Name:

A World of Correlations

Conference in memory of Alfréd Zawadowski

13-16 June, 2019

Budapest, Hungary

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Time	Speaker	Title

Friday - Hungarian Academy of Sciences

9:20-9:30	Gergely Zaránd	Opening
9.30-10:00	Eva Andrei	Strategies for transforming the band structure of 2D materials
10:00-10.30	Reinhold Egger	Fermi liquid theory for superconducting Kondo problems
10:30-11:00	Silvano De Franceschi	Artificial quantum impurities in superconductor-semiconductor nanostructures
11:00-11:30	**Coffee Break - Poster session**	
11.30-12.00	David Goldhaber-Gordon	Quantum Criticality in Quantum Impurities Built from Quantum Dots
12.00-12:30	Jaroslav Fabian	Electronic structure of 2D materials: gaps, spins, and magnets
12:30-13:00	Christopher Bäuerle	Unveiling the bosonic nature in an ultrashort single-electron pulse
13:00-14:30	**Lunch (conference photo)**	
14:30-15:00	Thomas Devereaux	Unbiased simulations of the Hubbard model and how to see charge collective modes with resonant inelastic x-ray scattering
15:00-15:30	Ian Affleck	The Majorana-Hubbard Model
15:30-16:30	**Coffee Break - Poster session**	
16:30-17:00	Pascal Simon	Majorana zero modes around skyrmionic textures'
17:00-17:30	Christoph Strunk	Dark states and wave-function shaping in clean carbon nanotubes
17:30-18:00	Rudi Hackl	Bardasis-Schrieffer modes as a probe of anisotropic Cooper pairing in iron-based superconductors
18:00-	Free evening	

Saturday - Thermal Hotel Margitsziget

9.30-10:00	Neven Barisic	High-Tc cuprates – story of two electronic subsystems
10:00-10:30	Peter Littlewood	Polaron physics and superconductivity in SrTiO3
10:30-11:00	**Coffee break**	
11.00-11.30	Henri Alloul	Incidence of charge ordering on the electronic structure and properties of the layered oxide NaxCoO2
11.30-12:00	Michele Fabrizio	Transient cooling low-frequency excitations by impulse perturbations: the case of K3C60
12:00-12:30	Jan von Delft	Uncovering non-Fermi-liquid behavior in Hund metals
12:30-14:00	**Lunch**	
14:00-14:30	Jan van Ruitenbeek	The challenges of connecting single molecules to metallic leads
14:30-15:00	Johannes Kroha	RKKY-induced Kondo breakdown and Fermi volume evolution in heavy fermions: Renormalization group and time-resolved THz spectroscopy
15:00-15:30	Thierry Martin	Evidence of Majorana fermions in the noise characteristic of normal metal-topological superconductor junctions
15:30-16:00	Natan Andrei	Quantum Work of Optical Lattices
16:00-16:30	**Coffee break**	
16:30-17:00	Paul Chaikin	Freezing on a Sphere: Classical 2D Wigner Crystallization and Particle Fractionalization on a Water Droplet
17:00-17:30	Baruch Horovitz	Spin resonance in current noise with Coulomb blockade
17:30-18:00	Dan Cox	Localization and Vortex Lattices on My Mind: Metaphors for Solid State Phenomena in Neuronal Assemblies
18:00-18:30	Jens Paaske	Stoner antiferromagnetism in the periodic driven Hubbard model
19:30-	**Conference dinner (for invitees)**	

Strategies for transforming the band structure of 2D materials

Eva Y. Andrei
Department of Physics and Astronomy
Rutgers University

Materials discovery has traditionally involved serendipity or painstaking exploration of a large phase space of chemically synthesized compounds. A new materials era started with the breakthrough isolation of the free standing one-atom thick Carbon crystal, graphene, followed by many others. The distinctive characteristic of these materials is that, with all the atoms residing at the surface, it is possible to access and manipulate their properties without changing the chemical composition. I will discuss a few examples where the electronic properties and band structure are transformed by non-chemical means: inducing magnetism and Kondo screening by removing single Carbon atoms in graphene [1.2]; generating flat bands and pseudo-magnetic fields by introducing a twist between layers [3,4], by buckling [5] or by introducing strain [6].

References

[1] Jiang, Y. *et al.* Inducing Kondo screening of vacancy magnetic moments in graphene with gating and local curvature. *Nature Communications* **9**, 2349 (2018).
[2] May, D. *et al.* Modeling of the gate-controlled Kondo effect at carbon point defects in graphene. *Physical Review B* **97**, 155419 (2018).
[3] Jiang, Y. *et al.* Evidence of charge-ordering and broken rotational symmetry in magic angle twisted bilayer graphene. *arXiv:1904.10153* (2019).
[4] Li, G. *et al.* Observation of Van Hove singularities in twisted graphene layers. *Nature Physics* **6**, 109-113 (2010).
[5] Jiang, Y. *et al.* Flat Bands in Buckled Graphene Superlattices. *arXiv:1904.10147* (2019).
[6] Jiang, Y. *et al.* Visualizing Strain-Induced Pseudomagnetic Fields in Graphene through an hBN Magnifying Glass. *Nano Letters* **17**, 2839-2843 (2017).

