laboratory, and Center for Emergent SuperconductivityUniversity of Illinois at Urbana-ChampaignUrbana, IL, 61801 USA

Quasiparticle scattering spectroscopy (QPS), also called point contact spectroscopy (PCS), is a well-established spectroscopic tool for detecting phonons, magnons, and Kondo impurities. In superconductors, details of the order parameter including gap structure and symmetry are detected via Andreev scattering. We have found this technique to be surprisingly sensitive to detecting a density of states arising from strong electron correlations in the "normal" (non-superconducting) state of a variety of systems that exhibit the ubiquitous "domed" phase diagram. In several families of the Fe pnictides and chalcogenides, we find an enhanced conductance at the onset of electronic nematicity above the structural phase transition (T_{SPT}) that survives into the electronic smetic state, below T_{SPT}. This is explained by an increased density of states at the Fermi level arising from orbital fluctuations in the nematic phase and the over-damped collective mode in the smectic phase. In the heavy fermion URu_2Si_2 we detect the Fano resonance and hybridization gap as a distinct asymmetric double-peaked structure that survives as high as T ~ 35 K. In these lectures, the QPS technique will be described and how it is used as a probe of quasiparticle scattering and density of states.

Collaborators: H.Z. Arham, W. K. Park, C.R. Hunt, J. Gillett, S.D. Das, S.E. Sebastian, Z. J. Xu, J. S. Wen, Z. W. Lin, Q. Li, G. Gu, A. Thaler, S. Ran, S.L. Bud'ko, P.C. Canfield, D.Y. Chung, M.G. Kanatzidis, P.H. Tobash, F. Ronning, E.D. Bauer, J.L. Sarrao, J. D. Thompson.

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High-T_c superconducting cuprates: the neutron scattering legacy

Yvan Sidis

Laboratoire Léon Brillouin, CEA-CNRS, CEA-Saclay, 91191 Gif-sur-Yvette, France

In condensed matter physics, neutron scattering technique is widely used to probe static and dynamical magnetic properties in a large range of energy and momentum. In copper oxide superconductors, a large number of neutron scattering studies suggests the existence of different types of competing instabilities, whose interplay with superconductivity remains to be understood. We propose an overview of the most salient results obtained over the last two decades.

In lightly hole doped cuprates, insulating or superconducting, spin excitations exhibit a ω/T scaling behavior and a net uniaxial anisotropy. Around the characteristic hole doping 1/8, evidence for static and/or fluctuations stripes can be found in $La_{2-x}M_xCuO_4$ (M=Sr,Ba,Nd). In the superconducting state, a S=1 collective mode develops and strongly interact with charge carriers. Upon entering the enigmatic pseudo-gap state, out of which the superconducting state emerges, an intra-unit-cell magnetic order has been revealed, supporting the existence of a loop current state.

Spin fluctuation theory of FE-Based Superconductivity

Peter Hirschfeld

Department of Physics, U. Florida, USA;

In contrast to cuprate superconductors, which manifest low-temperature properties which correspond to a gap with a common (dx2-y2) form, the gap structure in Fe-based superconductors appears to be far from universal [1]. I argue that, while aesthetically unappealing from a traditional theoretical perspective, such a situation affords a novel opportunity to develop a quantitative theory of unconventional superconductivity. I will review approaches to this problem that focus on pairing from spin and orbital fluctuations in the Fe d states, and discuss how well they allow us to understand current experiments on the superconducting state of various Fe-based systems. I will review experimental evidence for the sign-changing s-wave pair state, and discuss in particular situations where either electron or hole pockets are absent, suggesting that other states may be competitive.

In the second part of the lectures, I will focus on disorder effects on Tc and superconducting properties in these materials, richer than in one-band systems due to the need to separate intra- and interband scattering. I will discuss recent electron irradiation experiments that appear capable of resolving the debate on whether the gap changes sign or not. I will also consider local impurity states and what STM imaging can reveal about the state which supports them. In particular the creation of local nematic induced order may be important to understand transport anisotropy experiments on the Fe-based systems.

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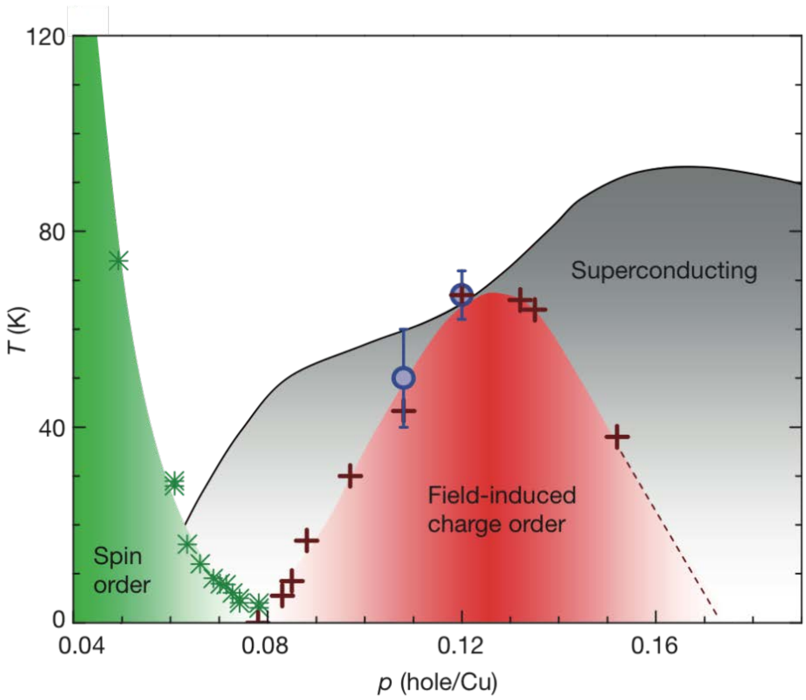
[+]Work in collaboration with A. Kreisel, Y. Wang, T. Maier, D.J. Scalapino, M. N. Gastiasoro, and B.M. Andersen

Quantum Criticality of Metals

Subir Sachdev

Harvard University

I will describe the theory of symmetry-breaking quantum phase transitions in metals, especially in two spatial dimensions. The transition involving onset of spin density wave order is relevant to the phase diagrams of numerous high temperature superconductors. I will discuss the rich phenomenology of this transition, including its connection to superconductivity and charge ordering, and the emergence of pseudospin symmetry. The aim is to achieve some understanding of the phase diagram of the hole-doped cuprates, such as the one below from the group of M.-H. Julien, *Nature* **477**, 191 (2011).



A16

Exotic Spin Physics in Low Dimensions: From Majorana Fermions to Spin Qubits

Daniel Loss

Universität Basel

Weak-coupling theories of unconventional superconductivity

Srinivas Raghu

Stanford University

We will describe the mechanism of unconventional superconductivity in the Hubbard model in the limit of weak-coupling, where asymptotically exact solutions can be obtained. We will consider the role of longer range (but finite) repulsive interactions and present explicit examples of ground states of unconventional superconductors in a variety of lattice systems obtained from this analysis.

Wilsonian theories of quantum critical metals and their instabilities

Srinivas Raghu

Stanford University

We study the problem of disorder-free metals near a continuous quantum critical point. We depart from the standard paradigm, and treat both fermions and bosons i.e. order parameter fields) on equal footing. We construct a Wilsonian effective field theory that integrates out only high energy boson and fermion modes. Below the upper critical dimension of the theory (d=3 spatial dimensions), we find new fixed points in which the bosons are described by the Wilson-Fisher fixed point and are coupled to a non-Fermi liquid metal. We describe subtleties with the renormalization group flow of four-Fermi interactions, which can be surmounted in a controlled large N limit. In this limit, we find that the theory has no superconducting instability.

Superconductivity at oxide surfaces, in oxide heterostructures, and at the LaAlO3/SrTiO3 interface

Jean-Marc Triscone

DPMC, University of Geneva,Switzerland

Oxide materials display within the same family of compounds a variety of exciting electronic properties ranging from ferroelectricity to ferromagnetism and superconductivity. These systems are often characterized by strong electronic correlations, complex phase diagrams and competing ground states. This competition makes these materials very sensitive to external parameters such as pressure or magnetic field. An interface, which naturally breaks inversion symmetry, is a major perturbation and one may thus expect that electronic systems with unusual properties can be generated at oxide interfaces [1,2]. A striking example is the interface between $LaAlO_3$ and $SrTiO_3$, two good band *insulators*, which was found in 2004 to be conducting [3], and, in some doping range, superconducting with a maximum critical temperature of about 200 mK [4].

In the lectures, I will motivate the search for novel properties at oxide interfaces; I will discuss induced superconductivity obtained at oxide surfaces using the so-called EDLT technique that allows very large sheet carrier densities to be modulated [5]; I will describe in detail the $LaAlO_3$/$SrTiO_3$ system in which the thickness of the electron gas is found to be a few nanometers at low temperatures. This electron gas with low electronic density, typically 5 10^{13} electrons/cm^2, and naturally sandwiched between two insulators is ideal for performing electric field effect experiments allowing the carrier density to be tuned. I will discuss the origin of the electron gas; superconductivity; field effect experiments and the phase diagram of the system [6]; the role of spin orbit; and the physics of high mobility samples that display Shubnikov de Haas oscillations. I will also talk about nickelate-based heterostructures that may be a way to realize new superconductors and that are attracting a lot of attention [7]. In such structures, charge transfer and charge ordering phenomena may induce novel properties as recently observed in (111) $LaNiO_3$/$LaMnO_3$ (LNO/LMO) superlattices where evidences for exchange bias were found. In this particular case, it indicates that a magnetic order is induced within the paramagnetic LNO material when embedded between ferromagnetic LMO layers [8].

[1] J. Mannhart and D. Schlom, Science **327**, 1607 (2010).
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Static charge order in underdoped YBCO measured by sound velocity

David LeBoeuf

Université Paris-Sud, Orsay

In the field of unconventionnal superconductivity, many discussions are focused on the description of phase diagrams where phase boundaries between two distinct states evolve as a function of an external parameter. Those phase boundaries can sometimes be hard to detect and thermodynamic measurements can help to pin and track down those boundaries. Amongst such measurements is sound velocity, a simple yet very sensitive probe of phase transition. I will describe several aspects of this probe, in particular how it can help determine the symmetry of the order parameter. To illustrate the potential of this technique, I will discuss recent measurements in unconventional superconductors and more specifically in the hole-doped high-Tc cuprate superconductor $YBa_2Cu_3O_y$. Sound velocity measurements in this material have been used lately to establish remarkable phase boundaries, such as the boundary of static charge order in the magnetic field - temperature phase diagram.

Optical properties of Superconductors

Dirk van der Marel

Département de Physique de la Matière Condensée, Université de Genève

The phenomenon of superconductivity is intimately intertwined with the optical properties of the material. First and foremost, the complete suppression of steady state electrical resistivity has its counterpart in the screening of time-varying fields, which diverges for frequency going to zero. Furthermore the superconducting gap opens a gap in the spectrum of electron-hole excitations, impacting the absorption of infrared photons as observed in the optical conductivity. Further phenomena which can be observed with optical techniques are collective modes, such as plasmons and excitons. The collective mode spectrum at low energies is affected by the state of matter of the material, and changes are often observed when the materials changes from superconducting to normal or vice versa.

The purpose of these lectures is, to introduce the phenomenology of the electromagnetic field coupled to the matter in the normal and superconducting state. Examples of various superconducting materials (low and high Tc) will be introduced and discussed. Furthermore an introduction will be given in linear response theory of correlated electrons, and the concepts of sum-rules will be discussed in relation to conservation principles and the average kinetic energy of a material.

Collective modes, such as plasmons in the normal state, Josephson plasmons, and excitons will be treated in the general context of collective modes of spin and charge degrees of freedom.

With regards to the normal state an introduction will be given to the Kubo-formalism, electron-boson coupling and manifestations of these in various spectroscopic probes, among which optical spectroscopy.

