Abstract book of the Young investigators online workshop on unconventional superconductivity in heavy fermions

17-19th of January, 2022

Design by No-nonsense Labs / Pablo Matera

COST is supported by the Horizon 2020 Framework Programme of the European Union

Contents

Aims and Scope

The advent of heavy-fermion superconductivity happened about seven years after the discovery of superfluidity in helium three, in the late seventies of past century. Since then, heavy fermions have continuously stirred superconductivity by discovering new and surprising phenomena, such as multiphase superconductivity, superconductivity at a quantum critical point or ferromagnetic superconductors. The field has spurred novel ground-breaking theoretical approaches to the mechanisms of unconventional superconductivity, which found their way in explaining superconductivity in many other systems, including cuprates, iron pnictides as well as hybrid combinations of magnets and superconductors.

Heavy Fermion superconductors display a wealth of superconducting phases. In heavy fermions, local magnetic moments entropy is transferred to the itinerant electrons at low temperatures, providing highly tunable systems, which change their ground state radically by applying pressure, magnetic fields or strain.

The goal of the workshop is to bring together young theorists, experimentalists, and material scientists active in the field of heavy fermion superconductivity and address topical problems. We welcome developments of novel and pioneering experimental and theoretical techniques, and work in progress.

Topics include:

- Heavy fermion superconductivity in d and f electron systemss
- Quantum criticality and pairing
- Novel spectroscopies and imaging techniques
- Phase diagrams, high magnetic fields, pressure and strain
- Superconducting vortex lattices

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Herrera, Edwin	*Universidad Autónoma de Madrid, Madrid*
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Shen, Bin	*Univ. of Augsburg, Augsburg*
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Xu, Haichao	*Fudan University, Shanghai*
Yanase, Youichi	*Department of Physics, Kyoto University, Kyoto*
Yang, Huan	*Nanjing University, Nanjing*

Program

17 January 2022, from 8h00 to 13h30 CET

China (CST): 15h00 to 17h30, break, 18h30 to 20h30.
Japan (JST): 16h00 to 18h30, break, 19h30 to 21h30.

https://us02web.zoom.us/j/84129952813?pwd=a2tzbXI3ZDYxMG1vTTQ1RXd3UlBqdz09

Meeting ID: 841 2995 2813
Access code: 881108

07h50-08h00: **Organizers**, opening.

Tutorial. Chair: Jeroen Custers.

08h00-08h40: **Yang Liu**, Center for Correlated Matter, Zhejiang, China. "Uncovering the peculiar 4f electrons in heavy fermions".

Session 1: Spectroscopy on correlated materials. Chair: Huiqiu Yuan.

08h40-09h00: **Haichao Xu** - Fudan University, Shanghai "Distinct Kondo screening behaviors in heavy fermion filled skutterudites with 4f1 and 4f2 configurations".

09h00-09h20: **Rafal Kurleto** - University of Colorado, Boulder "Photoemission signature of momentum-dependent hybridization in $CeCoIn_5$".

09h20-09h40: **Georg Poelchen** - ESRF, Grenoble, "Unveiling novel temperature scales at the surfaces of Ce-based heavy-fermion materials via ARPES measurement"

09h40-10h00: **Lin Miao**– Southeast University, Nanjing. "The ARPES study on spin-triplet superconductor candidate UTe_2".

10h00-10h20: **Petr Doležal** – Charles University, Prague "Lattice dynamics in $CePd_2Al_2$ and $LaPd_2Al_2$".

10h20-10h40: **Wu Xie** - Center for Correlated Matter and Department of Physics, Zhejiang University, Hangzhou "Incommensurate noncolinear magnetic structures in EuPtAs".

10h40-11h30 BREAK

Session 2: Unconventional Superconductivity. Chair: Jean Pascal Brison.

11h30-11h50: **Adrien Gourgout**– ESPCI, Paris. "Fermi surface transformation across the pseudogap critical point in the cuprate Nd-LSCO from thermoelectric measurements"

11h50-12h10: **Siyuan Wan**– Nanjing University, Nanjing, "Incommensurate antiferromagnetic order in Fe-doped $Bi_2Sr_2CaCu_2O_{8+\delta}$".

12h10-12h30: **Tomoya Asaba**– Kyoto University, Kyoto. "Exotic heavy fermion superconductivity in atomically thin $CeCoIn_5$ films"

12h30-12h50: **Mathieu Taupin**– TU Vienna, Vienna. "YbRh2Si2: Unconventional superconductivity and strange metal behavior".

12h50-13h10: **Jiasheng Chen**– Cavendish Lab. Univ. of Cambridge, Cambridge, country. "Superconductivity and Electronic Structure of YFe2Ge2."

13h10-13h30: **Jeremy Sourd** - University of Bordeaux, LOMA UMR-CNRS "Pocket selective doping of cerium in iron based superconductors".

18 January 2022, from 8h00 to 13h50 CET

China (CST): 15h00 to 17h30, break, 18h30 to 20h50.
Japan (JST): 16h00 to 18h30, break, 19h30 to 21h50.

https://us02web.zoom.us/j/82480471136?pwd=TzJwd2xkbG15dFJyNWdqdmRTazNjdz09

Meeting ID: 824 8047 1136
Access code: 738993

Tutorial. Chair: Anne de Visser.

08h00-08h40: **Maia Vergniory**, Donostia International Physics Center, Donostia, Spain. "The role of crystalline symmetries in topological materials"

Session 3: Topological States of Matter. Chair: Anne de Visser.

08h40-09h00: **Rongyan Chen** - Beijing Normal University, Beijing, "Optical study on LnSbTe (Ln= La, Ce, Sm, Gd, Ho) compounds".

09h00-09h20: **Javier Landaeta**– MPI-CPfS Dresden, Dresden. "Field-angle dependence reveals odd-parity superconductivity in $CeRh_2As_2$".

09h20-09h40: **Seunghyun Khim** – MPI-CPfS Dresden, Dresden. "Muon spin relaxation studies on unconventional superconductor $CeRh_2As_2$".

09h40-10h00: **Kosuke Nogaki**– Kyoto University, Kyoto. "Topological crystalline superconductivity and electronic band structure of $CeRh_2As_2$".

10h00-10h20: **Pablo Garcia Campos**– Neel Institut-CNRS/UGA, Grenoble. "Chiral superconductivity in UPt3".

10h20-10h40: **Rubén Seoane Souto** – Center for Quantum Devices, Niels Bohr Institute, University of Copenhagen "Magnetism and spin-polarized bound states in semiconductor-superconductor-ferromagnetic platforms".

10h40-11h30 BREAK

<u>Session 4</u>**: Quantum Criticality and Novel Quantum States. Chair: Huiqiu Yuan.**

11h30-11h50: **Bin Shen**– Univ. of Augsburg, Augsburg. “Ferromagnetic quantum criticality and strange metal behaviours in the pure Kondo lattice $CeRh_6Ge_4$”.

11h50-12h10: **Jiangfan Wang**– Beijing Nat. Lab. for Condensed Matter Physics, Institute of Physics, Chinese Academy of Science, Beijing. “Nonlocal Kondo effect and quantum critical phase in heavy-fermion metals”.