Fermi liquid theory for superconducting Kondo problems

Reinhold Egger
Heinrich-Heine-University of Düsseldorf

We present a Fermi liquid approach to superconducting Kondo problems applicable when the Kondo temperature is large compared to the superconducting gap. To illustrate the theory, we study the current-phase relation and the Andreev level spectrum for an Anderson impurity between two s-wave superconductors. In the particle-hole symmetric Kondo limit, we find a 4π periodic Andreev spectrum. The 4π periodicity persists under a small voltage bias which however causes an asymmetric distortion of Andreev levels. The latter distinguishes the present 4π effect from the one in topological Majorana junctions.

Artificial quantum impurities in superconductor-semiconductor nanostructures

Silvano De Franceschi
Univ. Grenoble Alpes and CEA Grenoble

A quantum dot coupled to a superconducting contact provides a tunable artificial analog of a magnetic atom in a superconductor, a paradigmatic quantum impurity problem. We have experimentally investigated this type of system in a variety of nanodevices based on semiconductor nanowires, mainly made of InAs, and different types superconducting metal electrodes, consisting of Al, V, or Ta. In some experiments, we used an additional normal-type contact as a weakly coupled tunnel probe to perform tunneling spectroscopy measurements of the elementary subgap excitations, known as Yu-Shiba-Rusinov states [1,2]. In other experiments involving devices with two superconducting contacts, we investigated the impact of an artificial magnetic impurity on the supercurrent transport regime [3]. I shall review these works with a particular emphasis on spin-related effects.

References:

1 E.J.H. Lee, X. Jiang, M. Houzet, R. Aguado, C.M. Lieber, S. De Franceschi, "Spin-resolved Andreev levels and parity crossings in hybrid superconductor-semiconductor nanostructures", Nature Nanotechnology 9, 79 (2014).

2. E.J.H. Lee, X. Jiang, R. Zitko, R. Aguado, C.M. Lieber, S. De Franceschi "Scaling of sub-gap excitations in a superconductor-semiconductor nanowire quantum dot", Phys. Rev. B 95, 180502(R) (2017).

3. J.C. Estrada Saldaña, R. Žitko, J.P. Cleuziou, E.J.H. Lee, V. Zannier, D. Ercolani, L. Sorba, R. Aguado, S. De Franceschi, "Supercurrent through a spin-split quasi-ballistic point contact in an InAs nanowire", arXiv:1801.01855.

Quantum Criticality in Quantum Impurities Built from Quantum Dots

David Goldhaber-Gordon
Stanford University

Many-body physics is normally encountered in complex bulk materials, where the underlying Hamiltonian may not be clear. I will describe an alternative approach – using nanopatterning to engineer and build an artificial realization of a well-defined Hamiltonian, then probing its properties experimentally [2].

I hope that this approach to many-body systems and quantum phase transitions, inspired in part by the work of Alfred Zawadowski, will drive theoretical and computational efforts, and ultimately will help us understand the richness of electronic materials such as heavy fermion metals. As a start, I will show that a specially-designed system of electrons with no obvious symmetry can be tuned using voltage on nanoelectrodes to a quantum critical point with an exact theoretical description even at finite temperature [1]. The excitations of nearby mobile electrons at the critical point are collective and look nothing like individual electrons: this is a non-Fermi liquid. Tuning across the critical point, the crossover from one phase to the other through the quantum critical region turns out to have surprising universal properties [2]. Finally, I will describe a new approach to realizing an interesting quantum critical system: 2-impurity Kondo.

References

1. R. M. Potok, I. G. Rau, H. Shtrikman, Y. Oreg, and D. Goldhaber-Gordon, Observation of the two-channel Kondo effect, Nature 446, 167-171 (2007).
2. A. J. Keller, L. Peeters, C. P. Moca, I. Weymann, D. Mahalu, V. Umansky, G. Zaránd, and D. Goldhaber-Gordon, Universal Fermi liquid crossover and quantum criticality in a mesoscopic system, Nature 526, 237–240 (2015)

Electronic structure of 2D materials: gaps, spins, and magnets

Jaroslav Fabian
Department of Physics, University of Regensburg

2D materials offer unprecedented opportunities for studying electronic interactions, as manifested in their unique optical and magnetic properties. The forefront for calculating the electronic structure is GW perturbation theory based on DFT. However, encountering inhibited screening in 2D these methods offer less focused predictions for the elementary gaps. I will show the results of computationally demanding quantum Monte Carlo simulations of the electronic band gaps in phosphorene and briefly review the theoretical and experimental status there. I will then move on to discuss proximity phenomena involving graphene and 2D magnets. I will show how the proximity induced ferromagnetic and antiferromagnetic exchange coupling in graphene leads to novel topological states, when combining spin-orbit and exchange physics.