Pseudo-gap state from quantum criticality

Catherine Pépin

Institut de Physique Théorique, Saclay

We re-visit the problem of the anti ferromagnetic Quantum Critical Point in two dimensions. Exploiting an analogy with the Anderson localization two dimensional disordered metals, we s observe the emergence of two types of bosonic modes at the QCP ; a " diffuson"-like mode and a "Cooperon"-like mode. Those modes are related by an intrinsic SU(2) symmetry, forming a composite order parameter, which condenses in the quantum critical region, creating a pseudo-gap. Thermal effect then generate strong fluctuations between the charge and superconducting sectors. Checkerboard modulations are present in the charge sector, making this state a good candidate for the experimental observations in NMR, Xrays, Quantum oscillations and STM. Links between the composite pseudo gap state and those experiments will be discussed.

Understanding and Controlling the Electronic Properties of Materials with Strong Correlations.

Antoine Georges

Collège de France, Paris (*)

Materials with strong electronic correlations -such as transition metal oxides - have remarkable electronic properties, some of which can be exploited in applications, present and future.

In these lectures, I will review recent progress in the theoretical understanding of these properties, with a dynamical mean-field theory perspective.

The proximity of a Mott insulating state, and corresponding instabilities, is a defining feature of a number of such materials, will emphasize however that the Hund's rule coupling induces strong correlation effects in metallic compounds which are not close to a Mott insulator. This is especially relevant for oxides of 4d transition metals such as ruthenates, and also for iron-based superconductors. The Hund's rule coupling will be shown to have antagonistic effects on the Mott gap and on the quasiparticle coherence scale. For Hund's correlated materials, the self-consistent embedded-atom construction at the heart of Dynamical Mean-Field Theory proves to be especially meaningful.

In the last part of the talk, I will consider the prospects for actually controlling the electronic properties of oxides through either structural strain or light pulses.

(*) Also at: Ecole Polytechnique, and Université de Genève

International Summer School on Superconductivity – Theory, Experiments, and Phenomena
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Superkondoctivity

Victor Alexandrov

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It is known that Kondo effect allows for superconductivity. It is also known that Spin orbit coupling can increase Kondo effect. I will show some developments in the case when two of these effects are together.

Temperature dependence of STS spectra in $Bi_2Sr_2CaCu_2O_{8+d}$

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We present our study of Bismuth based high-T_c superconductors with an emphasis on the $Bi_2Sr_2CaCu_2O_{8+d}$ (Bi-2212) compound. The measurements have been carried out by Scanning Tunneling Microscopy (STM), in high vacuum and at low temperature. Exploiting the inherent inhomogeneity of the Bi based compounds we analyze the temperature dependence of the spectra. We establish maps of the superconducting gap as well as conductivity maps at various energies. We perform fine analysis of the spectra, in particular the features that are the signatures of superconductivity. We then compare the results to what has been obtained earlier in other Bismuth based compounds.

Theoretical studies of disorder effects in LiFeAs

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At present there exists a series of unexplained STM data near various defect sites in the superconducting phase of iron pnictides, especially LiFeAs due to its favorable surface properties.[1,2] These results call for theoretical modeling. Unfortunately the nature of the scatterers are unknown in the experiments, and the large parameter dependence of theoretical models complicates the understanding of the measurements. Here, we take first step towards realistic modeling of disorder effects in LiFeAs by utilizing a five-band microscopic model where both the band and the superconducting pairing are based on the band-structure obtained from DFT. This yields density of states (DOS) and spectral gaps in agreement with those observed by STM and ARPES for this material. We study the general conditions for sub-gap bound states for both nonmagnetic and magnetic impurities.[3] Additionally we find that electronic correlations can induce orbital- and magnetic order locally around the impurities which may explain a recent magnetic impurity phase discovered by muSR.[4] The impurity-induced order leads to significant changes to the impurity LDOS as compared to the uncorrelated case, and we discuss the consequences for the understanding of STM data.

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[2] T. Hanaguri, *private communication.*

[3] Maria N. Gastiasoro, P. J. Hirschfeld, and Brian M. Andersen, *preprint 2013*

[4] C. Bernhard, C. N. Wang, L. Nuccio, L. Schulz, O. Zaharko, J. Larsen, C. Aristizabal, M. Willis, A. J. Drew, G. D. Varma, T. Wolf, and Ch. Niedermayer, Phys. Rev. B **86**, 184509 (2012).

Thermopower as a unique tool to probe Quantum Phase Transitions

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The thermoelectric power (*S*) can be used to probe the spin fluctuations (SFs) in proximity to the quantum critical point (QCP) in Fe-based superconductors. The sensitivity of *S* to the entropy of charge carriers allows us to observe an increase of S/T in $Ba(Fe_{1-x}Co_x)_2As_2$ close to the spin-density-wave (SDW) QCP [1]. This behavior is due to the coupling of low-energy conduction electrons to two-dimensional SFs, similar to heavy-fermion systems. The maximal S/T is observed in the proximity of commensurate-to-incommensurate SDW transition, close to the highest superconducting T_C. In the helical magnet MnSi the thermopower is dramatically enhanced at the phase transition from the magnetically ordered Fermi-liquid to the disordered non-Fermi-liquid phase [2]. Various phases were explored showing how thermopower can be used to explore the entropy of electronic system close to the quantum phase transition.

[1] S. Arsenijević, H. Hodovanets, R. Gaál, L. Forró, S. L. Bud'ko, and P. C. Canfield, Phys. Rev. B **87**, 224508 (2013).

[2] S. Arsenijević, C. Petrovic, L. Forró, A. Akrap, submitted to Phys. Rev. B.

Transport measurements of underdoped cuprates under high magnetic field

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In 2007, the first observation of quantum oscillations in the underdoped cuprate $YBa_2Cu_3O_{6.51}$ [1] has revealed the existence of a small Fermi surface covering only 1.9% of the first Brillouin zone. This result is in sharp contrast with overdoped cuprates where quantum oscillations corresponding to a large hole orbit occupying 65 % of the first Brillouin zone have been observed, in agreement with band structure calculations. In addition to the negative Hall and Seebeck coefficients evidenced at low temperature in underdoped $YBa_2Cu_3O_y$ [3-4], those results strongly suggest that a Fermi surface reconstruction of the large hole sheet into small electron pocket(s) occurs within the underdoped side of the phase diagram.

Recent NMR measurements [5] have shown that no spin order is present in the range of doping studied, and that a charge order is stabilized by applying a magnetic field at low temperatures. The presence of a competing order with superconductivity has also been confirmed by X-ray diffraction [6] and ultrasonic measurement [7].

In order to get more insight on this reconstruction mechanism, we have studied the evolution of the electronic properties of underdoped cuprates upon doping using hydrostatic pressure to tune the CuO_2 doping level of the planes and (or) to modify the oxygen ordering within the chains.

[1] N. Doiron-Leyraud et al, Nature 447, 565 (2007)
[2] B. Vignolle et al, *Nature* **445**, 952 (2008)
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[4] D. Leboeuf, *Nature* **447**, 565 (2007)
[5] T. Wu et al., Nature 477, 191-194 (2011).
[6] G. Ghiringhelli et al., Science 337,821 (2012).
[7] D. Leboeuf et al., arXiv:1211.2724 (2012).

Exploring the cuprate phase diagram by electronic Raman scattering

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After 27 years of research, the high critical temperature superconductivity is not yet understood and submitted to the most intensive debates. The coexistence and the competition of two distinct orders namely superconductivity and the pseudo-gap make the Cuprate phase diagram very complex. In our group (Spectroscopy of Quasi-Particles), we study strongly correlated systems by inelastic light scattering called the electronic Raman scattering. The electronic Raman scattering technique allows us to probe selected regions of the momentum space such as the principal axes (B1g geometry) and the diagonal axes (B2g geometry) of the Brillouin zone .

In this work we present experimental data on single crystals of $Bi_2Sr_2Ca_1Cu_2O_{8+\delta}$ in the superconducting and the normal states. In the superconducting state, we observe the "d" wave symmetry of the superconducting gap in a large doping range. In the normal state, we detect a strong depletion of the electronic background in a large energy range (from the low to high frequency) along the principle axes of the Brillouin zone (B1g). In sharp contrast, along the diagonal axes of the Brillouin zone (B2g), we detect a depletion only for an intermediate energy range and not at low frequency. These observations advocate in favor of an “anisotropic S wave " pseudo-gap which takes a different symmetry from the superconducting gap [1,2] .

1. Exploring the Dark Side of Cuprate Superconductors: s-wave Symmetry of the Pseudogap, S. Sakai et al. arXiv:1207.5070

2. Pseudogap in Cuprates by Electronic Raman Scattering, Alain Sacuto, Siham Benhabib et al. arXiv:1209.3171

From frustrated Fe-antiferromagnetism to Pauli para-magnetism via ferromagnetism: $Lu(Fe_{1-x}Co_x)_4Ge_2$

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Frustration or reduced dimensionality are often leading to systems with new interesting properties. While such effects have been widely investigated in isolators, much less work has been done on frustrated and/or low dimensional intermetallic systems, mainly because of very limited number of appropriate compounds. Recently we performed a detailed study of the intermetallic AFe4X2 family of compounds (A = Sc, Y, Lu, Zr; X = Si, Ge) and found clear evidence for frustrated Fe-antiferromagnetism. These compounds crystallize in the tetragonal ZrFe4Si2 structure type in which the iron atoms form chains of edge- linked tetrahedra along the c-axis. In all compounds we observed a Curie-Weiss behavior in c(T) at high temperatures indicating a para-magnetic Fe-moment m_{eff} = 3 m_B/Fe. All compounds with trivalent A elements presents an antiferromagnetic (AFM) transition coupled to a large structural transition. Low T_N's and large Q_{CW}/T_N ratios, e.g. TN = 32 K and Q_{CW} = 180 K in LuFe4Ge2, confirm the relevance of frustration. In contrast we earlier on showed $LuCo_4Ge_2$ to be a simple Pauli paramagnet with non-magnetic Co. In order to study the evolution from the frustrated AFM to the paramagnetic ground state we now investigated the alloy $Lu(Fe_{1-x}Cox)_4Ge_2$ by means of susceptibility, specific heat and resistivity measurements. Co substitution initially results in a decrease of T_N, but for larger Co contents we observe the formation of a nearly ferromagnetic (FM) state, with T_C rising up to 50 K. This FM state disappears at a quantum critical point close to pure $LuCo_4Ge_2$. Possible origin for this complex behavior shall be discussed in the context of LDA based calculations.

Response and collective modes in two–band superconductors

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We present a systematic study of the response properties of two–band (multi–gap) superconductors with spin–singlet (s–wave) pairing correlations. Particular emphasis is on the existence, the dispersion and the general role of a new massive order parameter collective mode, the so–called Leggett mode, which arises as a consequence of interband pairing correlations. The subtle interplay between the gauge mode or Nambu–Goldstone boson and the Leggett mode is studied in view of both the validity of the charge conservation law and the participation in the Higgs mechanism. The occurrence of the Leggett mode is analyzed within the framework of the (Nambu) kinetic theory with respect to its experimental observability in all physically relevant spin–independent collisionless response functions like the Lindhard density response, the dielectric function, the supercurrent response (condensate dynamic conductivity) and the electronic Raman response. Possible applications of this theory include systems like various cuprates, MgB_2, pnictides and non–centrosymmetric superconductors.

Nemattic susceptibility of electron- and hole-doped $BaFe_2As_2$ iron-based superconductors

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The interplay of structural, magnetic and superconducting phase transitions has been a recurrent theme in the study of iron-based superconductors. Ultrasound measurements of the soft mode of the structural phase transition (the elastic shear mode C_{66}) have proven very valuable in this context, because they allow studying the susceptibility of the electronic order parameter ultimately driving the structural phase transition (the “nematic” susceptibility). For example, these measurements reveal the strong coupling between superconductivity and nematic fluctuations[1,2] and also led to the suggestion of a “structural quantum critical point” at optimal doping in the Ba(Fe,Co)$_2$As$_2$ system [2]. In other systems, such as hole-doped (Ba,K)Fe$_2$As$_2$, which exhibits a wider superconducting dome, ultrasound measurements have not yet been reported. We have developed a novel approach to access C_{66} using a three-point bending setup in a capacitance dilatometer. Small platelet-like single crystals, as frequently available for iron-based systems, suit our technique perfectly. Our study of the electron-doped Ba(Fe,Co)$_2$As$_2$ and the hole-doped (Ba,K)Fe$_2$As$_2$ system [3] shows that the nematic susceptibility diverges at low temperatures in optimally doped Ba(Fe,Co)$_2$As$_2$, but not in optimally doped (Ba,K)Fe$_2$As$_2$, thus suggesting the absence of a quantum critical point in the latter system. However, signatures of weak nematic fluctuations are observed over most of the superconducting dome of (Ba,K)Fe$_2$As$_2$. This raises the question whether quantum criticality is really important for obtaining high transition temperatures and/or if nematic fluctuations are indeed directly involved in the pairing.