12h10-12h30: **Ziji Xiang**– Hefei Nat. Lab. for Physical Sciences at Microscale, Hefei, “Quantum Oscillations and Unconventional Charge Transport in Kondo Insulator YbB_{12}”

12h30-12h50: **Jake Ayres**– Univ. of Bristol, Bristol, “bad metal in Tl2201 and lack of QCP”

12h50-13h10: **Yunhe Pei** - University of Electronic Science and Technology of China, Chengdu “Unraveling the Hybridization Process in CeRh6Ge4 by Ultrafast Optical Spectroscopy”.

13h10-13h30: **Edwin Herrera**– Universidad Autónoma de Madrid, Madrid. “Two Dimensional heavy electrons in the hidden order state of URu2Si2”.

13h30-13h50: **Masahiro Naritsuka**– St Andrews. “Interplay of ferromagnetism and spin-orbit coupling in metamagnetic Sr4Ru3O10”.

19 January 2022, from 8h00 to 13h30 CET

China (CST): 15h00 to 17h30, break, 18h30 to 20h30.
Japan (JST): 16h00 to 18h30, break, 19h30 to 21h30.

https://us02web.zoom.us/j/88161537774?pwd=QkRQcGxBdkkyR01nbHorZHRqUHMzUT09

Meeting ID: 881 6153 7774
Access code: 091721

Tutorial. Chair Dai Aoki.

08h00-08h40: **Youichi Yanase**, Department of Physics, Kyoto University, Kyoto. "Symmetry and topology in heavy fermion superconductors".

Session 5: Spin-triplet Superconductors. Chair Dai Aoki.

08h40-09h00: **Kota Ishihara**– University of Tokyo, Kashiwa, "Chiral spin-triplet superconductivity in UTe2 probed by anisotropic low-energy excitations".

09h00-09h20: **Michal Valiska**– Charles Univ., Prague. "Magnetic reshuffling and feedback on superconductivity in UTe_2 under pressure".

09h20-09h40: **Adrien Rosuel** – Univ. Grenoble Alpes, Grenoble. "Upper critical field of the spin triplet superconductor UTe_2 by specific heat measurements".

09h40-10h00: **Lin Jiao**– National High Magnetic Field Laboratory and Florida State University, Tallahassee, "Chiral superconductivity in heavy fermion metal UTe_2".

10h00-10h20: **Kristin Willa** –KIT Karlsruhe, "Short ranged magnetic correlations investigated by thermal expansion and specific heat in UTe_2".

10h20-10h40: **Callum Stevens** – University of Edinburgh, Scotland "Magnetic fluctuations and superconductivity in UTe_2".

10h40-11h30 BREAK

<u>Session 6</u>: Novel states and band structure features in superconducting correlated matter. Chair: Hermann Suderow.

11h30-11h50: **Carolina Marques**– SUPA, Univ. of St Andrews, St Andrews. "The surface of Sr_2RuO_4: From unconventional orders to a magnetic-field tuned van Hove singularity".

11h50-12h10: **Roos Leenen**– HFML, Nijmegen. "The Fermi surface of the ferromagnetic superconductor UCoGe under external magnetic fields".

12h10-12h30: **Beilun Wu**– Universidad Autónoma de Madrid, Madrid. "Scanning tunneling spectroscopy at magnetic fields of 20T in superconducting KFe_2As_2".

12h30-12h50: **Jose Lado**– Aalto University, Espoo. "Artificial heavy fermions in a dichalcogenide van der Waals heterostructure".

12h50-13h10: **Huan Yang** - Nanjing University, Nanjing, "Twofold symmetry of c-axis resistivity in kagome superconductor CsV_3Sb_5 with in-plane rotating magnetic field".

13h10-13h30: **Feng Du**– Zhejiang University, Hangzhou. "Interplay between charge order and superconductivity in the Kagome metals AV_3Sb_5 (A= K, Rb)".

13h30-13h40: **Organizers**, closure

Schematic Program

	Monday 17th January	Tuesday 18th January	Wednesday 19th January
07:50-8:00	Opening - Organisers		
08h00-08h40	**Tutorial: Yang Liu** *Chair: Jeroen Custers*	**Tutorial: Maia Vergniory** *Chair: Anne de Visser*	**Tutorial: Youichi Yanase** *Chair: Dai Aoki*
	Session 1: Spectroscopy on correlated materials. *Chair: Huiqiu Yuan*	**Session 3: Topological States of Matter** *Chair: Anne de Visser*	**Session 5: Spin-triplet Superconductors** *Chair: Dai Aoki*
08h40-09h00	Xu	Chen	Ishihara
09h00-09h20	Kurleto	Landaeta	Valiska
09h20-09h40	Poelchen	Khim	Rosuel
09h40-10h00	Miao	Nogaki	Jiao
10h00-10h20	Doležal	Garcia Campos	Willa
10h20-10h40	Xie	Seoane Souto	Stevens
10h40-11h30	Break		
	Session 2: Unconventional Superconductivity. *Chair: Jean Pascal Brison.*	**Session 4: Quantum Criticality and Novel Quantum States** *Chair: Huiqiu Yuan*	**Session 6: Novel states and band structure features in superconducting correlated matter.** *Chair: Hermann Suderow*
11h30-11h50	Gourgout	Shen	Marques
11h50-12h10	Wan	Wang	Leenen
12h10-12h30	Asaba	Xiang	Wu
12h30-12h50	Taupin	Ayres	Lado
12h50-13h10	Chen	Pei	Yang
13h10-13h30	Sourd	Herrera	Du
13h30-13h50		Naritsuka	Closing - Organisers

Abstracts

Uncovering the peculiar 4f electrons in heavy fermions

Yang Liu

Center for Correlated Matter and Department of Physics, Zhejiang University, China

The 4f-electron delocalization plays a key role in the low-temperature properties of rare-earth metals and intermetallics. Often it is realized by the many-body Kondo effect, but the importance of anisotropic Kondo hybridization and other possible delocalization mechanism remains open questions. Here we will briefly review some recent progress in this field [1], focusing on the electronic structure. We will then discuss some of our recent works on CeRh6Ge4 and CeCu2Si2 [2,3], highlighting the importance of anisotropic c-f hybridization. Finally, we will discuss about future directions, in particular the scientific opportunity by combining MBE thin film growth with in-situ ARPES and STM measurements [4].

References

[1] Yang Liu, Sci. China. Phys. Mech. Astron. 64, 127431 (2021)
[2] Yi Wu et al., Phys. Rev. Lett. 126, 216406 (2021)
[3] Zhongzheng Wu et al., Phys. Rev. Lett. 127, 067002 (2021)
[4] Yi Wu et al., Nature Communications 12, 2520 (2021)

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Distinct Kondo Screening Behaviors in Heavy Fermion Filled Skutterudites with 4f1 and 4f2 Configurations

Haichao Xu

Fudan University

The filled-skutterudite structure is featured by a constant lattice parameter as varying the rare-earth elements, which allow comparative studies on the mechanism of exotic heavy fermion behaviors in this family. However, the large unit-cell and cubic structure pose great challenges on surface sensitive measurements. Consequently, it lacks ARPES study on filled-skutterudites to directly observe its electronic structure. Dr. Haichao Xu et. al. managed to obtain atomically flat surface of $CeOs_4Sb_{12}$ and $PrOs_4Sb_{12}$, and revealed their electronic structure by soft X-ray ARPES. By studying the resonant behavior of f-electron bands, they resolve distinct Kondo screening behaviors of these two systems with $4f^1$ and $4f^2$ configurations. These results provide a clean demonstration on how Kondo physics behaves differently in $4f^1$ and $4f^2$ configurations, causing drastically different ground states. The methods will also motivate future ARPES studies on the filled-skutterudite family with various intriguing phenomena. The related work has been published in PHYSICAL REVIEW LETTERS 126, 136402 (2021).