Unveiling the bosonic nature in an ultrashort single-electron pulse

Christopher Bäuerle
Institut Neél, CNRS Grenoble

Quantum dynamics is very sensitive to dimensionality. While two-dimensional electronic systems form Fermi liquids, one-dimensional systems – Tomonaga-Luttinger liquids – are described by purely bosonic excitations, even though they are initially made of fermions. With the advent of coherent single-electron sources [1- 4], the quantum dynamics of such a liquid is now accessible at the single-electron level.

Here, we report on time-of-flight measurements of ultrashort few-electron charge pulses injected into a quasi-one-dimensional quantum conductor. By changing the confinement potential, we can tune the system from the one dimensional Tomonaga **-** Luttinger liquid limit to the multi-channel Fermi liquid and show that the plasmon velocity can be varied over almost an order of magnitude. Our results [5] are in quantitative agreement with a parameter-free theory and demonstrate a powerful probe for directly investigating real-time dynamics of fractionalisation phenomena in low-dimensional conductors.

References

[1] G. Fève, A. Mahé, J.-M. Berroir, T. Kontos, B. Plaçais, D.C. Glattli, A. Cavanna, B. Etienne, Y. Jin, *Science* **316**, 1169-1172 (2007).

[2] E. Boquillon, V. Freulon, J.-M Berroir, P. Degiovanni, B.Plaçais, A. Cavanna, Y. Jin, G. Fève, *Science* **339**, 6123, 1054-1057, (2013)

[3] J. Dubois, T. Jullien, F. Portier, P. Roche, A. Cavanna, Y. Jin, W. Wegscheider, P. Roulleau and D.C. Glattli, *Nature* **502**, 659-663 (2013)

[4] C. Bäuerle, C. Glattli, T. Meunier, F. Portier, P. Roche, P. Roulleau, S. Takada, and X. Waintal, *Rep. Prog. Phys.* 81 056503 (33pp) (2018)

[5] G. Roussely, E. Arrighi, G. Georgiou, S. Takada, M. Schalk, M. Urdampilleta, A. Ludwig, A. D. Wieck, P. Armagnat, T. Kloss, X. Waintal, T. Meunier, and C. Bäuerle, Nature Communications **9** 2811 (2018)

Unbiased simulations of the Hubbard model and how to see charge collective modes with resonant inelastic x-ray scattering

Thomas Devereaux
Stanford University

It is now well accepted that there are many competing and intertwined phases as "solutions" of the Hubbard model that are separated by very small energies, typically 1/100th of the hopping strength. Therefore it is important to benchmark using unbiased methods which are the stable phases, and how they can be manipulated. In this talk I will present the results of quantum Monte Carlo and DMRG simulations that explore the relationship between stripes and superconductivity. We can show a strong interplay between CDW and long-range superconductivity that can be controlled by varying the next nearest neighbor hopping t'.

The Majorana-Hubbard Model

Ian Affleck
University of British Columbia

A type II superconducting layer in contact with a topological insulator in a magnetic field is predicted to house a Majorana mode at the centre of every vortex core. The low energy Hamiltonian consists of tunneling terms and interaction terms for the Majorana modes, analogous to the Hubbard model but for Hermitian fermion operators. Furthermore, the hopping terms can be tuned to zero by adjusting the chemical potential of the topological insulator to a special symmetry point, implying that the phase diagram as a function of dimensionless interaction strength can be studied experimentally. I will present theoretical predictions for this model in one and two dimensions.

Majorana zero modes around skyrmionic textures

Pascal Simon
University of Paris-South

Recent scanning tunneling spectroscopy measurements on a superconducting monolayer of lead(Pb) with nanoscale cobalt islands, have revealed puzzling quasiparticle in-gap states [1] which demand a better understanding of two-dimensional superconductivity in presence of spin-orbit coupling and magnetism. Thus motivated, we theoretically study a model of two-dimensional s-wave superconductor with a fixed configuration of exchange field and spin-orbit coupling terms allowed by symmetry. Using analytics and exact diagonalization of tight-binding models, we find that a vortex-like defect in the Rashba spin-orbit coupling binds a single Majorana zero-energy (mid-gap) state. In contrast to the case of a superconducting vortex [2], our spin-orbit defect does not create a tower of in-gap excitation states and our findings match the puzzling features observed in the experiment. Additionally, these properties indicate that the system realizes a pair of well-protected Majorana zero mode (MZM) localized at the core and the rim of the defect [3].

We also discuss how the quasiparticle states of the defect relate to the states of superconductors on top of magnetic textures, such as skyrmions. Magnetic skyrmions are nanoscale particle-like spin configurations that are efficiently created and manipulated. They hold great promises for next-generation spintronics applications. I will focus on the theoretical analysis of magnetic skyrmions proximitized by conventional superconductors. I will show that a topological superconducting phase can emerge in these systems and uncover a whole almost flat band of these modes on the edge of the magnetic texture, in contrast to a previously reported MZM in the core of the skyrmion [4]. I will discuss in details the origin of these MZMs by relating this problem to the the extensively-studied Rashba nanowire model. We have found that these modes are remarkably stable to electronic and geometric perturbations which we investigate by a combination of analytical arguments and numerical tight-binding calculations. Additionally, this analysis reveals that the number of MZMs on the edge scales linearly with its perimeter [5].