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Superconducting to Insulator transition in Boron-doped Diamond ; dimensionality and disorder effects.

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The superconductor to insulator transition (SIT) goes on fascinating theoretical and experimental physicists alike. Indeed, the influence of electronic correlations and disorder-induced localisation effects in the vicinity of the Superconducting to Insulator transition is still highly debated.

From an experimental point of view, the influence of disorder on the SIT has been mainly studied on both amorphous and granular systems. A popular approach to this problem is to decrease the dimensionality of the system (from 3D to 2D) and thus drive the latter transition by increasing the « effective disorder » of a superconducting film.

In this work, we propose that heavy-boron-doped single crystal diamond (Tc around a few K) provides an original and promising playground to test such ideas on epitaxial films. In particular, the doping level, the epilayer thickness and its crystalline quality may be varied independently.

To undertake such experiment, the film should present homogeneous doping profiles and well controlled interfaces, allowing to reduce the thickness without affecting directly the electronic disorder. We will discuss the opportunity given by the delta-doping technique with Microwave Plamsa-Enhanced Chemical Vapor Deposition to fulfil these criteria ; grow *thin* heavily-boron doped epilayers (down to 2 nm) with sharp boron interfaces but also varying directly the disorder at a given thickness and boron concentration.

We will report four point measurements (from 300K to 30mK) performed on a serie of covered or uncovered boron-doped epilayers (0.3-1% at. boron content) with thicknesses ranging from 2 μm down to 2 nm. Magnetotransport measurements have been carried out and the phase diagrams will be presented, as well as the angle dependence of the critical field for a few cases. The critical thicknesses below which the film properties depart from the bulk behaviour will be compared to the relevant length scales of the system in all phases (metallic, superconducting and insulating)

Investigation of Sr_2RuO_4 under uni-axial strain

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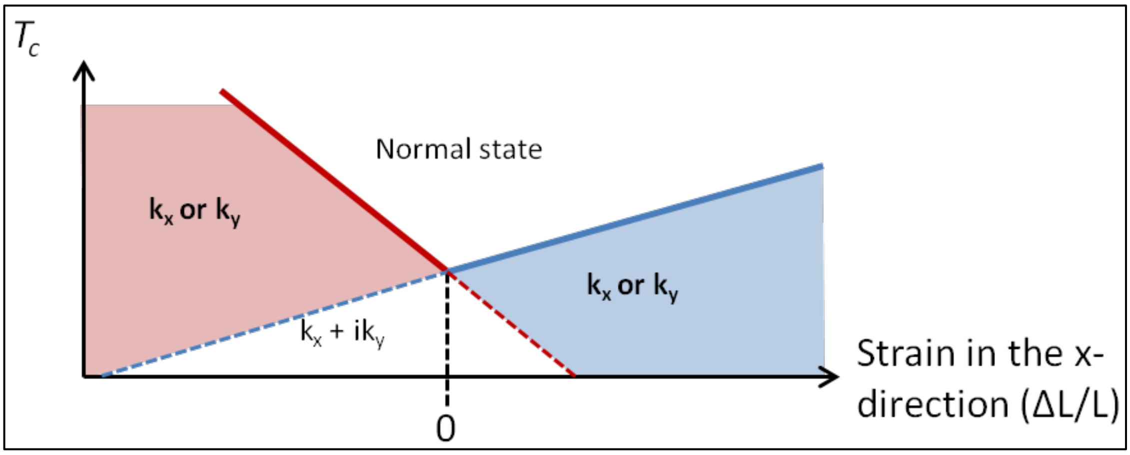
Sr_2RuO_4, which is believed to be a spin-triplet superconductor, is one of the most prominent candidates for p-wave superconductivity. Experimental evidence also suggests that its order parameter breaks time-reversal symmetry. However, to this day the details of the superconducting state in Sr_2RuO_4 remain controversial, and are the subject of much ongoing research. In this poster I report on AC magnetic susceptibility measurements on single crystals of Sr_2RuO_4 under in-plane uni-axial strain. The measurements are performed using a newly designed probe which enables us to vary the applied strain continuously from high compression to high tension whilst the sample is at cryogenic temperatures. The samples measured have a needle-like geometry, which ensures that the strain is homogeneous in the region probed. We report data from needles cut along the [100] and [110] directions, where we show the evolution of the transition of the sample temperature as a function of applied strain. The results are surprising given the $p_x \pm ip_y$ order parameter which has often been predicted for Sr_2RuO_4.



<u>Figure: T_c vs. strain prediction for the $p_x \pm ip_y$ order parameter thought to exist in Sr_2RuO_4</u>

New light on the sub-gap peaks in $YBa_2Cu_3O_{7-\delta}$

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We have performed Scanning Tunneling Microscopy and Spectroscopy (STM/STS) studies on the cuprate high temperature superconductor $YBa_2Cu_3O_{7-\delta}$. The distinctive features of the spectra are a superconducting d-wave shaped gap, with coherence peaks at 18-22 meV, a broader hump which peak is at 30-40 meV, and a dip around 50-55 meV. In addition, low energy structures, often seen as peaks, are seen at 5-10 meV. These multi-strcutures suggest a more complex orgin of the pairing than just the simple BCS d-wave pairing.

These in-gap peaks seem to be enhanced inside vortex cores, but our recent studies show that these structures appear consistently in zero field as well. Earlier studies suggested a connection between the normal state inside the vortex cores and these in-gap peaks, but the fact that these peaks are now seen in zero field spectra, even in spectra with superconducting coherence peaks, suggest that these peaks are a signature of a more general property.

Superconductor-insulator transition in NbN ultrathin films

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In order to better understand the various processes taking place at the superconductor-insulator transition (SIT), we have probed the global and local electronic properties of NbN ultrathin superconducting films. Otherwise, the study of such films is particularly interesting for applications in single photon detectors. In particular it has been recently demonstrated that the maximum detection efficiency occurs for stripe thicknesses close to the superconductor-insulator transition. The structural properties of the films are shown to play a key role in determining the electronic properties at low temperature. The samples are prepared ex-situ by our collaborators [1].

We addressed the problem of the superconductor-insulator transition in NbN thin films by studying the transport measurement characteristics [2] and locally, in a direct STS experiments.The SIT was approached by varying the thickness of the films and using a magnetic field applied perpendicular to the sample surface.

Our STS data reveal profound changes in the local behavior of the superconducting films as the SIT is approached [3]. We observe a progressive decrease of the coherence peak height and small spatial inhomogeneities of the superconducting gap (Δ). Moreover, the gap below T_c develops on a spectral background which becomes more and more "V-shape". Combining STS and transport measurements, we shed new light about the mechanisms responsible for the T_c and Δ reduction when approaching the superconductor-insulator transition by reducing the film thickness.

The magnetic field induced insulating transition was studied by transport measurement in a 2.16nm thick NbN film. Assuming that a quantum transition occurs at the absolute zero temperature, a finite-size scaling analysis was carried out to determine the correlation length exponent v and the dynamical critical exponent z. These two parameters determine the universality class of the transition [4]. In order to cross-check the values found for the exponents, we have also studied the effect of the temperature and electrical field [5].

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Theoretical visualization of atomic-scale impurity states in FeSe

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We compute the impurity induced local density of states in undoped FeSe with a resolution comparable to that obtained from STM experiments. We solve ten orbital Bogoliubov-deGennes (BdG) equations to obtain lattice green's function and transform them to wannier basis computed by downfolding DFT bands onto a ten orbital tight binding model. We study ideal point like impurity using this method.

Singularity of the London penetration depth at quantum critical points in superconductors

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We present a general theory of the singularity in the London penetration depth at symmetry-breaking and topological quantum critical points within a superconducting phase. While the critical exponents, and ratios of amplitudes on the two sides of the transition are universal, an overall sign depends upon the interplay between the critical theory and the underlying Fermi surface [1]. We determine these features for critical points to spin density wave and nematic ordering, and for a topological transition between a superconductor with Z_2 fractionalization and a conventional superconductor. We note implications for recent measurements of the London penetration depth in $BaFe_2(As_{1-x}P_x)_2$ (Hashimoto *et al.,* Science **336**, 1554 (2012)).

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Neutron scattering study of magnetic excitations in a 5d-based double-perovskite Ba_2FeReO_6

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There is great interest in double perovskite materials, from a fundamental viewpoint of studying correlated electron magnetism as well as spintronics applications. We report theoretical calculations and experimental powder inelastic neutron scattering data on magnetic excitations in the 5d-based double perovskite Ba_2FeReO_6. We find evidence of multiple spin wave branches consistent with local moment magnetism on Fe sublattice coexisting with highly correlated and spin-orbit coupled local moments on Re.

Space group symmetry, spin-orbit coupling and the low-energy effective Hamiltonian for iron-based superconductors

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Iron-based superconductors are, in general, multi-band semi-metals with competing instabilities (itinerant spin-density wave, nematic structural transition, superconductivity). This motivates us to use the method of invariants, originally developed for semi-conductors, when constructing an effective theory for these materials. We use the space group, which, being non-symmorphic, leads to peculiar consequences at the Brillouin zone corner, the M-point, precisely where the low-energy states reside. Our model displays good quantitative agreement with the multi-band tight-binding models, while obeying all the symmetries.

The model can easily incorporate the spin-orbit coupling. We predict several consequences of the spin-orbit coupling on the spin-density wave orders. We analyze the spectrum in the presence of collinear or coplanar (C4) SDW. On the symmetry grounds, we show that, even with the spin-orbit coupling, each state is Kramers degenerate in the symmetry unbroken and the collinear SDW phase. On the other hand, the coplanar SDW breaks the Kramers degeneracy. The nodal collinear SDW is shown to be unstable toward any finite spin-orbit coupling.

We study the quasiparticle dispersion of the low-energy effective model in the presence of an A1g (s-wave) spin singlet superconducting order. In the absence of the spin-orbit coupling, this phase can be characterized with three k-independent pairing amplitudes. This minimal model yields isotropic gaps on both hole Fermi surfaces. The gap structure (anisotropy, the relative sign, and the presence of nodes) on the electron Fermi surfaces is determined by the ratio of the pairing parameters. In the presence of the spin-orbit interaction, two additional k-independent spin triplet pairing terms are allowed. These result in the gap anisotropy on the hole Fermi surfaces and a qualitative change of the gap structure on the electron Fermi surfaces.

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Superconductor-normal metal quantum phase transition in dissipative and non-equilibrium systems [1]

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In physical systems, coupling to the environment gives rise to dissipation and decoherence. For nanoscopic materials this may be a determining factor of their physical behavior. However, even for macroscopic many-body systems, if the strength of this coupling is sufficiently strong, their ground state properties and phase diagram may be severely modified. Also dissipation is essential to allow a system in the presence of a time dependent perturbation to attain a steady, time independent state. In this case, the non-equilibrium phase diagram depends on the intensity of the perturbation and on the strength of the coupling of the system to the outside world.

In this work, we investigate the effects of both, dissipation and time dependent external sources in the phase diagram of a many-body system at zero and finite temperatures. For concreteness we consider the specific case of a superconducting layer under the action of an electric field and coupled to a metallic substrate. The former arises from a time dependent vector potential minimally coupled to the electrons in the layer. We introduce a Keldysh approach that allows to obtain the time dependence of the superconducting order parameter in an adiabatic regime.
We study the phase diagram of this system as a function of the electric field, the coupling to the metallic substrate and temperature.