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Photoemission signature of momentum-dependent hybridization in $CeCoIn_5$

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We have studied electronic structure of the CeCoIn5 heavy fermion superconductor using angle-resolved photoemission spectroscopy (ARPES) at low temperature (6 K). The spectra have been collected at photon energy of 122 eV what corresponds to the 4d-4f resonant transition. The Fermi maps collected in wide angular range show considerable matrix element effects. Comparison with one-step photoemission model simulations performed using relativistic multiple scattering Korringa-Kohn-Rostocker approach shows that Ce-In termination was probed in the experiment. Also, these simulations allowed us to identify surface states visible in the photoelectron spectra. Significant hybridization effects have been observed: mass renormalization (meff~80 me) and momentum dependent quasiparticle weight distribution over first Brillouin zone. We were able to extract f-electron density distribution in momentum space with reduced influence of matrix elements by applying a symmetrization procedure. Obtained momentum dependency is consistent with the results of the tight binding modelling.

References

[1] R. Kurleto, M. Fidrysiak, L. Nicolaï, J. Minár, M. Rosmus, Ł. Walczak, A. Tejeda, J. E. Rault, F. Bertran, A. P. Kądzielawa, D. Legut, D. Gnida, D. Kaczorowski, K. Kissner, F. Reinert, J. Spałek, and P. Starowicz, *Phys. Rev. B* ***104***, *125104 (2021)*.

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Unveiling distinct temperature scales at the surfaces of Ce-based heavy-fermion materials by ARPES measurements

Georg Poelchen

ESRF, Grenoble

In the surface region of strongly-correlated f materials, the electronic environment can be heavily modified with respect to the bulk leading to new energy scales and remarkable differences from the bulk properties. To study such differences directly, surface-sensitive angle-resolved photoemission spectroscopy (ARPES) was performed for the antiferromagnetic Kondo lattice $CeRh_2Si_2$. Temperature-dependent spectra were taken for the Ce- and Si-terminated surfaces in a wide temperature range, which reveal characteristic 4f patterns for weakly and strongly hybridized Ce, respectively. The temperature dependence of the Fermi level peak differs strongly for both cases implying that the effective Kondo temperature at the surface and in the bulk can be rather distinct. The greatly reduced crystal-electric-field (CEF) splitting at the Ce surface gives reason to believe that the surface may exhibit a larger effective Kondo temperature because of a higher local-moment effective degeneracy. In a similar ARPES study, our measurements for the heavy-fermion superconductor $CeIrIn_5$ reveal a 4f-derived electron landscape that is remarkably distinct for the different surface terminations implying novel temperature scales in the surface region, too. In this regard, our studies highlight how ARPES can be used to study different surface terminations and, thus, allowing a direct comparison of the 4f-derived electronic structure for Ce in different environments.

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The ARPES study on spin-triplet superconductor candidate UTe2

Lin Miao[1]*, L. Andrew Wray[2]

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People are searching for spin-triplet superconductors which are proposed a platform for majorana fermion-based topological computation. Uranium ditelluride (UTe2) was found with exotic properties, including re-entrant superconductivity and chiral edge states, constituting itself a candidate of spin-triplet superconductor, even a Weyl superconductor [1,2]. Here in this talk, we will focus on the low-energy electronic band structure of the UTe2. Our angle-resolved photoemission spectroscopy experiment confirmed the Fermi surface of UTe2 is consists of two orthogonal light bands originating from the Te (4p) and U(5d) atomic chains. The Uranium atomic multiplet excitations are discovered through O-edge resonant ARPES. In addition, we see possibly f-band signals on the boundary of Brillioun zone but need further confirmation [3].

References

[1] S. Ran, et al., Science 365, 684–687 (2019).
[2] L. Jiao, et al.,Nature 579, 523–527 (2020)
[3] L. Miao et al., Phys. Rev. Lett. 124, 076401 (2020)

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Lattice dynamics in $CePd_2Al_2$ AND $LaPd_2Al_2$

P. Doležal[1*], P. Cejpek[1], S. Tsutsui[2,3], K. Kaneko[4], D. Legut[5], K. Carva[1] and P. Javorský[1]

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[3]*Institute of Quantum Beam Science, Graduate School of Science and Engineering, Ibaraki University, Hitachi, Ibaraki, 316-8511, Japan*
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The presented contribution is focused on the study of phonon dispersion curves in $(Ce,La)Pd_2Al_2$ compounds. The main motivation for the investigation is a new quantum state (called vibron state) which presence was proposed in $CePd_2Al_2$. The considered interaction between phonons and 4f electrons goes beyond Born-Oppenheimer approximation, therefore the study of lattice dynamics plays a key role. The inelastic X-ray scattering technique was used for mapping the phonon modes at X and Z points as well as in Λ and Δ directions, where the symmetry analysis of phonon modes was performed. The measured spectra are compared with the theoretical calculation, showing very good agreement. The obtained results are discussed with respect to the formation of a vibron state, mainly the temperature behaviour of A_{1g} phonon mode, which was found to be in contrast with predictions based on the theory of vibron state.

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Incommensurate noncolinear magnetic structures in EuPtAs

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[2]Deutsches Elektronen-Synchrotron (DESY), Notkestraße 85, 22607 Hamburg, Germany
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Magnetic systems lacking inversion symmetry and with significant spin-orbit coupling can exhibit the aymmetric Dzyaloshinskii-Moriya (DM) exchange interaction between magnetic moments, in addition to the Heisenberg-type exchange interactions, which can give rise to a number of complex non-collinear magnetic ground states [1], such as helical magnetic structures. Furthermore, in some systems such as MnSi, and more recently in EuPtSi, this has been shown to lead to a magnetic skyrmion phase with a topological-nontrivial nature [2,3]. Such observations have stimulated the search for skyrmion-like topological spin textures (TST) in rare-earth based compounds [4]. For example, neutron diffraction and Hall effect measurements on CeAlGe have revealed a field-induced Meron phase where there is a double-k magnetic ground state with a topological charge Q = 1/2 [5], while isostructural NdAlSi exhibits a chiral spin texture driven by topological Weyl fermions [6].

We have recently characterized the magnetic properties and phase diagram of EuPtAs [7], which is isostructural to CeAlGe. Using x-ray resonant magnetic scattering (XRMS) at P09/PETRA III of DESY, we have studied the magnetic structures in different phases. Our results suggest that EuPtAs exhibits incommensurate magnetic structure below TN followed by a lock-in transition at TM.

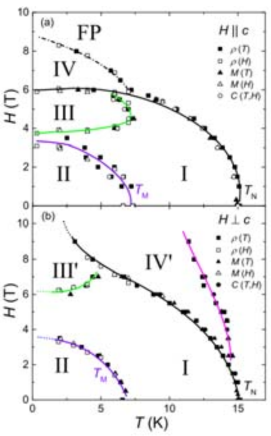

Fig. 1. Field-temperature phase diagrams of EuPtAs for H || c and H ⊥ c, where the possible different magnetic phases are labeled.

Together with the neutron scattering measurements, our preliminary studies indicate noncolinear magnetic structure in EuPtAs at zero field, while the studies in magnetic fields applied along different directions, especially the search for potential TST, are still underway.