References

[1] G.C. Ménard et al., Nature Comm. 11, 1013 (2017).
[2] C. Caroli, P.G. de Gennes, and J. Matricon, Physics Letters 9, 307(1964).
[3] G. C. Ménard, et al., arXiv:1810.09541, Nature Comm. (2019).
[4] G. Yang, P. Stano, J. Klinovaja & D. Loss, PRB 93, 224505 (2016).
[5] M. Garnier, A. Mesaros, P. Simon, arXiv:1904.03005

Dark states and wave-function shaping in clean carbon nanotubes

Christoph Strunk
Regensburg University, Germany

Illumination of atoms having a lambda-shaped level structure with two laser frequencies can trap electrons into a coherent superposition of two nearly degenerate orbital states, an effect called coherent population trapping in quantum optics. These states emission - being called "dark states" - are strongly decoupled from the dynamics and suppress fluorescence. We measure an all-electric analogue of this effect in the transport through a carbon nanotube quantum dot [1]. Missing resonant lines and negative differential conductance result from the destructive interference of two transmission channels.

In the second part of the talk quantum transport through CNT-quantum dots in a high magnetic field is discussed. We find that in finite length CNTs, uniquely combining bipartite hexagonal lattice and cylindrical topology, a high magnetic field along the nanotube axis can tune the wave function of a single trapped electron all the way from a “half-wave resonator” behavior, i.e., a traditional “quantum box”, to a “quarterwave resonator”, where an antinode at one end occurs [2]. This explains the peculiar dependence of the conductance on the magnetic field.

References

[1] A. Donarini et al., *Nature Comm.* **10**, 381 (2019).
[2] M. Marganska et al., *Phys. Rev. Lett.* **122**, 086802 (2019).

Bardasis-Schrieffer modes as a probe of anisotropic Cooper pairing in iron-based superconductors

Rudi Hackl
Walther Meissner Institute
Bavarian Academy of Sciences and Humanities, Garching, Germany

We present results of Raman scattering experiments on $Ba_{1-x}K_xFe_2As_2$ ($0.22 \le x \le 0.7$) [1] and $CaKFe_4As_4$ [2] focusing on electronic excitations in the superconducting state below T_c. The redistribution of spectral weight from low to high energies upon crossing T_c allows us to derive the gap energies. The gaps on the individual bands are almost isotropic and vary between 1 and 8 k_BT_c. Inside the large gaps narrow lines are found for $Ba_{1-x}K_xFe_2As_2$ for doping levels $0.35 \le x \le 0.48$. The spectra in $CaKFe_4As_4$ are similar to those of $Ba_{0.65}K_{0.35}Fe_2As_2$. Among the suggested explanations of the in-gap modes we observe the Bardasis-Schrieffer excitons, resulting from anisotropic pairing interactions $V_{\mathbf{k},\mathbf{k}'}$, to be in full agreement with the theoretical predictions. In addition, we study the relative pairing strength in different channels using functional renormalization group and spin fluctuation theory and find the same ground state and hierarchy of pairing channels suggesting that spin fluctuations are an important if not the leading interaction in the pnictides [1].

References

[1] T. Böhm et al., NPJ Quantum Mater. **3**, 48 (2018).
[2] D. Jost et al., Phys. Rev. B **98**, 020504(R) (2018).

High-Tc cuprates – story of two electronic subsystems

Neven Barisic
Institute of Solid State Physics, TU Wien,
Department of Physics, Faculty of Science, University of Zagreb

We have performed a thorough experimental study of $HgBa_2CuO_{4+\delta}$, which in many respects is a model cuprate compound. From the comparison with data for other cuprates we are able to separate universal behavior from compound-specific features. The most remarkable finding is the existence of an underlying Fermi-liquid scattering rate [1] that remains essentially unchanged across the phase diagram [2,3]. Guided by established universalities, and by the knowledge that the cuprates are inherently inhomogeneous, we propose a simple model in which exactly one localized hole per planar copper-oxygen unit is gradually delocalized and becomes itinerant with increasing doping and temperature [4]. The model is percolative in nature, with parameters that are nearly compound- and doping-independent and experimentally constrained. It comprehensively captures pivotal unconventional experimental results, including the temperature and doping dependence of the pseudogap phenomenon, the strange-metal linear temperature dependence of the planar resistivity, and the doping dependence of the superfluid density.