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DOI: 10.1080/14786435.2013.798704

The Pauli-limited multiband superconductor $RbFe_2As_2$

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The compounds AFe_2As_2 – where A denotes an alkali metal element like K or Rb – offer the possibility to probe the unconventional superconductivity in iron pnictides. In contrast to the optimally doped compounds like $Ba_{1-x}K_xFe_2As_2$, their upper critical magnetic fields H_{c2} are easily accessible and no additional chemical disorder is introduced by substitutional atoms. In order to study the effect of superconductivity on the crystal structure, we measured the thermal expansion and magnetostriction of a $RbFe_2As_2$ single crystal at temperatures T between 50 mK and 4 K and magnetic fields $\mu_0 H$ up to 14 T. The quantum oscillations observed in our magnetostriction measurements indicate a strongly correlated electron system in accordance with the enhanced Sommerfeld coefficient and Pauli susceptibility of KFe_2As_2 [1]. In addition, they reveal, together with the thermal expansion, the multiband character of the electronic structure and superconductivity. The T-H phase diagram constructed from our field-dependent measurements shows the typical behavior of an orbitally limited superconductor for H parallel to the c-axis, while for H within the ab-plane the superconducting phase transition becomes discontinuous below T = 1.2 K. For this field direction the orbital limit strongly exceeds $H_{c2}(T = 0)$, thus pointing to a Pauli-limited upper critical field .The derived uniaxial-pressure dependences of T_c and H_{c2} are discussed in comparison with KFe_2As_2.

[1] F. Hardy *et al.*, arxiv:1302.1696

Proposal for Quantum Optics techniques applied to study out of equilibrium strongly correlated electron systems

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The characterization of quantum states of light is a standard tool in Quantum Optics and Quantum Information. Balanced Homodyne Detection is the experimental technique which allows the reconstruction of any optical quantum state . Our goal is to apply this technique to the study of out of equilibrium strongly correlated electron systems.

Here we propose to join Pump&Probe techniques with Quantum Optics ones in order to characterize quantum states of ultra-short light pulses after the interaction with a perturbed material. This approach constitutes an original experimental framework to investigate the quantum nature of the out of equilibrium dynamics of strongly correlated electron systems after the perturbation of a light pulse.

Leggett modes in iron-based superconductors as a probe of Time Reversal Symmetry Breaking

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Since their discovery, it has been suggested that pairing in pnictides can be mediated by spin fluctuations between hole and electron bands. In this view, multiband superconductivity would substantially differ from other systems like MgB2, where pairing is predominantly intraband. Indeed, interband-dominated pairing leads to the coexistence of bonding and antibonding superconducting channels. Here we show that this has profound consequences on the nature of the low-energy superconducting collective modes. In particular, the so-called Leggett mode for phase fluctuations is absent in the usual two-band description of pnictides. On the other hand, when also the repulsion between the hole bands is taken into account, a more general three-band description should be used, and a Leggett mode is then allowed. Such a model, that has been proposed for strongly hole-doped 122 compounds, can also admit a low-temperature s+is phase which breaks the time reversal symmetry. We show that the (quantum and thermal) transition from the ordinary superconductor to the s+is state is accompanied by the vanishing of the mass of Leggett-like phase fluctuations, regardless the specific values of the interaction parameters. This general result can be obtained by means of a generalized construction of the effective action for the collective degrees of freedom that allows us also to deal with the non-trivial case of dominant interband pairing[1].

[1] M.Marciani, L.Fanfarillo, C.Castellani, L.Benfatto, arXiv: 1306.5545 (2013)

The effect of pressure on superconductor materials

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We study the effect of high pressure on superconductors of different origins through electrical resistivity measurements under pressure (<20GPa) between 4 and 300 K. Layered transition dicholcogenides develop charge density waves (CDW) associated to permanent phonon distortions that should be sensitive to pressure. We have measured both 2H-$TaSe_2$ and 2H-TaS_2, where superconductivity coexists with the CDW at zero applied pressure. Both show a similar behavior under pressure. In 2H-$TaSe_2$ (2H-TaS_2) T_c increases at low pressures attains a maximum at 24GPa (11GPa), while T_{CDW} decreases up to 5GPa where a sudden increase of T_{CDW} is observed. This sudden small jump is due to the passage from an incommensurate CDW (ICDW) to a commensurate CDW. The maximum of T_c coincides with the extrapolated annulations of T_{ICDW}, suggesting that both superconductivity and the ICDW are dependent on the Fermi surface nesting, while the CCDW is more dependent on electron-phonon coupling.

We have also measured the 1111 pnictide CaFeAsF, where a structural transition from a tetragonal phase to an orthorhombic phase develops at T_0~135K, followed by an antiferromagnetic ordering at T_N~120K. Both transitions decrease with pressure, but, while T_0 becomes zero at P~8GPa, T_N seems to recover at higher pressures. Magnetoelastic Landau theory shows that crossing between both transitions necessarily implies a change of symmetry for the antiferromagnetic ordering at high pressures. Curiously, superconductivity only appears as a function of pressure at T_0=0, i.e. when the material abandons the orthohombic distortion.

Time- and angle-resolved photoemission spectroscopy on optimally doped Bi2212 using a position-sensitive time of flight spectrometer

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Angle resolved photoemission spectroscopy (ARPES) is known to be a powerful technique to analyze the electronic structure of complex materials. In the last few years it was shown that adding a femtosecond time resolution by means of pump probe experiments ARPES provides access to the non-equilibrium state and the respective electron dynamics [1]. Here, we report on time resolved ARPES measurements using a position sensitive time of flight spectrometer [2]. Using this instrument we collect four dimensional sets of data in “a single shot”, namely time, kinetic energy and two mutually independent in plane momentum components k_x, and k_y. We achieve a time- and energy- resolution of 100 fs and 50 meV respectively and a momentum resolution better than 0.002 $Å^{-1}$. Regarding our recent experiments on optimally doped Bi2212 in the pseudogap phase we observed a photoinduced change in k_F which scales linearly with the optical excitation density. We will discuss the observed phenomenon in the context of a photo-excited change of the doping level.

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Coupling of the arsenide optical phonon to magnetism in iron pnictides

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Charge, spin and lattice degrees of freedom are strongly entangled in iron superconductors. A neat consequence of this entanglement is seen in the Raman signal of the A_{1g} As-phonon which presents an anomalous response when going through the magneto-structural transition.
The phonon, active only in the A_{1g} symmetry in the paramagnetic state, shows a large signal in the A_{1g} and B_{1g} symmetries in the magnetic state. In this work we assume that the observed behavior is a consequence of the electron-phonon coupling in the anisotropic magnetic state and study the phonon Raman response and the phonon polarization. To this end we consider a five orbital tight-binding model [1] coupled to phonons via the dependence of the hopping parameters on the As position which enters through both the Fe-As-Fe angle α and the Fe-As orbital overlaps. The Raman intensity is calculated using the charge-phonon theory [2,3] which can be related to Fano theory. We find that while both mechanisms result in a finite B_{1g} response, the behavior of the A_{1g} and B_{1g} Raman phonon intensities is qualitatively different when coupling via the angle or via the orbital overlap dependence.
We discuss our results in view of the experimental reports [4]. We also argue that we would find the opposite symmetry dependence in the 11 compounds.

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Electronic dimers in the spin-density wave phase of iron-pnictides

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There is growing evidence for unidirectional, so-called nematic response in iron-pnictide superconductors. Recently, an STM study of $Ca(Fe_{1-x}Co_x)_2As_2$ have revealed the existence of Co-induced electronic dimers within the spin density wave (SDW) ordered phase.[1] These dimers are approximately eight lattice constants long and oriented along the antiferromagnetic a-axis. This finding is consistent with recent transport measurements showing that the resistivity anisotropy is dopant-induced and exhibits a larger resistivity along the ferromagnetic b-axis (perpendicular to the dimers). This raises the question; why a Co ion substituting for Fe in these materials generates a local unidirectional dimer in the Fe-As planes?

Here, we answer this question by an explicit microscopic 5-band calculation of the reconstructed local electronic density near a point-like impurity within the SDW phase. The competition between the local magnetic impurity instability and the underlying SDW order leads to a unidirectional local magnetic impurity structure oriented along the antiferromagnetic a-axis with an associated electronic density dimer which we show to be spaced by approximately eight lattice constants.

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Strong coupling behavior of the neutron resonance mode in unconventional superconductors

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We analyze whether and how the neutron resonance mode in unconventional superconductors is affected by higher order corrections in the coupling between spin excitations and fermionic quasiparticles and find that in general such corrections cannot be ignored. In particular, we find that in two spatial dimensions (d=2) the corrections are of same order as the leading, weak coupling contributions demonstrating that the neutron resonance mode in unconventional superconductors is a strong coupling phenomenon. The origin of this behavior lies in the quantum-critical nature of the low energy spin dynamics in the superconducting state and the feedback of the resonance mode onto the fermionic excitations.

While quantum critical fluctuations occur in any dimensionality d≤3, they can be analyzed in a controlled fashion by means of the ε-expansion (ε=3-d), such that the leading corrections to the resonance mode position are small. Even if higher order corrections are taken into account, the resonance mode emerges only if the phase of the superconducting gap function varies on the Fermi surface, making it a powerful tool to investigate the microscopic structure of the pair condensate.

Effect of weak disorder on the phase competition in iron pnictides

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We investigate the phase competition between magnetism and superconductivity for iron pnictides in the presence of weak disorder. The competition of these two ordered states has been studied in detail by Fernandes and Schmalian [1] who came to the conclusion that in the case of unconventional s^{+-} pairing, the superconducting and antiferromagnetic phase may coexist microscopically but are near to a parameter regime of mutual exclusion. Correspondingly, the multicritical point in the phase diagram is close to the transition from a tetracritical to a bicritical point.

Close to the multicritical point, the free energy of the system can be expanded simultaneously in terms of magnetic and superconducting order parameters and the coefficients can be determined microscopically. We include the effect of impurity scattering in the model and investigate its influence on the phase diagram of iron pnictides.

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RIXS studies on the high-energy spin excitations of iron-pnictide compounds $BaFe_2As_2$ and $Ba_{0.6}K_{0.4}Fe_2As_2$

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Tremendous research works have been done for iron-pnictide superconductors since its discovery. Their superconductivity has been more and more accepted to be unconventional and the spin fluctuations are found to be potentially important for superconducting paring by these studies. An intense research effort has been focused on characterizing the spin excitation spectrum in the magnetically ordered parent phases of the iron-pnictide [1,2], and it is well established that the spin-excitation spectrum consists of sharp, highly dispersive magnons [2], but the fate of these high-energy magnetic modes upon sizable doping is so far unresolved. We demonstrate by using resonant inelastic X-ray scattering that the optimally hole-doped superconducting $Ba_{0.6}K_{0.4}Fe_2As_2$ retains well-defined dispersive high-energy modes of magnetic origin as that of the parent antiferromagnetic $BaFe_2As_2$.[3] The persistence of spin excitations well into the superconducting phase suggests that the spin fluctuations in iron-pnictide superconductors originate from a distinctly correlated spin state, and thus connects iron-pnictide to cuprate superconductors, in spite of the fundamental differences in the electronic structure, superconductivity emerges in a similar spin-liquid background [4].