References

[1] I. Dzyaloshinsky, *J. Phys. Chem. Solids.* **4** (1958) 241–255 ; T. Moriya, *Phys. Rev.* **120** (1960) 91–98 .
[2] S. Mühlbauer et al., *Science* **323** (2009) 915.
[3] C. Tabata, et al., *J. Phys. Soc. Jpn.* **88** (2019) 013702;
[4] T. Kurumaji, et al., *Science* **365**, 914 (2019); Nat. Commun. **10** (2019) 5831.
[5] P. Puphal et al., *Phys. Rev. Lett.* **124** (2020) 017202;
[6] J. Gaudet et al. *Nat. Mater.* **10** (2021) 1038;
[7] W. Xie et al, *Phys. Rev. B* **104** (2021) 174425.

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Fermi surface transformation across the pseudogap critical point in the cuprate Nd-LSCO from thermoelectric measurements

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In cuprate superconductors, the nature of the pseudogap phase and its interplay with superconductivity are still unclear. Its onset at a doping p* is characterized by a drop in carrier density n from n=1+p above p* to n=p below p* [1]. In Nd0.4La1.6-xSrxCuO4 (Nd-LSCO), this shows up as a low-temperature upturn in the resistivity ρ and Hall coefficient RH at dopings below p*=0.23 [2]. Here we present a series of thermoelectric measurements in Nd-LSCO across p*, in magnetic fields large enough to suppress superconductivity. For a heat current in the CuO2 planes, the Seebeck coefficient S shows a large increase at low temperature below p*, confirming the loss of carrier density. For a heat current perpendicular to the CuO2 planes, we find that S is isotropic for p > p*, i.e. Sc/T and Sa/T are equal (and positive) in the T=0 limit. In sharp contrast, Sc becomes negative at low temperature when p < p*, revealing a profound change in the Fermi surface topology across p*. Recent Angular Dependent MagnetoResistance measurements show that resistivity can be accurately calculated using a Boltzmann transport model with a k-dependent scattering rate [3]. This also allows to calculate the Seebeck coefficient. We find that the correct sign and temperature dependence can only be obtained if one introduces an energy dependent scattering rate.

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Incommensurate antiferromagnetic order in Fe-doped $Bi_2Sr_2CaCu_2O_{8+\delta}$

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In cuprate superconductors, due to strong electronic correlations, there are multiple intertwined orders which either coexist or compete with superconductivity. Among them the antiferromagnetic (AF) order is the most prominent one. In the region where superconductivity sets in, the long-range AF order is destroyed. Yet the residual short-range AF spin fluctuations are present up to a much higher doping and their role in the emergence of the superconducting phase is still highly debated. Here, by using a spin polarized scanning tunneling microscope, for the first time, we directly visualize an emergent incommensurate AF order in the nearby region of Fe impurities embedded in the optimally doped $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212). Remarkably the Fe impurities suppress the superconducting coherence peaks with the gapped feature intact, but pin down the ubiquitous short-range incommensurate AF order. Our work shows an intimate relation between antiferromagnetism and superconductivity.

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Exotic heavy fermion superconductivity in atomically thin $CeCoIn_5$ films

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Previous studies on topological superconductivity have been mainly focused on s-wave superconductors, where fine-tuning of the Fermi energy is required. In contrast, in two-dimensional (2D) d-wave superconductors with strong spin-orbit interaction, topological superconductivity can emerge without fine-tuning the band structure due to the parity-mixed d+p wave state. Here we report an in-situ scanning tunneling microscopy study of atomically thin films of $CeCoIn_5$, a d-wave heavy-fermion superconductor. Both hybridization and superconducting gaps are clearly resolved even in monolayer $CeCoIn_5$, providing direct evidence of 2D superconductivity of heavy quasiparticles. More remarkably, in these atomically thin films, while the superconducting transition temperature is suppressed to nearly half of the bulk, the out-of-plane upper critical field is significantly enhanced and by far exceeds the Pauli and bulk orbital limits. The results reveal the emergence of exotic superconductivity such as the d+p wave state, providing a new playground for exploring topological superconductivity.

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$YbRh_2Si_2$: Unconventional superconductivity and strange metal behavior

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The heavy fermion compound $YbRh_2Si_2$ is an excellent platform to study quantum criticality [1]. Its fan of linear-in-temperature electrical resistivity behavior, emerging from a magnetic field-induced quantum critical point [2], was associated with a jump in the Fermi surface volume [3] and dynamical energy-over-temperature scaling in the THz conductivity [4]. Recently, using sub-millikelvin electrical resistivity measurements, superconductivity – previously seen away from the QCP [5] – was found to condense directly out of the material's extreme strange metal state, which extends over 3.5 orders of magnitude in temperature [6]. I will discuss the complex superconducting phase diagram, the proposed pairing mechanism [6], and whether or not $YbRh_2Si_2$ and other strange metal heavy fermion compounds should be considered as Planckian scatterers [7].

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Superconductivity and Electronic Structure of YFe2Ge2

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The iron-germanide superconductor YFe2Ge2 presents a rare example of a layered iron-based superconductor with neither pnictide nor chalcogenide elements. Besides its anomalous T1.5 low-temperature normal-state resistivity and unusually high Sommerfeld coefficient C/T ≈ 100 mJ/molK2, YFe2Ge2 also displays a rather isotropic electronic structure, unlike any other iron-based superconductors [1-5]. Yet, its thermodynamic properties, such as low-temperature heat capacity, shows striking similarities to those of the heavily hole-doped iron arsenides (K/Rb/Cs)Fe2As2. Moreover, superconductivity in this material appears strongly susceptible to lattice disorder [3, 4], which hints at an unconventional pairing mechanism. Inelastic neutron scattering [6] has further shown that strong in-plane stripe-type and ferromagnetic spin fluctuations coexist in YFe2Ge2, suggesting its proximity to magnetic ordering.

In this talk, I will present results of our studies on the superconducting order parameter and electronic structure of YFe2Ge2 enabled by availability of high-quality single crystals. Low-temperature heat capacity and penetration depth measurements point towards an $s^{\pm}$-wave order parameter, while quantum oscillation measurements confirm the three-dimensional Fermi surface indicated by DFT calculations and reveal a uniform renormalization of carrier masses.

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Pocket selective doping of cerium in iron based superconductors

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We studied the Fermi surface reconstruction associated with heavy fermion behavior of cerium in the typical crystalline and electronic structure of ZrCuSiAs type iron based superconductors, that might apply to CeFePO, CeFeAsO or CeRuPO. We show that considerations of non local Kondo coupling between the cerium f electron and the transition metal d electrons induces nodes in the effective hybridization between light and heavy bands over the Brillouin zone, in such a way that the added f electrons coming from cerium to the large Fermi surface can populate either the hole pockets or the electrons pockets, depending of the low energy symmetry considered for the cerium orbital. We will present a tight binding model that takes into account of this effect at sufficiently low temperature and propose several physical probes. Finally we will discuss a Lifshitz transition that might be associated with a change of the superconducting gap symmetry, studied in the mean field picture of heavy quasiparticles pairing mediated by residual magnetic RKKY interactions between cerium atoms.