References

[1] N. Barišić et al., PNAS 110, 12235 (2013); S. I. Mirzaei et al., PNAS 110, 5774 (2013); M. Chan et al., Phys. Rev. Lett. 113, 177005(2014); P. Popčević et al., npj Quantum Materials 3, 42 (2018)
[2] N. Barišić et al., arXiv:1507.07885
[3] Y. Li et al., Phys. Rev. Lett. 117, 197001 (2016)
[4] D. Pelc et al., Science Advances 5, eaau4538 (2019)

Polaron physics and superconductivity in SrTiO3

Peter Littlewood
University of Chicago

The coupling of collective electronic modes with phonons in strongly-coupled superconductors was a topic that Fred made a number of recurring and important contributions to: in 2D metals, in CDW systems, and in the cuprates. A classic system has recently been revisited, that of Strontium Titanate.

Doped $SrTiO_3$ is an enigmatic low-carrier-density metal close to a regime of quantum paraelectricity. There is evidence from many experiments for moderate coupling of carriers to longitudinal optic phonons, which evolves from a regime of adiabatic coupling to anti-adiabatic coupling as the carrier density is reduced, and it is in this apparently non-adiabatic regime that there is a peak in the superconducting transition temperature.

I will discuss the predictions of a simple Holstein model for carriers coupled to a LO phonon, with electron-electron interactions treated at the same level. We show that strong coupling arises between LO phonons and the plasmon, which strengthens on the approach to the ferroelectric quantum critical point, and which can mitigate the problem of anti-adiabaticity by pushing a coupled phonon-plasmon mode to low energies. The theory is used to produce the electron spectral function for comparison to photoemission and tunneling spectra, and also to calculate the superconducting T_c.

Incidence of charge ordering on the electronic structure and properties of the layered oxide NaxCoO2

Henri Alloul
Laboratoire de Physique des Solides, Université Paris-Sud, Orsay

The discovery of charge density wave order in the underdoped high T_c cuprates has initiated a large set of experiments aiming at disclosing eventual correlations between the charge order and the pseudogap "phase". The charge ordered state signalled in YBCO by the detection of Quantum oscillations due to small electron pockets is not fully understood. I suggested quite early on [1] that charge orders were specific to the distinct cuprate families and connected with the ionic dopant ordering, for instance the O chains in YBCO.

I want here to present the similar case of the layered cobaltates Na_xCoO_2 in which the electronic properties of the triangular CoO_2 planes are dramatically influenced by the insertion of Na^+ which act as chemical dopants [2]. In these compounds we have demonstrated by systematic x-rays and NMR/NQR experiments with x from 0.3 to 1 that stable phases with well defined Na content are separated by composition gaps [3]. We did evidence that each stable phase is associated with a specific Na order in register with a Co charge disproportionation . For instance for x=2/3 the experiments reveal a Kagome sub-lattice of Co atoms [4] on which holes are delocalized together with a sub-lattice of non-magnetic Co^{3+} sites, which correspond to filled t_{2g} levels.

We have been able recently to produce high qualtty single crystals of some specific Na ordered phases which allowed us to perform refined studies of their ground state transport properties [5]. The Hall effect is found to exhibit important T variations (even sign changes) which reveal the incidence of the Co charge order on the Fermi surface topology [6]. Those are apparent as well as Quantum oscillations which reveal rearrangements of the Fermi Surface with decreasing T or with external applied field. Band structure calculations should help us to characterize these new classes of topological materials.

References

[1] H. Alloul, "What is the simplest model which captures the basic experimental facts of the physics of underdoped cuprates?" (arXiv: 1302.3473), C. R. Physique **15**, 519 (2014).

[2] I.R. Mukhamedshin, H. Alloul , G. Collin and N. Blanchard "^{59}Co NMR Study of the Co States in Superconducting and Anhydrous cobaltates" (arXiv 0402074), Phys. Rev. Lett. **94**, 247602 (2005).

[3] I.R. Mukhamedshin, A.V. Dooglav, S.A. Krivenko, H. Alloul, « Evolution of Co charge disproportionation with Na order in Na_xCoO_2 » arXiv:1406.7470, Phys. Rev. B **90**, 115151 (2014)

[4] H. Alloul, I. R. Mukhamedshin, T. A. Platova and A. V. Dooglav, "Na ordering imprints a metallic kagome lattice onto the Co planes of $Na_{2/3}CoO_2$ ", Europhysics Letters **85**, 47006 (2009).

[5] I. F. Gilmutdinov, I. R. Mukhamedshin, F. Rullier-Albenque and H. Alloul "Synthesis of sodium cobaltate Na_xCoO_2 single crystals with controlled Na ordering", (arXiv: 1711.01611), JPCS **121**,145 (2018).

[6] I. F. Gilmutdinov, PhD thesis KFU , Kazan ; and in preparation.

Transient cooling low-frequency excitations by impulse perturbations: the case of K3C60

Michele Fabrizio
Trieste, International School for Advanced Studies

I present a simple mechanism to transiently cool down low-energy degrees of freedom through an impulse perturbation whose frequency hits a high-energy absorption peak. This mechanism could explain the observation of a superconducting-like optical response well above the equilibrium Tc in K3C60 irradiated by a mid-infrared laser pulse.
I first provide evidences that the observed phenomenon can be actually interpreted as cooling following absorption by a mid-infrared excitation. Next, I identify what such mid-infrared excitation corresponds to, and, finally, through a simple Boltzmann-type of equation, I show explicitly that a laser pulse that hits such excitation can effectively cool down low energy quasiparticles.