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[2] Zhao, J. *et al.* Spin waves and magnetic exchange interactions in $CaFe_2As_2$. *Nature phys.* **5**, 555 (2009).
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Light-induced coherence in underdoped YBCO far above equilibrium Tc

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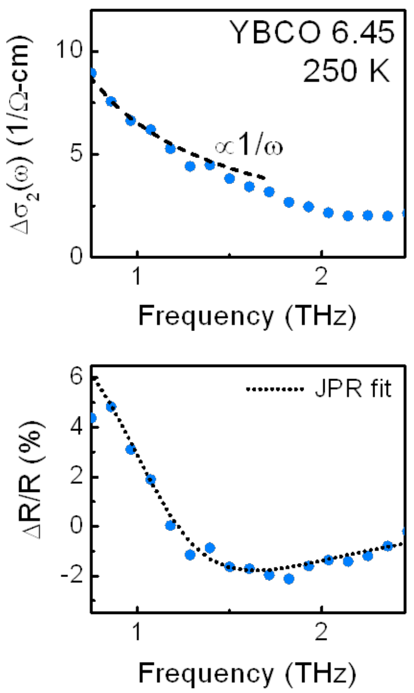
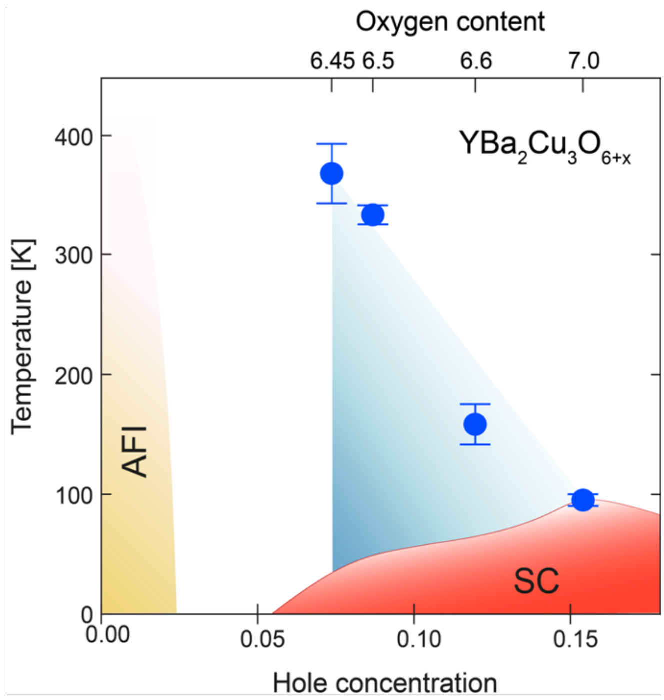
Mid-IR optical excitation was used to resonantly drive the apical oxygen in underdoped YBa2Cu3Ox along the c-axis, inducing a transient state that exhibits the low-frequency optical properties of a perfect conductor, in which the carrier scattering time is much longer than the lifetime of the state. The transient response is characterized by a London-like inverse frequency dependence in the inductive part of the conductivity and by a plasma resonance that appears as an edge in the reflectivity. We report this effect in three compounds (x = 6.45, 6.5, 6.6), with an onset temperature that decreases with increasing doping (~ 400 K, 340 K, 180 K respectively). The observed plasma resonance appears at frequencies comparable with the Josephson plasma resonance seen in equilibrium below the superconducting transition temperature. The measured optical response is consistent with an effective medium interpretation in which regions of superconductivity coexist with regions that retain their equilibrium properties.





Ceramic Combinatorial Synthesis of Cuprate Superconductors and Magnetic Separation

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The search for new cuprate superconductors at the time after their discovery was mainly driven by the principle of chemical analogy and serendipity followed by attempts of combinatorial chemistry, using 2D (pixel or gradient) approaches. Later, we have introduced a combinatorial strategy based on a single ceramic sample, containing N starting oxide materials mixed at random Given T, P and time such a sample can develop into a large number different phases, depending on local reactions within a pellet.

As Ca, Sr, Ba, La, Y, Pb, Bi, Tl, Hg and Cu are those elements, leading to cuprate superconductors, single sample reactions starting by a random mixture of these elements were performed. Theoretical estimation revealed that in such multi component samples, the concentration of individual phases may reach the level of about 50 ppm.

In view of this, balk measurements are not very useful, because of a broad distribution of compounds. For single sample reactions starting by Ca, Sr, Ba, La, Y, Pb, Bi, Tl and Cu, the bulk Tc was 115 K .

This critical temperature was confirmed by SQUID measurements on separated single grains catched by magnetic separation. X-ray powder diffraction confirmed the formation of *YBa2Cu3O7*−δ, together with other phases making part of single grains (50-100 µm).

Keywords: Superconductor, Combinatorial chemistry, SQUID, Magnetic separation

Intercluster conductivity of pairs of simple t-J clusters and consequences for interpretations of the pseudogap in underdoped cuprates

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The pseudogap in the c-axis infrared conductivity of underdoped cuprate superconductors [1,2] is qualitatively and even quantitatively similar to that in the interladder conductivity of underdoped cuprate ladders [3]. This suggests the possibility of a common and probably very local origin. Motivated by this finding, we have studied the temperature dependence of the intercluster conductivity of pairs of identical simple t-J clusters, such as cyclic chains and ladders (for a related study of the conductivity between the CuO2 planes, see [4]). The resulting pseudogaps, in particular their dependence on J/t and temperature, will be discussed and compared with experimental data of Refs. [1,2,3].

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Triplet pairing long ranged proximity effect in superconductor-ferromagnet bilayers

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The proximity effect between a superconductor and a ferromagnet was known to be a short ranged effect due to the discrepancy between the anti-parallel electron spin alignment in a singlet superconductor and the parallel alignment in the ferromagnet. Many experiments comply with this theory and show that the superconductor order parameter penetrates the ferromagnet over a very short length scale of only a few nanometers: $\xi_F=(\hbar D/2E_{ex})^{1/2}$ where E_{ex} is the exchange energy and D is the diffusion coefficient. Recently, however, a much longer ranged penetration of the order parameter was observed in some systems. One explanation to this phenomenon is suggested to be the formation of triplet pairs of equal spin on the ferromagnet side.

We show that a long ranged proximity effect occurs in bilayers of a ferromanget ($La_{2/3}Ca_{1/3}MnO_3$) and a superconductor ($YBa_2Cu_3O_{7-\delta}$ or $Pr_{1.85}Ce_{0.15}CuO_4$). It is manifested in scanning tunneling spectroscopy as gaps and zero bias conductance peaks (ZBCPs) in the local density of states of the ferromagnet. Since the LCMO has domain walls which are wide compared to the coherence length of the YBCO superconductor the appearance of superconducting-like features on the ferromagnet side is consistent only with a triplet pairing scenario. Additionally, the effect of magnetic field on these features and the fact that they appear over areas much larger than the domain walls helps us discern between two proposed mechanisms for triplet pairing. Our results also provide information about the symmetry of the induced order parameter and suggest that it can be anisotropic unlike the s-wave order parameter which is induced in normal metal-superconductor junctions.

Search for chalcogenide based superconductors: Sulfur based solution growth

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As part of our effort to develop tools for searching for new chalcogenide based superconductors we are expanding the range of S-based binary melts that we can use for solution growth of single crystals. As a recent example, we have been able to grow single crystals of Rh17S15 and separate them for excess binary melt via high temperature decanting. In addition to refining the details of the Rh-S binary phase diagram, microscopic, thermodynamic and transport measurement on Rh17S15 crystals confirm their Tc ~ 5.5 K as well as their remarkably large Hc2(T) behavior. We also able to grow Bi2Rh3S2 and In2Rh3S2 single crystals by using Rh-S eutectic region as solvent for high temperature solution growth.

Synthetic Spin Orbit Interaction and Majorana Fermions

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We consider quasi one-dimensional systems in proximity to an s-wave superconductor. The crucial ingredient for most MF proposals are helical spin textures leading to an exotic p-wave pairing due to proximity effect with an ordinary s-wave superconductor. A well-known mechanism responsible for helical modes is spin-orbit interaction (SOI) of Rashba type. While intrinsic values of SOI are limited by material parameters, the recently proposed synthetic SOI produced by a helical magnetic field can reach extraordinary values that are limited only by the spatial period of the helical field $2\pi/k_n$ [1-3]. However, in all these setups the chemical potential must be tuned inside the gap opened by the magnetic field so that the Fermi wavevector k_F is close to $k_n/2$ [2-4]. Thus, it is natural to ask if helical modes exist in low-dimensional superconductors such that the system automatically tunes itself to $k_n=2k_F$. Surprisingly, the answer turns out to be affirmative for a rather broad class of systems. These are RKKY systems that consist of localized magnetic moments coupled by itinerant electrons via the Rudermann-Kittel-Kasuya-Yosida (RKKY) interaction. A $2k_F$-peak in the spin susceptibility of the superconductor in the one-dimensional limit supports helical order of localized magnetic moments [5]. As a prototype for our model we consider atomic chains and semiconducting nanowires with magnetic atoms or nuclear spins placed on top of a bulk s-wave superconductor. We show that these setups are generically deep inside the topological phase and host MFs without requiring any fine-tuning at all.

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Symmetry of gap functions and pairing instabilities in multiband superconductors: 3D effects

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Thomas A. Maier – *Center for Nanophase Materials Sciences and Computer Science and Mathematics Division, Oak Ridge National Laboratory, USA*
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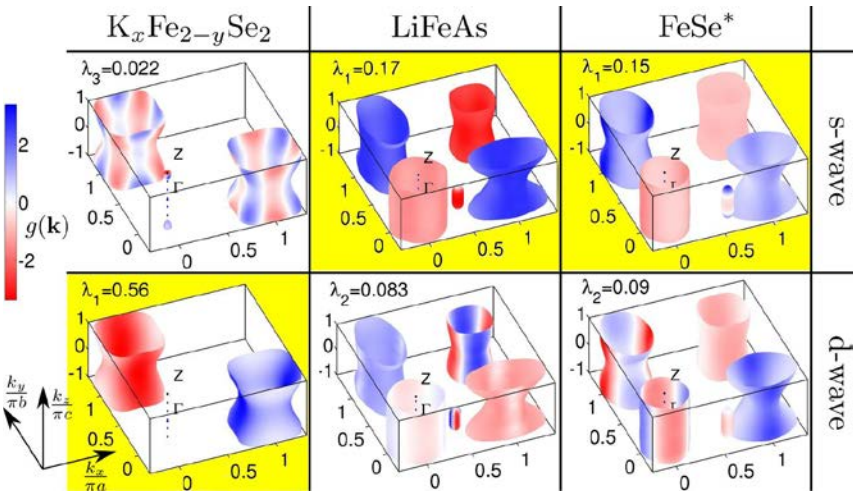
The superconducting pairing symmetry in Fe-based superconductors is examined using spin-fluctuation pairing theory to reveal gap structures that are influenced by the 3D nature of the Fermi surface and the pair scattering processes. We start from a 10-orbital model that leads to the different matrix elements of the pairing vertex which have been shown to be essential in determining the symmetry of the pairing instability. We investigate the electronic structures and pairing states of the $K_xFe_{2-y}Se_2$, the LiFeAs and the FeSe systems, where 3D effects are important.

In the $K_xFe_{2-y}Se_2$ system, only electron pockets are present, leading naturally to d-wave pairing; however hybridization effects due to the I4/mmm crystal symmetry and spin-orbit coupling are shown to work in favor of the “bonding-antibonding s-wave” state. In the LiFeAs system, electronic correlations are expected to be important. Therefore we compare results of the gap structure from the spin-fluctuation pairing calculation starting from DFT models and from fits to experimental band structures with gaps observed in ARPES experiments. The results on large hole and electron pockets are strikingly good, while on the delicate inner hole pocket(s) there are significant discrepancies. For the FeSe compound we investigate influences of pressure (which changes the band structure and Fermi surface) on the superconducting instability and gap function. We do not find strong pressure-dependent enhancements of pairing strengths from this mechanism, and discuss possibilities to explain the large pressure dependence of T_c observed in experiment.



Gapfunctions for s- and d-wave instabilities in the systems under investigation as calculated starting from 5-orbital models; the leading instabilities are highlighted by yellow panels.

Ultrafast evolution of the model Mott-Hubbard compound V2O3

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The ultrafast response of the prototype Mott-Hubbard system Cr-doped V2O3 was studied with various pump-probe techniques, namely reflectivity in the optical wavelength window, X-ray diffraction, and time resolved angle resolved photoelectron spectroscopy. These three techniques allowed us to unequivocally disentangle the electronic and the lattice response of the system to a femtosecond laser excitation, which was kept in all three cases at a wavelength of 800 nm. We present a comparative study of these transient responses, which put in evidence the strong electron-phonon coupling of this model strongly correlated material.