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The role of crystalline symmetries in topological materials

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Since the theoretical proposal of the first 2D and 3D topological insulators (TIs) more than 15 years ago, solid-state realizations of topological materials have been discovered at a rapid pace. The recently developed theories of Topological Quantum Chemistry and Symmetry-Based Indicators (SIs), based on symmetry eigenvalues and irreducible representations have in particular facilitated high-throughput materials discovery and revealed that topological phases in band structures are more common than originally thought. Indeed, over half of all of the known stoichiometric, solid-state, nonmagnetic materials are topological at the Fermi level, over 85% of the known stoichiometric materials host energetically isolated topological bands, and that just under 2/3 of the energetically isolated bands in known materials carry the stable topology of a TI or TCI. In this talk we will introduce topological electronic materials discovery in nonmagnetic and magnetic crystalline solids from the prediction based on TQC. We will end up this talk with some insight into topological superconductivity.

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Optical study on LnSbTe (Ln= La, Ce, Sm, Gd, Ho) compounds

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Topological materials with nontrivial electronic bands have drawn tremendous interests in condensed matter physics due to their exotic physical properties and their potential applications. However topological materials with strong electronic correlation are much less explored and might host more interesting physics. The WHM (W=Zr, Hf, or Lanthanides, H=Si, Ge, Sn, or Sb, and M=O, S, Se, or Te) family, which are reported to be Dirac nodal line semimetals or weak topological insulators, can serve as a good platform to study the interactions between topology, magnetism and other emergent instabilities. In this talk, I will introduce our recent optical spectroscopic results on several WHM compounds, with W= La, Ce, Sm, Gd and Ho, H=Sb, and M=Te. Despite of their very similar calculated band structures, their optical responses are quite different. Apart from the expected spin-orbital coupling related gaps, we also observed charge-density wave (CWD) gaps in CeSbTe, GdSbTe and HoSbTe[1]. At the same time, Kondo effect was identified in CeSbTe. These complex systems provide a promising arena to explore the entanglement of topology, CDW and Kondo effect.

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Field-angle dependence reveals odd-parity superconductivity in $CeRh_2As_2$

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$CeRh_2As_2$ is an unconventional superconductor with multiple superconducting phases and T_c = 0.26 K. When H || c, it shows a field-induced transition from a low-field superconducting state SC1 to a high-field state SC2 with a large critical field of H_{c2} = 14 T. In contrast, for H ⊥ c, only the SC1 with H_{c2} = 2 T is observed. A simple model based on the crystal symmetry was able to reproduce the phase-diagrams and their anisotropy, identifying SC1 and SC2 with even and odd parity superconducting states, respectively. However, an additional observed change of the normal state order at the same transition field opens up routes for different explanations that could not be ruled out yet. Here, we present a comprehensive study of the angle dependence of the upper critical fields using magnetic ac-susceptibility, specific heat and torque on single crystals of $CeRh_2As_2$. The experiments show that the state SC2 is strongly suppressed when rotating the magnetic field away from the c-axis and disappears for an angle of 350. Perfect agreement with our model calculations allow to nail down the suggested odd-parity state with pseudospin triplet d vector in the plane.

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Muon spin relaxation studies on unconventional superconductor $CeRh_2As_2$

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We study the magnetic and superconducting (SC) properties of the unconventional superconductor $CeRh_2As_2$ (T_c = 0.26 K) by means of muon spin relaxation (μSR) experiments. No clear evidence of oscillation was identified in zero-field μSR spectra down to 0.27 K while the relaxation rate moderately increases below ~ 0.4 K. This could be potentially associated with the suggested quadrupole density wave order at $T_0 \approx 0.4$ K. In low transverse-field (TF) μSR measurements, a profound increase of the relaxation rate was observed in the SC state. The SC relaxation rate (σ_{SC}), regarded as a direct measure of the London penetration depth ($\sigma_{SC} \propto 1/\lambda_L^2$), gradually develops with lowering temperature and then almost flattens below T/T_c ~ 0.2 being strongly indicative of suppressed quasiparticle excitations at low temperatures. Furthermore, TF-μSR measurements under an external field of 2 tesla revealed a power-law-like temperature-dependent relaxation rate in the normal state below 3 K, possibly connected to critical spin fluctuations. Our observations suggest $CeRh_2As_2$ to have a nearly fully-gapped SC order parameter in the vicinity of a quantum critical point.

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Topological crystalline superconductivity and electronic band structure of $CeRh_2As_2$

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The recent discovery of superconductivity in $CeRh_2As_2$ clarified an unusual H-T phase diagram with two superconducting phases [1]. $CeRh_2As_2$ crystallizes in the centrosymmetric tetragonal $CaBe_2Ge_2$-type structure with stacking Ce layers and Rh_2As_2 layers. Importantly, Rh_2As_2 layers at the top and bottom of the Ce layer have different compositions. Therefore, the inversion symmetry is locally broken at the Ce sites, although the global inversion center exists in the middle of the two Ce sites. The space group of $CeRh_2As_2$ is P4/nmm (No.129) including the nonsymmorphic glide symmetry. Surprisingly, the phase diagram was predicted in theoretical work about locally noncentrosymmetric superconductors [2]. The similarity of these phase diagrams between the experiment [1] and theory [2] suggests that the local inversion symmetry breaking plays an essential role in $CeRh_2As_2$, and the superconducting phase in the high magnetic field region is the pair-density-wave (PDW) state. PDW state is odd parity superconducting state in which the superconducting gap function changes sign depending on Ce layers. The most crucial property of this phase is the odd-parity superconductivity in spite of dominantly spin-singlet pairing. These character of PDW state suggests a possibility of topological superconductivity as spin-triplet superconductors are. Thus, the locally noncentrosymmetric crystal is a platform of odd-parity superconductivity without requiring rare spin-triplet pairing.

In this talk, using the group theory, we first clarified the algebra of symmetry operations in the Bloch representation and decomposed the Hilbert space on the glide-invariant planes $k_z = 0, \pi$ into the glide sectors. Supposing the PDW state in the high-field superconducting phase as proposed, based on these results, we derived the Fermi-surface formula of Z_2 invariants specifying the topological crystalline superconductivity protected by the nonsymmorphic glide symmetry [3]. Second, we conducted the first-principles calculation for the electronic structure of $CeRh_2As_2$. Combining the results, we evaluate the Z_2 invariants and found the topological crystalline superconductivity [4].

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Chiral superconductivity in UPt_3

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Symmetry and topology are tools to describe states of quantum matter: in a superconducting state, breaking additional symmetries other than gauge symmetry is a long sought after indication for unconventional pairing.

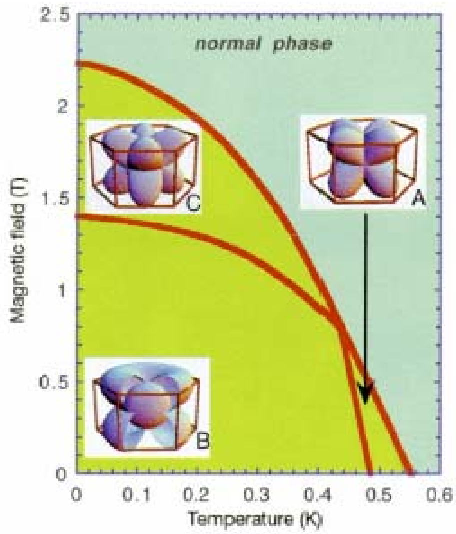

Figure 1: Phase diagram from ref. [3]

UPt_3 presents at low temperatures a strong electron mass renormalization (more than 100 times the free electron mass) due to spin fluctuations of the 5f electrons. These heavy fermions form Cooper pairs below 0.55 K.