References

[1] M. Fabrizio, Phys. Rev. Lett. 120, 220601 (2018).
[2] A. Nava, C. Giannetti, A. Georges, E. Tosatti, and M. Fabrizio, Nat. Phys. 14, 154 (2018)

Uncovering non-Fermi-liquid behavior in Hund metals

Jan von Delft
Ludwig-Maximilians-University, Munich

Hund metals are multi-orbital materials with broad bands which are correlated via the ferromagnetic Hund coupling *J*, rather than the Hubbard interaction *U*. J implements Hund's rule, favoring electronic states with maximal spin. Examples include transition metal oxides with partially filled d-shells, such as ruthenates, or iron-based superconductors.

In Hund metals the interplay between spin and orbital degrees of freedom can lead to spin-orbital separation (SOS), meaning that the energy scales below which spin and orbital degrees are screened differ, $T_{spin} < T_{orb}$. The low-energy regime below T_{spin} shows Fermi-liquid behavior. The intermediate energy window, T_{spin}, T_{orb}, by contrast, shows incoherent behavior, featuring almost fully screened orbital degrees of freedom coupled to almost free spin degrees of freedom. Experimentally, the incoherent regime shows bad-metal behavior, hence it is of great interest to understand it theoretically. It has been conjectured to have non-Fermi-liquid (NFL) properties, but the nature of the putative underlying NFL state has not yet been clarified.

We have studied its properties within the context of a minimal 3-orbital Hubbard-Hund model for a Hund metal. Treating this model using dynamical mean field leads to a self-consistent Anderson impurity model in which bath and impurity both have spin and orbital degrees of freedom. We have studied the Kondo version of this impurity model, which can be tuned such that the NFL energy window is very wide. This allows us to unambiguously identify the NFL fixed point governing this intermediate-energy regime. In this regime the dynamical spin and orbital susceptibilities show anomalous NFL power law behavior. We compute the power law exponents using both conformal field theory and the numerical renormalization group, finding excellent agreement between both methods.

The challenges of connecting single molecules to metallic leads

Jan van Ruitenbeek
Leiden University

In a brief summary I will show that important progress has been made in the study of single-molecule electron transport. Yet, serious problems remain in the quantitative understanding of the experiments. We will discuss some of the difficulties, and focus in the problems associated with the choice of the leads. Some of these problems can be addressed by exploiting graphene as electrode material. We demonstrate the possibility of creating adjustable tunnel junctions between the edges of two graphene sheets, and the prospects of this technique for molecular transport experiments and applications in molecule recognition.

RKKY-induced Kondo breakdown and Fermi volume evolution in heavy fermions: Renormalization group and time-resolved THz spectroscopy

Johann Kroha,
University of Bonn

The fate of the fermionic quasiparticles near a magnetic quantum phase transition (QPT) in heavy-fermion (HF) compounds has been controversial for many years. It is generally believed that the Kondo destruction is driven by the critical fluctuations near the QPT. A novel renormalization group treatment of the quantum interference of Kondo and RKKY couplings reveals, however, that the HF quasiparticles can be destroyed by the RKKY interaction even without critical fluctuations [1], with far reaching, possible consequences for the QPT scenario: The lattice Kondo temperature, T_{Ky}, is suppressed in a universal way by the dimensionless RKKY coupling y and remains finite at the critical Kondo breakdown value $y=y_c$, while the heavy quasiparticle weight vanishes continuously.

This universal behavior agrees quantitatively with STM spectroscopy on continuously tunable two-impurity Kondo systems [2] and with most recent time-resolved terahertz (THz) spectroscopy [3]. We discuss how the latter constitutes a new method to distinguish different types of strongly correlated many-body states from weakly correlated ones by different delay times of the reflected signal in response to an incident THz pulse [3]. In particular, we use this technique to measure the quasiparticle weight in the heavy-fermion compound $CeCu_{6-x}Au_x$, x=0, 0.1, 1.0) for temperatures from 2 K up to 300 K and corroborate the observations by temperature-dependent, high-resolution dynamical mean-field theory (DMFT) calculations for the multi-orbital Anderson lattice model. The experiments and theory show that at high temperatures the large Fermi volume, a hallmark of strong correlations in the HF state, at high temperatures is largely carried by the crystal electric field (CEF) excitations, but by the Kondo HF band alone once the CEF excitations are frozen out [4]. These observations may resolve recent controversies about the existence of a large Fermi volume at temperatures far above the Kondo scale.