Equation of State and Superconductivity in the 2D Hubbard Model

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MPI-PKS Dresden / University of Michigan

We present results for the equation of state of the two-dimensional Hubbard model on an isotropic square lattice as obtained from a controlled and numerically exact large-cluster dynamical mean field simulation.[1] Our results are obtained for large but finite systems and are extrapolated to infinite system size using a known finite size scaling relation. We present the energy, entropy, double occupancy and nearest-neighbour spin correlations extrapolated to the thermodynamic limit and discuss the implications of these calculations on pseudogap physics of the 2D-Hubbard model away from half filling. We find a strong behavioural shift in energy below a temperature T* which becomes more pronounced for larger clusters. Further, we examine the presence of superconductivity in the 2D Hubbard model and its effect on both the energetics and c-axis optical properties relevant to the high-T_c cuprates.[2,3]

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Ferromagnetic Superconductivity in UGe_2

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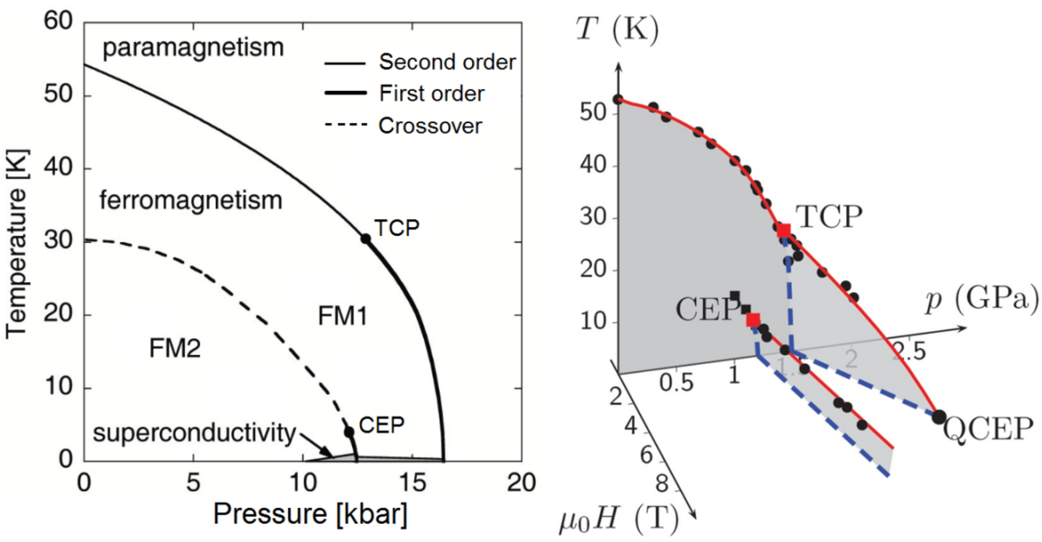
UGe_2 orders ferromagnetically below 53 K at ambient conditions. Application of pressure decreases the Curie temperature, and it is supressed to absolute zero at just over 15 kbar, the location of a ferromagnetic quantum critical point (QCP). Novel states of matter, such as superconductivity, might be expected to emerge in the vicinity of a QCP. In UGe_2 superconductivity occurs at lower pressures, peaked around a second transition. This transition between two phases of ferromagnetism, labelled FM1 and FM2, is also supressed to an unconventional (first order) QCP by application of pressure. The microscopic nature of these phases is not yet known, though the transition is characterised by a jump in magnetization from weakly polarised FM1 to more strongly polarised FM2.

The Hall effect, at its simplest, is a measure of the Fermi surface size and changes in Fermi surface crossing the FM1-FM2 transition could be detectable by Hall effect and magnetoresistance measurements, hopefully helping to elucidate the nature of this phase transition and the microscopic mechanisms responsible for the associated superconductivity. Here we report preliminary results showing a clear change in Hall coefficient crossing the FM1-FM2 transition.



Left: Pressure-temperature phase diagram showing established phase transitions, from paramagnetism (PM) to FM1, then to FM2, with decreasing temperature. The PM-FM1 transition becomes first order at high pressure, beyond the tricritical point (TCP). The FM1-FM2 transition sharpens from a broad crossover to a first order phase transition beyond the critical end point (CEP). Superconductivity emerges surrounding the FM1-FM2 QCP, and is destroyed at the PM-FM1 QCP. Source: Huxley *et al*, PRL, **91** 20 (2003).

Right: Pressure-temperature-field phase diagram showing first order planes extending from the TCP and CEP. Beyond the PM-FM1 QCP the ferromagnetic state can be induced by application of magnetic field, up to a putative quantum critical end point (QCEP). The FM1-FM2 transition is also metamagnetic, though the CEP remains relatively fixed with field at approximately 7 K . Source: Taufour *et al*, JPCS, **273** 012017 (2011).

Thermopower as a sensitive probe of electronic nematicity in iron pnictides

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(Dated: July 4, 2013)

The in-plane anisotropy of the thermoelectric power and electrical resistivity on detwinned single crystals of isovalent substituted $EuFe_2(As_{1-x}P_x)_2$ are investigated. The thermopower anisotropy is more pronounced than the resistivity anisotropy and clearly visible already at temperatures above the structural and magnetic phase transitions. Remarkably, a sign change of the thermopower anisotropy below the structural transition is observed. We associate this change with the interplay of two contributions namely anisotropic scattering and orbital polarization, which dominate at high- and low-temperatures, respectively. Furthermore, we present evidence that suggests the possibility of a (partial) detwinning through an applied magnetic field ($\propto$ 1 T) in the AFM ordered phase of the Eu^{2+} moments below 19 K. Most remarkably, the detwinned state seems to persist without a field up to a temperature of approximately 195 K.

Search for IUC magnetic order close to optimal doping in superconducting cuprates

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Andrew Wildes *(ILL, FRANCE)*

The phase diagram of high temperature superconductors is dominated by a pseudo-gap (PG) phase with highly unusual physical properties [1]. Many theories attribute its origin to the proximity of a competing state, but there is a wide disagreement about the nature of this state. Beyond usual charge or spin instability, it has been proposed that the PG phase involves circulating currents (CC) flowing around the CuO_2 square lattice with two (phase CC-Θ_{II}) circulating current loops per CuO_2 plaquette [2]. In the vicinity of each Cu site, current loops generate staggered orbital magnetic moments without breaking the lattice translation invariance. Such an intra-unit-cell (IUC) magnetic order can be detected by polarized neutron scattering technique.
Using polarized neutron scattering on the spectrometer 4F1 at Orphée Reactor at Saclay, we successfully reported the existence of a magnetic order in the PG state of 3 cuprate families: $YBa_2Cu_3O_{6+\delta}$ (YBCO) [3-4], $HgBa_2CuO_{4+\delta}$ (Hg1201) [5], $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212) [6]. The change of the magnitude of the observed effect with different neutron polarization [4] demonstrates the magnetic nature of the phenomenon, and rules out an experimental artifact. The observed symmetry is consistent with the theoretically-predicted broken-symmetry state, CC- Θ_{II} phase [2]. The IUC order develops below a temperature T_{mag} that matches the PG temperature T* as defined by the resistivity measurement for these families of compounds. Our systematic study, carried on many single crystals with various hole dopings demonstrates that the existence of an IUC magnetic state is a genuine properties of the PG phase of superconducting cuprates. Moreover, our polarized neutron scattering measurement suggests that the pseudogap is a symmetry breaking state, a conclusion which is now corroborated by ultrasound measurements [7].
As one approaches the quantum critical doping (p_c~0.2), where the PG state vanishes according to thermodynamic measurements, one expects a reduced magnetic critical temperature (T_{mag}) as well as a weaker magnetic intensity. We recently investigated YBCO sample around optimal doping (p=0.16), where the SC transition is maximum. Due to the weakness of the magnetic signal, the observation around such optimal doping is more difficult. Using a flipping ratio calibration on stronger Bragg peaks, we have been nevertheless able to observe the IUC magnetic order that develops around T_{mag} in $YBa_2CuO_{6.85}$ (T_c=89 K, p~0.15). Moreover, by performing momentum scans across the Bragg reflection, we report for the first time a shortening of the magnetic correlation length: the persistence of the signal away from the Bragg peak at low temperature means that the scattering remains short range even at temperature well below T_{mag}. Diffraction measurements showed also a critical slowing down of magnetic fluctuations on both sides of the transition temperature, T_{mag}.

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Pressure dependent quasi-particle relaxation in a one dimensional Mott insulator

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We report a near-infrared pump-probe experiment at high static pressures aimed to the measurement of the pressure scaling of the incoherent many-body relaxation in a Mott insulator [1]. The organic compound ET-F2TCNQ, is a room-temperature 1D Mott insulator characterized by a weak electron-lattice interaction and a high correlation energy (0.8 eV) [2]. These features make it an ideal material for the investigation of purely electronic excitations in presence of strong correlations. The optical spectrum along the a axis displays a narrow charge transfer (CT) resonance and it has been recently shown that its photoexcitation induces a metallic state modulated on the 10 fs scale by the coherent evolution of double occupancies (doublons) and empty sites (holons) [3,4].
Our goal here is to describe how these many-body excitations' lifetimes are related to the microscopic parameters of this compound, namely the onsite correlation energy U, the intersite correlation V, and the hopping t.
Experiments in fermionic optical lattices suggest that in 3D the relaxation time depends exponentially from the ratio U/t [5], and in our case high pressures represent an ideal tuning parameter. As pressure is applied, the CT band redshifts and broadens because of the increased overlap in the system. This translates in an increase of the V and t parameters, while U, being an onsite property, stays constant. A fit of the measured steady state infrared optical conductivity with the corresponding optical response for a pure extended Hubbard model allows a reliable determination of the microscopic parameters U, V, t.
The lifetime for the holon-doublon excitation are instead extracted through a degenerate narrowband pump-probe reflectivity measurement of the CT resonance as a function of pressure. The lifetime of the holon-doublon pairs (around 500 fs at ambient conditions), that is dictated by the interaction with a dissipative bath (e.g. molecular vibrations), gets reduced with the increased hopping. On the basis of the experimentally observed pressure trend, we propose a micrscopic model that describes the simultaneous interplay of the electronic parameters (U, V, t) and of the coupling to the bath.

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Domain Wall and Reverse Domain Superconductivity in Superconductor/Ferromagnet Hybrid Structures[1]

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We have investigated the effect of inhomogeneous stray fields of a ferromagnet on the nucleation of the superconducting order parameter in superconductor/ferromagnet (S/F) systems magnetically coupled. Low-temperature scanning tunneling microscopy and spectroscopy measurements were performed on a Pb/[Co/Pd] system, which has a nontrivial H-T phase diagram under externally applied magnetic fields. Conductance maps and tunneling spectroscopy of these systems show clear indications of domain wall and reverse domain superconductivity. Close to the transition temperature (Tc) and in zero applied field, we visualized the emergence of superconductivity in regions above the separation between adjacent magnetic domains on length scales of the order of the coherence length. We also find an increase in Tc for certain values of applied field above magnetic domains of the opposite polarity.

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Vestigial order

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When there is a sequence of transitions separating an ordered (broken symmetry) crystalline state from a disordered liquid state, the intermediate phases which spontaneously break a subset of the symmetries of the crystalline state can be said to have vestigial order. Familiar examples from classical physics include hexatic phases in the theory of 2D melting and nearly smectic nematic phases in 3D. Here, in the context of the phases of highly correlated electronic materials, we analyze a solvable O(N) quantum rotor model of the formation of an electron-nematic phase through the partial melting of a unidirectional (striped) density wave phase by thermal or quantum fluctuations, or as a function of increasing quenched disorder. We comment on the relevance of these considerations to the formation of nematic phases in the cuprates, Fe-pnictides, $Sr_3Ru_2O_7$, and quantum Hall systems, as well as for a possible electron cholesteric phase in the cuprates.