Time-reversal symmetry breaking is expected as superconductivity is not mediated by electron-phonon coupling but is predicted to be driven by spin fluctuations. UPt_3 is the only material known to present three dif-ferent superconducting phases [1]. The boundary between the A and the chiral B phases is crossed upon cooling in zero field at 0.5 K. In the B phase, two energetically degenerated chiral domains may coexist. Theoretical predictions propose the existence of fractional vortices and an unusual flux distribution at the domain wall separating chiral domains [2].

Here, I report the observation of the alignment of the magnetic flux with the domain boundaries and the existence of half-Φ_0 structures, using a scanning SQUID microscope.

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Magnetism and spin-polarized bound states in semiconductor-superconductor-ferromagnetic platforms

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Topological superconductors are attractive platforms for fault-tolerant quantum devices. In 1-dimension, they host well-separated Majorana quasiparticles at their ends, which can encode information in a protected way. The first proposed platforms for topological superconductivity require relatively large magnetic fields, setting constraints on the device's geometries [1]. Ferromagnetic insulating materials (FIM), such as EuS or EuO, can help overcome these limitations, eliminating the requirement of external magnetic fields. Recently, robust zero-energy states have been reported in the semiconductor-superconductor-ferromagnetic insulator platform [2], consistent with the presence of Majorana bound states.

In this presentation, I will discuss how FIM magnetism can help inducing topological properties in the device. I will discuss recent Coulomb blockade measurements of semiconducting InAs nanowires, partially covered with Al and EuS shells and tunnel-coupled to normal leads. By comparing experimental results to a theoretical model, we associate inelastic cotunneling features in even-odd periodic Coulomb-blockade spectra with spin-polarized subgap Andreev levels. Our study suggests the presence of zero-field spin-splitting exceeding the induced superconducting gap [3].

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Ferromagnetic quantum criticality and strange metal behaviours in the pure Kondo lattice CeRh6Ge4

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Antiferromagnetic quantum criticality and its close proximity to unconventional superconductivity have been investigated in various strongly correlated electron systems [1]. However, despite extensive experimental studies, evidence for the existence of an intrinsic ferromagnetic quantum critical point (FM QCP) is still lacking [2]. Due to the low energy scales, heavy fermion compounds provide an outstanding platform for the study of quantum phase transitions, as their ground states can be readily tuned by non-thermal parameters, such as pressure and magnetic field. In this workshop, I will talk about our recent work on the heavy fermion compound CeRh6Ge4, in which a pressure-induced FM QCP is observed at pc $\approx$ 0.8 Gpa. Furthermore, quantum critical behaviors at pc are manifested by strange metal behaviors in resistivity and specific heat [3]. I will also briefly cover some of the peculiarities of this compound revealed by quantum oscillations [4], ARPES [5], neutron scattering [6], and ultrafast optical spectroscopy [7].

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Nonlocal Kondo effect and quantum critical phase in heavy-fermion metals

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Heavy-fermion metals typically exhibit an unconventional quantum critical point or quantum critical phase at zero temperature due to the competition of the Kondo effect and magnetism. Previous theories were often based on certain local types of assumptions, and a fully consistent explanation of experiments has not been achieved. We developed an improved Schwinger boson large-N approach to explore the effect of spatial correlations on the Kondo lattice, and introduced the concept of nonlocal Kondo effect in the presence of deconfined spinons and holons[1]. Our work predicts a global phase diagram containing a non-Fermi liquid quantum critical phase with a hidden holon Fermi surface and a partially enlarged electron Fermi surface for strong quantum fluctuations, but a single quantum critical point for weak quantum fluctuations. This provides a microscopic mechanism for the unusual metallic spin liquid recently reported in the frustrated Kondo lattice CePdAl. The same method is recently applied to the anisotropic ferromagnetic Kondo lattice model[2]. Our theory provides a unified understanding of heavy-fermion quantum criticality.

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Quantum Oscillations and Unconventional Charge Transport in Kondo Insulator YbB_{12}

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In Kondo insulators, a narrow hybridization gap is opened by strong electron-electron interaction. Distinct from the conventional band insulators, the ground state of Kondo insulators is characterized by enriched novel physical properties. By performing electrical transport and magnetic torque measurements under extreme conditions such as very low temperatures and intense magnetic fields, we discovered quantum oscillations (QOs) in both magnetization and resistivity in the bulk insulating state of the Kondo insulator YbB_{12} [1-4]. Such unexpected phenomena confirm the presence of exotic electronic states in this compound. In particular, the Fermi-liquid (FL)-like behaviors of the QOs strongly imply that they stem from unconventional charge-neutral quasiparticles, whose appearence may point towards intriguinng underlying physics such as f-electron fractionalization and gauge invariance breaking.

How can electrical transport measurements detect the Landau quantization of charge-neutral quasiparticles? Our recent work [3,5] identified a cascade of Fermi-surface Lifshitz transitions in YbB_{12} and further verified unusual characteristics of the QOs, thus revealed that YbB_{12} is described by a two-fluid scenario: the Lifshitz transitions and the QOs, both of which only occur for the charge-neutral FL-like states, are manifested in charge transport through the strong scattering between the neutral quasiparticles and the charge carriers that remain in non-FL states. The oscillatory scattering rate is determined by the oscillatory joint density of states. Our results provide important insight into the involved nature and complicated behavior of the electronic states in Kondo insulators.

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Incoherent transport across the strange-metal regime of overdoped cuprates

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I will summarize our recent studies of overdoped cuprates with an emphasis on the observation of an H-linear in-plane magnetoresistance across the strange-metal regime [1]. We interpret our findings as evidence for incoherent charge transport that can not be described using conventional Boltzmann transport approaches. In conjunction with a study of the in-plane Hall carrier number [2] which is sensitive to those carriers that can retain coherent and can be modelled within a Boltzmann framework, I will then briefly discuss the possibility that unconventional superconductivity in the cuprates is in fact borne from those charge carriers that exhibit incoherent transport behavior [3].

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Unraveling the Hybridization Process in CeRh6Ge4 by Ultrafast Optical Spectroscopy

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We report the ultrafast optical pump-probe spectroscopy measurements on the recently discovered quantum critical ferromagnet CeRh6Ge4 [1]. Our experimental results reveal the two-stage development of the hybridization between localized f moments and conduction electrons with lowering temperature, as evidenced by (1) the presence of hybridization fluctuation for temperatures from ~85 K (T*) to ~140 K (T†), and (2) the emergence of collective hybridization below the coherence temperature, T*, marked by the opening of an indirect gap of $2\Delta \approx 12$ meV. We also observe three coherent phonon modes being softened anomalously below T*, reflecting directly their coupling with the emergent coherent heavy electrons. The observed two-stage hybridization process is in close resemblance to that in CeCoIn5 [2]. Our findings establish the universal nature of fluctuation and coherence during the hybridization process in heavy fermion systems.

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Two dimensional heavy electrons in the hidden order state of URu_2Si_2

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We study atomically flat terraces on surfaces of the heavy fermion metal URu2Si2 using millikelvin scanning tunneling spectroscopy. We find two-dimensional heavy fermions (2DHF) with an effective mass 17 times the free electron mass. The 2DHF show electron-in-a-box quantization due to lateral confinement at nanometric sized terraces. We measure the lifetime of the 2DHF quantum states due to interaction with bulk states and study their behavior at edges and inside the superconducting phase. Density functional theory calculations provide a heavy surface band derived from U orbitals inside a gapped part of the bulk band structure. Our results provide a route to realize quantization of coherent correlated states in nanostructured surfaces and interfaces of f-electron based compounds.