References

[1] A. Nejati, K. Ballmann, J. Kroha, PRL 118, 117204 (2017).
[2] J. Bork, Y.-H. Zhang, L. Diekhöhner et al., Nature Phys. 7, 901 (2011).
[3] C. Wetli, S. Pal, J. Kroha, K. Kliemt, C. Krellner, O. Stockert, H. v. Löhneysen, Manfred Fiebig, Nature Physics 14, 1103 (2018).
[4] S. Pal, C. Wetli, F. Zamani, O. Stockert, H. v. Löhneysen, M. Fiebig, J. Kroha, Phys. Rev. Lett. 122, 096401 (2019).

Evidence of Majorana fermions in the noise characteristic of normal metal-topological superconductor junctions

Thierry Martin
University of Marseille

A finite topological superconductor nanowire bears a Majorana fermion at its ends, leading to unique transport properties when connected to normal metal leads. We consider in this review two theoretical proposals based on noise measurements in normal metal - topological superconductor junctions. The first one considers a Hanbury-Brown and Twiss setup where a topological superconductor is connected to two normal metal leads. The second proposal deals with the finite frequency noise of a single normal metal - topological superconductor junction. Both are computed using a unified framework of non equilibrium Keldysh Green's functions using a Hamiltonian approach. Calculations are performed non-perturbatively in the tunnel hopping parameter and address both subgap and above gap regimes. Concerning the Hanbury-Brown and Twiss setup, we find in the subgap case that when the two normal metal leads are biased with equal voltage, the noise crossed correlations are negative, as in the case of a three terminal normal metal junction. On the other hand when subgap voltages are opposite, the noise crossed correlations are positive. Predictions when the two Majoranas at the end of the topological superconductors hybridize, and when the chemical potential of the topological superconductor drives the system out of the topological phase are discussed. In the second proposal, the finite frequency emission and absorption noises are computed for a single junction. We observe noticeable structures in these quantities, related to simple transport processes involving the Majorana bound state. Both results offer an original tool for the further characterization of the presence of Majorana bound states in condensed matter systems.

Quantum Work of Optical Lattices

Natan Andrei
Rutgers University

A typical quench experiment consists of a sudden release of a cold atomic gas from an optical lattice. The local properties of the quench dynamics have been extensively studied, however the global properties of this non-equilibrium quantum systems have received less attention. Here we study some aspects of global non-equilibrium behavior by calculating the amount of work done by the quench as measured through the work distribution function.

Using Bethe Ansatz techniques we determine the Loschmidt echo and from it the work distribution function of a gas of bosons initially held in a deep periodic lattice and subsequently either partially or completely removed. We find the average work and its universal edge exponents at threshold and determine the longtime decay of the Loshcmidt echo. We highlight striking differences caused by the interactions as well as the changes in the geometry of the system. We study repulsive as well as attractive interactions. In particular, we examine the prominent role played by bound states in the work distribution and show that, with low probability, they allow for work to be extracted from the quench.

Freezing on a Sphere: Classical 2D Wigner Crystallization and Particle Fractionalization on a Water Droplet

Paul Chaikin
New York University

Spin resonance in current noise with Coulomb blockade

Baruch Horovitz
Ben-Gurion University, Beer-Sheva, Israel

The long-standing problem of the appearance of the Larmor frequency in an STM current noise with a non-polarized tip is studied [1]. The experiment aims to study a single spin site, yet we assume the presence of a second spin to account for the data. We then study currents passing two Coulomb blockaded spin sites in parallel, requiring different spin orbit mixing in the two tunneling elements. The model shows a strong spin resonance at either Larmor frequency, and predicts also a resonance at the difference of these frequencies.

References

[1] B. Horovitz and A. Golub, arXiv:1904.11221

Localization and Vortex Lattices on My Mind: Metaphors for Solid State Phenomena in Neuronal Assemblies

Dan Cox
Department of Physics, UC Davis

In honoring our friend and colleague, Fred Zawadowski, I often think about the great breadth of Fred's research interests and contributions, from tunneling systems to charge density waves to superfluid helium. In that spirit, I will discuss a broad perspective in for two models in theoretical neuroscience in which solid state physics ideas can potentially be of relevance to our understanding of the brain. First, in considering damage to the olfactory bulb network, which plays a key role in amplifying and sorting signals from odor receptors in the nose, I will argue that there may be an analogy of weak localization for the spatiotemporal oscillatory "gamma wave" responses known to be present in the olfactory bulb. Such damage is known to arise in the early stages of Parkinson's disease. Next, I will note similarities between antiferromagnets and flowing vortex lattices with a fixed point model of the grid cells known to play a role in spatial navigation. These cells are damaged in Alzheimer's disease, but the emergent fixed point structure is fairly robust against damage, which would likely not be the case for a competing model in which grid cells arise via interference of neuronal signal oscillations.