Ginzburg-Landau formalism for multiband superconductors

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We derive the Ginzburg-Landau (GL) formalism for a multiband superconductor from the microscopic BSC model. In the derivation, we employ the standard Gor'kov procedure but with an additional truncation in order to match accuracies of the obtained terms. The second truncation is meant to remove contributions to band gaps of orders higher than $\tau^{1/2}$ (where τ is the proximity to the critical temperature), not inherent in the GL domain and appearing only in the presence of multiple bands. There are two qualitatively different scenarios of the obtained formalism: when the solution for T_c is non-degenerate and when it is degenerate. For the first scenario, we obtain the unique Landau order parameter in the system and the band gaps are proportional to this order parameter. The GL theory of a multiband superconductor maps effectively onto a single-component GL formalism in this case. For the degenerated regime, the number of relevant Landau order parameters of the system equals to the degeneracy factor. The last scenario is considered for a three-band system with strong interband couplings, which may be relevant for pnictides. In this case T_c is two-fold degenerated, thus there are two order parameters. We found that the ground state of such system develops a nontrivial phase difference between the band gaps, referred to as the state with the phase frustration or the chiral solution[1].

Another example of multiband superconductors is nanofilms with atomically uniform thickness. The single-particle energy spectrum in nanofilm is tightly bound in the perpendicular quantum-confined direction. This leads to the formation of a series of single - particle subbands. Here the system size perpendicular to the film is much smaller than the bulk Cooper-pair radius and the order parameter exhibits fast spatial variation in the direction perpendicular to the nanofilm. Therefore, the Gor'kov derivation of the three-dimensional GL formalism is not applicable. We derive the GL formalism appropriate for nanofilms and demonstrate that the presence of the size quantization leads to a multiband formalism. We start the derivation from the microscopic BCS theory first by integrating out the perpendicular coordinates in the gap equation. Afterwards, we employ the Gor'kov truncation procedure and subsequent additional reconstruction in the similar way as in the derivation of the GL equations for the multiband superconductor. We obtain unique coherence length and the 2D magnetic screening length for all subbands. In the limit when the number of subbands is large, the quantum-size effects are weakened. Then the magnetic screening length becomes inversely proportional to the film thickness which is the well-known Pearl result for superconducting films[2].

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Spectral properties of a superconducting quantum dot system

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We study the Josephson current through a quantum dot embedded between two superconductors showing a phase difference. The system is described by a single-impurity Anderson model coupled to BCS superconducting leads. We utilize diagrammatic perturbation techniques in the Coulomb interaction to capture the relevant physical phenomena. We study the effect of Coulomb interaction on the Andreev bound states present in the electron spectral function and its effect on the transport properties. Results of the Hartree-Fock approximation, second-order perturbation theory and the random phase approximation at zero temperature are presented.

Electrodynamics of Superconducting Ultra-Thin Films Probed by Quasi-Optical THz Spectroscopy

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Over the last years, study of ultra-thin films of conventional superconductors like niobium nitride (NbN) or tantalum Nitride (TaN) has attracted broad attention since these systems have been identified as model systems for the superconductor-insulator quantum phase transition (SIT). Recent findings manifest that the superconducting properties are tremendously affected in the vicinity of the SIT going beyond the scope of BCS theory. Besides pure academic interest, ultra-thin superconducting films play a key role in the development of sophisticated devices such as single photon detectors.
Quasi-optical THz spectroscopy is a particularly suited tool with direct access to superconducting properties, such as the superconducting energy gap, shedding light on current academic questions as well as understanding and improving the performance of novel devices.

With our THz-spectroscopy approach we measure amplitude and phaseshift of coherent radiation (0.09-1.2 THz) passing through thin film systems. We present the performance and possibilities of our experimental set-up, and we apply it to ultra-thin superconducting films of NbN and TaN. We fit the experimental data to weak-coupling BCS theory, and we obtain frequency- and temperature-dependent superconducting properties such as the complex optical conductivity, the complex dielectric function, the energy gap, the penetration depth, and the superfluid density

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Quasiparticle mass enhancement close to the quantum critical point in $BaFe_2(As_{1-x}P_x)_2$

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Cuprate high-Tc superconductors exhibit enigmatic behavior in the nonsuperconducting state. For carrier concentrations near “optimal doping” (with respect to the highest Tcs) the transport and spectroscopic properties are unlike those of a Landau–Fermi liquid. On the Mott-insulating side of the optimal carrier concentration, which corresponds to underdoping, a pseudogap removes quasi-particle spectral weight from parts of the Fermi surface and causes a breakup of the Fermi surface into disconnected nodal and antinodal sectors. Here, we show that the near-nodal excitations of underdoped cuprates obey Fermi liquid behavior. The lifetime τ(ω, T) of a quasi-particle depends on its energy ω as well as on the temperature T. For a Fermi liquid, 1/τ(ω, T) is expected to collapse on a universal function proportional to (ℏω)^2 + (pπkBT)^2. Magneto-transport experiments, which probe the properties in the limit ω = 0, have provided indications for the presence of a T2 dependence of the dc (ω = 0) resistivity of different cuprate materials. However, Fermi liquid behavior is very much about the energy dependence of the lifetime, and this can only be addressed by spectroscopic techniques. Our optical experiments confirm the aforementioned universal ω- and T dependence of 1/τ(ω, T), with p ~ 1.5. Our data thus provide a piece of evidence in favor of a Fermi liquid-like scenario of the pseudogap phase of the cuprates.

Robustness of edge states in non-centrosymmetric superconductors

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Nodal superconductors without inversion symmetry have non-trivial topological properties, manifested by topologically protected flat-band edge states [1,2]. Since the bulk is not fully gapped, the edge states of nodal superconductors can in principle be susceptible to impurities, which break translational symmetries.

Using recursive Green's function techniques we study the robustness of these edge states against both magnetic and non-magnetic disorder.
We show that for weak and dilute non-magnetic impurities, a finite number of mid-gap edge states remains at zero-energy.
We compute the zero bias conductance of a junction between a normal lead and a non-centrosymmetric superconductor as a function of disorder strength.
It is found that the flat-band edge states give rise to a nearly quantized zero-bias conductance even in the presence of non-magnetic impurities.
Further insight in the origin of the topological protection of these states is gained by analyzing the spin structure of edge and bulk states of the superconducting system. Recurring to a single impurity calculation by quasiparticle interference, we directly observe the suppression of back-scattering of the edge states, and its emergence upon introduction of magnetic defects.

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β-$YbAlB_4$: A critical nodal metal

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β-$YbAlB_4$ is the first Yb based heavy fermion superconductor and has a non Fermi Liquid behavior in the normal state that develops without external tuning by pressure or doping, making it intrinsically quantum critical [1]. Application of a magnetic field is found to drive the development of a Fermi Liquid in which the Fermi temperature is determined by the Zeeman energy [2]. Here we present a theory for the intrinsic quantum criticality in which the main ingredient is an anisotropic hybridization matrix with line nodes in momentum space that carry a vorticity and resemble topological defects. Our theory predicts that the application of a field induces a novel kind of Lifshitz transition, in which a quasi-two dimensional Fermi Liquid with density of states $N^*(B) \propto 1/\sqrt{B}$ nucleates around the line node in momentum space [3]. This picture can also account for the ESR anomalies recently observed in this system [4,5].

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Fermi liquids near Pomeranchuk instabilites: a tractable crossing-symmetric equation approach

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The tractable crossing symmetric formalism is developed for the 3D and 2D cases. We first consider spherical and circular Fermi surfaces and then extend this to 2D square lattice systems. Limiting cases, such as small (q,ω), vanishing momentum-energy transfer ($q \to 0$, $\omega \to 0$), vanishing q but non-zero ω are considered. This is applied to the study of various properties of 3D and 2D Fermi systems. Of particular interest is the physics near Pomeranchuk instabilities: in Fermi systems, interactions can cause symmetry-breaking deformations of the Fermi surface, called Pomeranchuk instabilities. In Fermi liquid theory language, this occurs when one of the Landau harmonics $F^{s,a} \to -(2l + 1)$; e.g. $F^{s,a} \to -1$ are related to ferromagnetic transition (a), and density instabilities(s). The corresponding points in parameter space may be viewed as quantum critical points. Using graphical and numerical methods to solve coupled non-linear integral equations that arise in the crossing symmetric equation scheme, we obtain results in two and three dimensions close to Pomeranchuk instabilities.

Electronic Spin Susceptibility Enhancement in Pauli Limited Unconventional Superconductors

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We calculate the wave-vector dependent electronic spin susceptibility $\chi_{\alpha\beta}(q, H_0)$ of a superconducting state in uniform magnetic field H_0. We consider Pauli limited materials with d-wave symmetry, and a 2D cylindrical electronic Fermi surface. We find that both longitudinal and transverse components of the susceptibility tensor are enhanced over their normal state values in the high-field, low-temperature region of the H - T phase diagram. We identify several wave vectors, connecting field-produced hot spots on the Fermi surface, which correspond to the enhancement of either $\chi_{\parallel}$ or $\chi_{\perp}$ components.

Josephson junctions with Si|FM (ferromagnet) barriers

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Hanna Sickinger, Edward Goldobin, Dieter Koelle, Reinhold Kleiner *Physikalisches Institut, Experimentalphysik II, Universität Tübingen, Germany*

Josephson junctions are promising elements for RSFQ logic [1] and flux qubits [2]. We fabricated and investigated Josephson junctions with barriers made of Si-Fe alloy aiming to achieve high critical current densities in the state. In order to vary parameters like composition and thickness independently in a single wafer run, a combinatorial sputtering technique for alloy and multi layer deposition of Fe and Si is presented. Our approach is based on a common planetary-type sputter system. Both materials were deposited with monotonic thickness gradients which were aligned perpendicular to each other. Alloys are formed by stacking of alternately deposited submonolayers of Fe and Si. Various Nb/Al based Josephson junctions with FeSi alloy interlayers and different combinations of Si|Fe multilayers were prepared. The – characteristics and ( ) exhibited RSJ-like and Fraunhofer-like behavior, respectively, while the critical current density as a function of the Fe content showed a non-trivial behavior.

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Electronic structures of heavy-fermion $Ce_2Ni_3Ge_5$, $CeNiGe_3$, and exotic BCS-like $YNiGe_3$ superconductors

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Band structures of pressure-induced Ce2Ni3Ge5 [1], CeNiGe3 and exotic BCS-like YNiGe3 [2] superconductors have been computed employing the full potential local-orbital (FPLO) code [3] within both the local density approximation (LDA) and LDA+U approaches. These investigations were focused mainly on changes in the topology of the Fermi surface (FS) of these compounds and their non-superconducting counterparts. Our calculated FSs of only the two considered Ce-based heavy-fermion superconductors reveal specific nesting properties. They support a previously postulated presence of antiferromagnetic spin fluctuations (SF) that can be responsible for unconventional superconductivity in these systems. In turn, the topology of the FS in YNiGe3 exhibits a possibility of multi-band superconductivity, which can explain the observed anomalous jump at the superconducting critical temperature in its specific heat.

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An asymptotically exact weak-coupling theory of superconductivity in a multiband spin-orbit coupled system: the case of Sr2RuO4

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We study the superconductivity pairing mechanism in Sr2RuO4 in the limit of small interaction by extending a renormalization group (RG) calculation developed by Raghu et al[1] to include multiband and spin-orbit coupling (SOC) effects. We show these effects to be crucial to discriminate between the possible order parameters. In contrast to the usual theory of an "active" gamma band with a large superconducting gap and "passive" alpha and beta bands with smaller gaps induced by a proximity effect, we obtain pseudo-spin triplet gaps of the same order of magnitude on all three bands for a large range of the inter-orbital interaction parameter. The inclusion of SOC in the microscopic model allows us to study ab initio the breaking of degeneracy between the different d vector orentiations. Implications for experiments will be discussed.

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Fluctuation mediated pairing in a multiband spin-density-wave system

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TU Dresden

The coexistence of spin-density-wave (SDW) order and superconductivity (SC) has gained significant attention in the field of iron pnictides due to strong experimental evidence for microscopic coexistence in a number of compounds. We present a technique for studying pairing mediated by spin and charge fluctuations in the presence of a SDW background in a multiband system. It is applied to a two-band model, which is commonly used as a minimal model for the pnictides. Our approach is more realistic than previous studies that use phenomenological pairing potentials. It turns out that the fluctuations strongly modify the effect of the bare interaction potentials. A change of the bare interactions can tune the system from simple s^{+-} pairing to a nodal s^{+-} gap. Moreover, while the bare interactions only give s^{+-} pairing, the fluctuation mediated interaction leads to a finite parameter range with p-wave pairing.