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Interplay of ferromagnetism and spin-orbit coupling in metamagnetic $Sr_4Ru_3O_{10}$

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A magnetic field can control the ground state of metamagnetic materials, opening up new possibilities for spintronic applications. However, a microscopic understanding of the interaction of the detailed electronic structure and susceptibility to emergent orders is still lacking, which would greatly facilitate optimization of their properties. We use low-temperature scanning tunneling microscopy (STM) and spectroscopy to investigate the metamagnetism in the trilayer ruthenate $Sr_4Ru_3O_{10}$[1-3]. To elucidate the role of the microscopic electronic structure in the metamagnetic properties, we performed STM-based magnetostriction measurements and quasiparticle interference (QPI) on the exact same sample. We found that the orthorhombicity of the material was critical to its metamagnetic properties, as confirmed by magnetization measurements. With the help of advanced modeling of the quasiparticle interference, we can determine the low energy electronic structure and obtain clear spectroscopic evidence for the in-plane anisotropy induced by spin-orbit interactions in the spin-polarized electronic structure[4].

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Symmetry and topology in heavy fermion superconductors

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Symmetry and topology are fundamental properties of systems. In particular, the space inversion parity often plays an essential role for emergent phenomena in quantum phases. Historically, superconductors have been classified based on the space inversion parity, as spin-singlet (spin-triplet) Cooper pairs lead to the even-parity (odd-parity) superconductivity in the usual setup. The parity gives rise to a strong constraint on the topology, and odd-parity superconductors are promising candidates for the topological superconductivity.

In the talk, I will give a pedagogical review of candidate topological superconductors based on the symmetry of superconductivity. Conditions for the s-wave, d-wave, and odd-parity topological superconductors are reviewed. For d-wave topological superconductors, high-Tc cuprate superconductors and heterostructure of $CeCoIn_5$ are proposed. Topology of odd-parity spin-triplet superconductors, UPt_3 and UCoGe, is clarified. I also present our studies on recently discovered superconductors UTe_2 and $CeRh_2As_2$. Even-odd parity transition in a locally noncentrosymmetric superconductor $CeRh_2As_2$ is discussed based on a theoretical prediction [1] and multiple superconducting phases in a spin-triplet superconductor candidate UTe_2 are analyzed [2]. Based on first-principles band calculations, topological superconductivity is predicted in UTe_2 and $CeRh_2As_2$ [3,4]. If the time is allowed, I show emergent superconducting phenomena due to spontaneous parity violation and propose UTe_2 as a candidate.

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Chiral spin-triplet superconductivity in UTe_2 probed by anisotropic low-energy excitations

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The new uranium-based superconductor UTe_2 attracts much interest as a paramagnetic analogue of ferromagnetic superconductors [1]. The extremely high upper critical field along the magnetic hard axis, reentrant superconductivity, and only small reduction of the Knight shift in UTe_2 indicates indicate the spin-triplet superconducting state likely mediated by ferromagnetic fluctuations. Furthermore, scanning tunneling spectroscopy [2] and optical Kerr effect measurements [3] suggest a chiral superconducting state with topologically nontrivial surface states. Focusing on the superconducting gap, previous experimental studies reported the gap structure with point nodes which is consistent with the spin-triplet superconductivity [4]. However, the positions of the point nodes, which are quite important to confirm the multicomponent superconducting order parameter and superconducting symmetry, are still unrevealed. Thus, we performed the magnetic penetration depth measurements with the magnetic field along each crystallographic axis to detect the anisotropy of the low-energy excitations, from which we can estimate the positions of the point nodes. Based on our results, we can rule out the single component order parameters, and we find that the most plausible superconducting state is a chiral $B_{3u}+iA_u$ state, which provides fundamentals of the topological properties in UTe_2 [5].

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Magnetic reshuffling and feedback on superconductivity in UTe2 under pressure

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The discovery of superconductivity in the heavy-fermion paramagnet UTe2 has attracted a lot of attention, particularly due to the reinforcement of superconductivity near pressure- and magnetic-field-induced magnetic quantum phase transitions. A challenge is now to characterize the effects of combined pressure and magnetic fields applied along variable directions in this strongly anisotropic paramagnet. Here, we present an investigation of the electrical resistivity of UTe2 under pressure up to 3 GPa and pulsed magnetic fields up to 58 T along the hard magnetic crystallographic directions b and c. We construct three-dimensional phase diagrams and show that, near the critical pressure, a field-enhancement of superconductivity coincides with a boost of the effective mass related to the collapse of metamagnetic and critical fields at the boundaries of the correlated paramagnetic regime and magnetically-ordered phase, respectively. Beyond the critical pressure, field-induced transitions precede the destruction of the magnetically-ordered phase, suggesting an antiferromagnetic nature. By bringing new elements about the interplay between magnetism and superconductivity, our paper appeals for microscopic theories describing the anisotropic properties of UTe2 under pressure and magnetic field.

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Upper critical field of the spin triplet superconductor UTe2 by specific heat measurements

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Three years ago, superconductivity was discovered in the paramagnetic compound UTe2. The possibility of triplet superconductivity, maybe driven by ferromagnetic fluctuations, and topological superconductivity, triggered a lot of studies. Nevertheless, the pairing symmetry and mechanism remain unknown. The main arguments for triplet superconductivity in UTe2 are, its upper critical field Hc2, which exceeds the paramagnetic limit along all crystallographic directions, and the temperature dependence of the NMR Knight-shift. The three axis of a same UTe2 crystal were investigated by specific heat measurements up to 15T, in order to establish the phase diagram of Hc2 by bulk measurements, and to explore the thermodynamics of the normal phase under field. These measurements allow us to discuss the anomalous anisotropy between Hc2 and the lower critical field Hc1 [1]. Different scenarios for the explanation of the anomalous Hc2 behaviour will also be presented. The normal state specific heat has a complex, anisotropic field dependence. Our measurements confirm the presence of a Lifshitz anomaly for fields along the easy magnetization axis [2]. Along the hard magnetization axis, electrical transport measurements have revealed a reinforcement of the superconductivity above 15T up to 34T. Specific heat measurements have been performed along this axis, up to 36T, in order to detect the bulk superconducting transition above 15T as well as the metamagnetic transition occurring at 34T.

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Chiral superconductivity in heavy fermion metal UTe_2

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Spin-triplet superconductivity is a condensate of electron pairs with spin-1 and an odd-parity wavefunction. A particularly interesting manifestation of triplet pairing is a chiral p-wave state which is topologically non-trivial and a natural platform for realizing Majorana edge modes. Triplet pairing is however rare in solid state systems and so far, no unambiguous identification has been made in any bulk compound. By scanning tunneling microscopy (STM) studies, we study the newly discovered heavy fermion superconductor, UTe_2. Several interesting features are discovered in this compound. First, signatures of coexisting Kondo effect and superconductivity which show competing spatial modulations within one unit-cell. Second, STM spectroscopy at step edges reveal signatures of in-gap states with "chiral" symmetry, which are predicted to exist at the boundaries of a topological superconductor. Third, the presence of chiral states suggests that UTe_2 is a strong candidate material for chiral-triplet topological superconductivity. Our work also unveils evidence for counterintuitive behaviors of massless Dirac fermion in the frame of relativistic quantum mechanism.