Stoner antiferromagnetism in the periodic driven Hubbard model

Jens Paaske
University of Copenhagen

The rapid development of laser and ultrafast spectroscopy techniques has recently inspired a number of proposal for Floquet-engineered ‘quantum phases’ such as topological insulators and frustrated magnets corresponding to the Floquet Hamiltonians of periodically driven electron systems. In this talk, I assess the steady-state nonequilibrium Stoner mechanism for a 2D Hubbard model driven by a periodic electric field and damped by a thermal fermionic bath. The Keldysh saddle point equations are solved to find the nonequilibrium magnetization, and a one-loop fluctuation analysis is shown to yield a Floquet modified spin-wave spectrum. Most importantly, however, the ac drive is shown to produce a highly excited, generically non-thermal distribution of fluctuations, from which the stability of long-ranged magnetic order is shown to suggest a zero-temperature nonequilibrium analogue of the Hohenberg-Mermin-Wagner theorem, balancing damping rate with driving amplitude.

Kondo-like State in a Simple Model for Metallic Glasses

A. Zawadowski[a]
Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801
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A simple model is constructed for tunneling two-level systems interacting with conduction electrons in metallic glasses. The coupling constants do not commute in momentum space. Scaling theory shows a strong similarity with the antiferromagnetic Kondo effect, and it is shown that at low temperature a bound state is formed in which the motion of the tunneling atom and the angular dependence of the screening electron cloud varying in time are strongly correlated.

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Recently, great attention has been directed to tunneling two-level systems (TLS)[1,2] in metallic glasses where an atom or group of atoms has two levels close in energy and the conduction electrons are scattered by these centers.[3] In several cases resistivity minima have been observed with logarithmic temperature dependence. These observations are inspired by the similarity between these systems and the Kondo effect in dilute magnetic alloys.[4] In case of the present problem, tunneling motion of the atom is associated with screening by conduction electrons and thus it is closely related to the x-ray–absorption problem. The problem has been attached by Kondo himself,[5,6] who has shown that if the electron scattering appears exclusively in one scattering channel (e.g., in s channel) then the repeated screening processes result in scaling behavior in terms of the electron–band-width cutoff D, but no spectacular physical effect could be expected because the problem does not scale into the strong-coupling region.[5,7,8]

The situation is, however, essentially different if the two scattering processes in which the atom of the TLS center either does not or does change its position have different noncommutative angular dependence. First, Kondo has pointed out[6] that in this noncommutative case logarithmic contributions to the electrical resistivity exist even in the leading-logarithmic approximation. This result was obtained in fourth-order perturbation theory[5,9] and Kondo[6] exploited the similarity between the present problem and the behavior of magnetic impurities in dilute alloys. The role of impurity spin is taken over by the internal degree of freedom of the TLS, and spin polarization in the conduction band is substituted by the angular dependence of the screening. The aim of the present paper is to demonstrate this analogy beyond the fourth order in perturbation theory by constructing a simplified model where the first-order scaling equation can be solved; then the analogy becomes obvious.

The general model[9] can be given as $H = H_0 + H_1$, where

$$H_0 = \sum_{\vec{k}} \epsilon_k a_{\vec{k}}^\dagger a_{\vec{k}} - \tfrac{1}{2}\Delta_0 \sigma^z + \tfrac{1}{2}\Delta_1 \sigma^x. \tag{1}$$

Here $a_{\vec{k}}$ is the annihilation operator for the conduction electron with energy ϵ_k and with momentum $\vec{k}$ and the electron spin is not labeled as it does not play any role in the present theory. σ^z and σ^x are the Pauli operators acting on the states of the TLS; furthermore, Δ_0 and Δ_1 are the energy splitting and the intrinsic tunneling rate, respectively. It is assumed that Δ_0 and Δ_1 are negligible with respect to the other variables such as energy ω, temperature T, and conduction-electron cutoff D. The interaction of conduction electrons with the TLS is given as

$$H_1 = \sum_{\substack{i=x,y,z \\ \vec{k},\vec{k}'}} (a_{\vec{k}'}^\dagger V_{k'k}^{\,i} a_{\vec{k}}) \sigma^i, \tag{2}$$

where $V_{k'k}^{\,i}$ are the coupling constants. In realistic models it is usually assumed that $V_{kk'}^{\,y} = 0$ for the bare value.

The scaling equation for $V_{k'k}^{\,i}$ can be obtained, e.g., by Anderson's "poor man's derivation."[10] Eliminating some part of the phase space by lowering the cutoff D, the coupling strengths must be changed in order to keep the scattering amplitude invariant. With the result of perturbation theory,

$$V_{k'k}^{\,s}(x) = V_{k'k}^{\,s} - 2i\rho_0 \int dS_{\vec{k}}\, S_F^{-1} V_{k'\bar{k}}^{\,i} V_{\bar{k}k}^{\,j} \epsilon^{ijs} \ln x,$$

one gets the scaling equation

$$\frac{\partial V_{kk'}^{\,s}}{\partial \ln x} = 2i\rho_0 \int \frac{dS_{\bar{k}}}{S_F} (V_{k'\bar{k}}^{\,i} V_{\bar{k}k}^{\,j}) \epsilon^{ijs}, \tag{3}$$

where $x = D/|\omega|$ and $\sigma^i\sigma^j = i\epsilon^{ijk}\sigma^k$, ρ_0 is the density of states for conduction electron at the Fermi surface, dS_k/S_F is the normalized surface ele-