Experiments with φ Josephson junctions

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Josephson junctions (JJs) with a ferromagnetic interlayer can have a phase drop of π or 0 in the ground state, depending of the thickness of the ferromagnet (π JJs or 0 JJs). Also 0-π JJs can be realized where one part of the junction is in the π state while the other part is in the 0 state.

A generalization of a π JJ is a φ JJ, which has the phase ±φ in the ground state. The value of φ can be chosen by design and tuned in the interval $0 < \varphi < \pi$. The φ JJs we used in our experiment are fabricated as 0-π JJs with asymmetric current densities in the 0 and π facets [1]. This system can be described by an effective current-phase relation [1], which is tunable by an externally applied magnetic field.

We present the experimental evidence of such a φ JJ [2]. In particular we demonstrate that: (a) a φ JJ has two states −φ and +φ, (b) the unknown state can be detected (read out) by measuring I_c (I_{c+} or I_{c-}), and (c) we can prepare a particular state by applying a magnetic field or a special bias sweep sequence. These properties can be utilized to use a φ JJ, for example, as a memory cell (classical bit) [3].

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Fermi liquids near Pomeranchuk instabilites: a tractable crossing-symmetric equation approach

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Cuprate high-Tc superconductors exhibit enigmatic behavior in the nonsuperconducting state. For carrier concentrations near “optimal doping” (with respect to the highest Tcs) the transport and spectroscopic properties are unlike those of a Landau–Fermi liquid. On the Mott-insulating side of the optimal carrier concentration, which corresponds to underdoping, a pseudogap removes quasi-particle spectral weight from parts of the Fermi surface and causes a breakup of the Fermi surface into disconnected nodal and antinodal sectors. Here, we show that the near-nodal excitations of underdoped cuprates obey Fermi liquid behavior. The lifetime τ(ω, T) of a quasi-particle depends on its energy ω as well as on the temperature T. For a Fermi liquid, 1/τ(ω, T) is expected to collapse on a universal function proportional to (ℏω)^2 + (pπkBT)^2. Magneto-transport experiments, which probe the properties in the limit ω = 0, have provided indications for the presence of a T2 dependence of the dc (ω = 0) resistivity of different cuprate materials. However, Fermi liquid behavior is very much about the energy dependence of the lifetime, and this can only be addressed by spectroscopic techniques. Our optical experiments confirm the aforementioned universal ω- and T dependence of 1/τ(ω, T), with p ~ 1.5. Our data thus provide a piece of evidence in favor of a Fermi liquid-like scenario of the pseudogap phase of the cuprates.

Vortex pinning mechanisms in ab-plane direction in CSD-YBCO films

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Solution-derived YBCO nanocomposites have emerged as excellent low cost and scalable superconducting materials with properties that can be finely tuned through processing to reach high performance long length coated conductors at high magnetic fields. The understanding of vortex pinning mechanisms and vortex dynamics by measuring the angular-dependent critical current density J_c through *I(V)* curves in a large range of temperatures and magnetic fields enables us to identify the different contributions associated to the defect structure of the superconductor. This angular dependence exhibits a peak for magnetic field orientations parallel to the ab-planes, which is foreseen to mainly arise in YBCO films from the effects of intrinsic pinning and stacking faults.

We have analyzed the temperature and magnetic field dependence of the height and width of J_c*(H//ab)*-peak in order to discriminate between the contributions of both types of pinning centers and we have evaluated the power law exponent *N* of the *I(V)* curves, which presents an inverse correlation to J_c associated to the intrinsic pinning, firstly observed by Civale *et al.*[1] in PLD samples.

We identify a crossover line H_{cr} (T) for each studied sample that separates the (H,T) phase diagram in two regions: Intrinsic pinning dominated region for low temperatures and high magnetic fields and a Stacking Fault pinning dominated region for higher temperatures and lower magnetic fields. Comparison between a standard film and different nanocomposite films allows us to discriminate the role of the stacking faults generated during the growth process induced by the presence of the second phase nanoparticles. The Scanning Transmission Electron Microscopy analysis undertaken in these same samples have been extremely valuable to correlate the effect of the different pinning contributions with the microstructure.

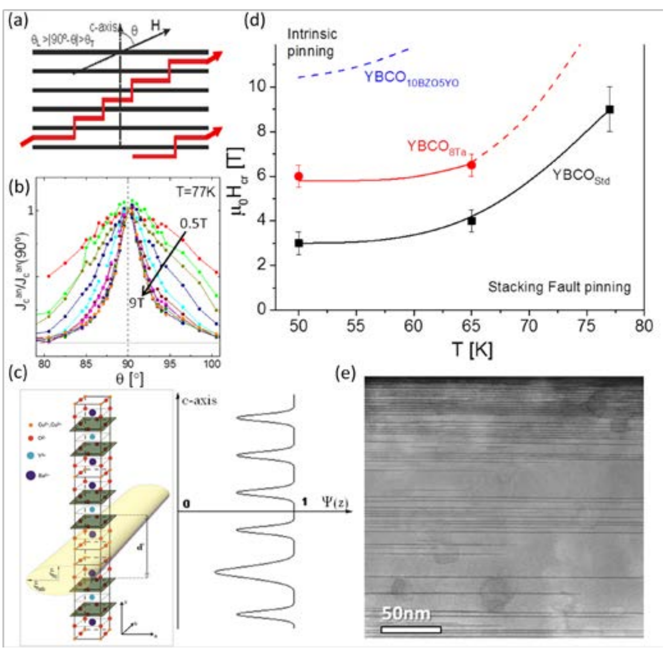

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Figure: (a) Staircase model for an anisotropic pinning center. **(b)** Angular dependence of the critical current density Jc around H||ab for different magnetic fields of a YBCO nanocomposite. **(c)** Stacking fault within the YBCO structure and qualitative modulation of the superconducting parameter Ψ along the crystallographic c-axis. **(d)** Magnetic phase diagram showing the separation of different pinning domination regions for a standard YBCO and two YBCO nanocomposites. **(e)** STEM image of a YBCO nanocomposite.

Field-induced magnetic transition in an iron pnictide superconductor

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We report a high magnetic field study up to 55 T of the optimally-doped iron-pnictide superconductor Ca10(Pt_3As_8)((Fe_1-xPtx)2As_2)5 (x = 0.097) with a TC of 10 K using magnetic torque, tunnel diode oscillator technique and transport measurements. We determine the superconducting phase diagram, revealing an anisotropy of the irreversiblity field up to a factor of 10 near TC and an upward curvature of the data for H perpendicular to ab.

Unexpectedly, beyond the superconducting state we find a field-induced magnetic transition at 22 T in the magnetic torque data when the magnetic field is applied perpendicular to the ab plane. This transition becomes significantly sharper by suppressing the thermal fluctuations while lowering the temperature to 0.35 K. The anomaly can be well described by a spin-flop model, presumably resulting from antiferromagnetic fluctuations in the Fe-As plane.

High critical current density in $(Ba_{0.6}K_{0.4})Fe_2As_2$ polycrystals and round wires with randomly oriented grains

Jeremy D. Weiss, J. Jiang, C. Tarantini, F. Kametani, A. Polyanskii, B. Hainsey, D. Larbalestier, and E. E. Hellstrom

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We present very much improved properties of $(Ba_{0.6}K_{0.4})Fe_2As_2$ (Ba-122) made as round wires and bulks in which transport critical current densities beyond 10^5 Acm^{-2} (0T, >10K) are obtained.[1] A mechanochemical reaction is used to synthesize the material and extrinsic current blockers are eliminated through carful low-temperature and high pressure synthesis.[2] The enhanced grain connectivity may also be ascribed to less depressed grain boundary order parameters in the K-doped material when compared to other ferropnictide superconductors, and to the enhanced vortex stiffness of this low anisotropy compound.

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Suppression of Geometrical Barrier for Vortices in Platelet Superconductors

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Inspired by the observation of a structured vortex dome in flat superconducting samples, we investigate the magnetic response of (two) aligned platelet-shape superconducting strips subject to a perpendicular magnetic field. In the Meissner state, we find that the field is most strongly enhanced inside the gap and hence the penetration as determined by the geometric barrier occurs from the inner edges. The penetrated field assumes a dome-like shape in each strip which skews towards the gap. For narrow gaps, i.e., gaps smaller than the strip thickness, the system's response changes parametrically due to a field- squeezing inside the gap (estuary problem) provoking a considerable rearrangement of the shielding currents. Compared to a platelet-shaped sample without a gap, the diamagnetic response collapses for narrow gaps and the geometric barrier effect vanishes in this limit. With the break-down of the overall magnetization loop, the specific response of the superconducting material needs to be taken into account. Inspired by the `microscopic' analysis developed for the surface barrier problem, we study the distortion of the vortex dome and its consequences on the magnetic response.

Low temperature magnetic domain imaging

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Topologically protected states are predicted at interfaces in systems with a complex order parameter. Promising locations for this behaviour include ferromagnetic domain walls in the superconductors URhGe and UGe_2, as well as the predicted unconventional vortices of UPt_3.

Probing these states first requires the imaging of magnetic structures. Sub-kelvin temperatures are a must, but interesting behaviour is also predicted at high pressure. Magneto-optics is widely used to images domain structures, relying on the change in polarisation of light reflected from the surface of a magnetised sample.

Here, the design of a cryogenic magneto-optical (Kerr) microscope system is presented. It combines polarised-light microscope imaging and scanning optical magnetometry (at two different wavelengths) to create a domain structure image.

A high-NA objective lens and photo-elastic modulator respectively allow for high spatial resolution and sensitivity to Kerr rotation. Preliminary results demonstrating this performance are presented here.

Dynamic Correlations and Scaling of local Quantum Criticality in Dissipative Environments

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The quantum dynamics of strongly interacting, finite systems in contact with non-interacting environments with extended states near and far from equilibrium is of current interest in various fields of physics. The Dicke, the Jaynes-Cummings, the Rabi, the Caldeira-Leggett, and the Kondo model e.g. belong to this class of systems. In dissipative environments such systems may undergo continuous zero-temperature phase transitions which leads to singular behavior of dynamic correlation functions.

Here, we study the quantum-critical destruction of Kondo screening in local moment systems in contact with baths of fermions and bosons featuring powerlaw behavior in their local density of states and spectral density. These models are often referred to as pseudogap Bose-Fermi Kondo models and allow to study the non-trivial interplay between two different mechanisms of critical Kondo destruction [1]. An SU(2) symmetric version of these models has been studied by the perturbative renormalization-group method [2,3]. Here, we study the SU(M)xSU(N) generalization in the dynamical large-N limit [4], and obtain all critical exponents through a scaling ansatz. We confirm the results by solving the large-N equations numerically. Full scaling functions of the dynamical susceptibility and the local T-matrix are obtained.

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Electronic band structure of $BaMn_2As_2$

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The iron-based superconductors are known to exhibit significant Hund's rule coupling that leads to non-negligible electronic correlations. Previous angle-resolved photoemission spectroscopy (ARPES) experiments on iron-based superconductors reported a typical overall bandwidth renormalization of 2-5. Here we report an ARPES study of iso-structural $BaMn_2As_2$ with a half-filled 3d shell. We determined the band structure and there is a band gap of 200 meV. In contrast to common expectation, the overall bandwidth is nearly similar to local density approximation (LDA) calculation, which indicates small electronic correlations in this particular material. Our photon energy dependent photoemission spectra provide evidence that bands near E_F have strong resonance effect at the photon energy corresponding to the core level of As 3*d* and Mn 3*p*, which implies that the Mn 3*d* states strongly hybridize with the As 4*p* states. The hybridization is competing against the Hund's rule coupling thus reducing correlation effects significantly. This work is supported by CAS grants and US DOE.

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