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Short ranged magnetic correlations investigated by thermal expansion and specific heat in UTe_2

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The recent discovery of superconductivity in the heavy fermion UTe_2 [1] has led to an enormous interest in this material. It hosts various unusual phenomena like metamagnetism, field reentrant superconductivity and pressure-induced magnetic and superconducting phases [2]. There are still many open questions especially concerning the magnetic properties of the normal state. While no ordered magnetic moment has been observed, a mixture of ferromagnetic, anti-ferromagnetic and valence fluctuations has been proposed. In this talk, I will present our thermodynamic (thermal-expansion, specific-heat, magnetostriction and susceptibility) measurements on the normal state of UTe_2 [3]. In all of these quantities, clear evidence for a broad Schottky-like anomaly around T*=12K is observed with a calculated entropy of roughly Rln2. Combining our thermodynamic measurements with previously published high magnetic-field transport data [4] allows us to construct an H - T phase diagram which resembles that of the ferromagnetic superconductor URhGe. From our thermodynamic data, we calculate the electronic Grüneisen parameter related to T*. It is found to be comparable in magnitude to that of the metamagnetic field indicating a common origin. Our thermodynamic measurements thus suggest that the existence of short-range ferromagnetic fluctuations cannot be ruled out, although no direct evidence for their existence has been found to date.

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Magnetic fluctuations and superconductivity in UTe_2

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UTe_2 is an exciting unconventional equal spin paired superconductor, in which anisotropic magnetic fluctuations are proposed to provide the pairing interaction. Since 2018 there has been a significant improvement in single crystal synthesis which has resulted in higher Tc samples up to 2 K to date [1]. Many bulk properties show sample dependence and that complicate their interpretation of sample properties. This talk will discuss the magnetic field variation of the susceptibility at ambient pressure in the normal state and examine the correlation between this and the superconducting transition temperature across a range of samples.

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The surface of Sr_2RuO_4: From unconventional orders to a magnetic field tuned van hove singularity

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In strongly correlated electron materials, charge, spin, and orbital degrees of freedom exhibit an intimate relationship, leading to new emergent phases that seemingly break the symmetries of the underlying crystal and are highly sensitive to external stimuli. This is well illustrated in the Ruddlesden-Popper series of the strontium ruthenates, $Sr_{n+1}Ru_nO_{3n+1}$, where a wide range of properties attributed to such physics can be found, including unconventional superconductivity, quantum criticality, metamagnetic transitions and ferromagnetism. The first member of this series, Sr_2RuO_4, has an enigmatic superconducting state whose order parameter remains an open question. Multiple experiments now indicate that it is closely linked to a van Hove singularity (vHs) in the vicinity of its Fermi level (EF), however resolving what the order parameter is remains a challenge. Quasi-particle interference (QPI) imaging can in principle provide phase-sensitive information about the superconducting order parameter, however, tiny structural distortions in the surface layer seem to suppress superconductivity, resulting in a significant reconstruction of the Fermi surface and low energy electronic states [1]. Here, we use ultra-low temperature Scanning tunnelling microscopy to establish the existence of four vHs within 5 meV of EF at the surface layer of Sr_2RuO_4, unveiling a checkerboard charge order and hitherto unreported nematicity of the electronic states [1]. Including these orders into a tight-binding model, we can fully account for the four vHs. Continuum local density of states calculations that take into account the tunneling matrix elements show excellent agreement with the observed QPI patterns [2]. By applying a magnetic field up to 14 T, we observe one of the van Hove singularities to Zeeman split, with one branch extrapolated to reach the Fermi level at ~32 T – providing a text-book example of tuning towards a magnetic field-driven Lifshitz transition.

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The Fermi surface of the ferromagnetic superconductor UCoGe under external magnetic fields

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UCoGe is a heavy fermion system and one of the few known materials to display co-existence of ferromagnetism (TCurie ≈ 2.7 K) and superconductivity (Tsc ≈ 0.6 K) at ambient pressure. Magnetic fluctuations originating from the uranium 5f electrons are important for both superconductivity and magnetism in this material [1]. Understanding the relationship between the 5f moments and the conduction electrons may therefore be key to understanding the unconventional superconductivity.

If an external magnetic field is applied along the magnetic easy-axis (c-axis), the magnetic fluctuations and the superconductivity are rapidly suppressed, and a number of anomalies can be observed in resistivity and thermopower [2]. Some of these anomalies are associated with Lifshitz transitions of the Fermi surface.

To gain further information about the nature of these field-induced transitions and the behaviour of the Fermi surface, we measured magnetic susceptibility in fields up to 30 T and temperatures down to 48 mK. The transitions all appear extremely distinctly in the susceptibility, and we have, moreover, been able to track the magnetic field dependence of multiple Fermi surface pockets via de Haas-van Alphen oscillations.

To support our experimental data, we carried out DFT calculations of the UCoGe bandstructure using the WIEN2k package [3], and extended these calculations to examine the effect of an external magnetic field.

In this talk I will present our magnetic susceptibility results and make an effort to couple them to our calculations to give insight into the co-evolution of the magnetization and the heavy electron Fermi surface in magnetic field.

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Scanning tunneling spectroscopy at magnetic fields of 20T in superconducting KFe2As2

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KFe2As2 is a heavily hole-doped Fe-based superconductor with a critical temperature of 3.4K and an out-of-plane upper critical magnetic field of 1.5T. The normal phase of KFe2As2 presents conduction electrons with strongly enhanced effective mass ranging from 6 to 18 me, as obtained from quantum oscillation measurements, or as deduced from a large Sommerfeld coefficient of around 90 mJ/mol K2 [1,2]. Moreover, much discussion has been raised on the symmetry and nodal structure of the superconducting gap, and on the possible existence of a nematic order in this compound [3]. Here we present dilution refrigerator scanning tunneling microscopy results in KFe2As2. We show the vortex lattice and discuss the band structure from quasi-particle interference, observed at different magnetic fields up to 20T. Experiments have been made on a newly built dilution-fridge-based scanning tunneling microscope equipped with a fully superconducting magnet capable of reaching 22T, which we will also describe in detail [4].

References

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Artificial heavy fermions in a dichalcogenide van der Waals heterostructure

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Van der Waals materials have allowed realizing a variety of emergent quantum states, including topological phases and unconventional superconductors. However, heavy-fermion correlated states, usually found in complex rare-earth compounds dominated by Kondo physics, remained elusive in the two-dimensional world.

The realization of heavy-fermion physics in two-dimensional materials would provide a whole new playground to explore exotic forms of quantum criticality, quantum magnetism, hidden order, and unconventional superconductivity. Here we will discuss the experimental realization [1] of a designer van der Waals heterostructure where artificial heavy fermions emerge from the Kondo coupling between a lattice of localized magnetic moments and itinerant electrons in a dichalcogenide 1T/1H-TaS_2 heterostructure. We discuss how, using scanning tunneling microscopy and spectroscopy, we can reveal either the localized magnetic moments and the associated Kondo effect, or the conduction electrons with a heavy-fermion hybridization gap. Our results bring the physics of heavy-fermion rare-earth compounds to the two-dimensional world, opening a pathway towards designing and controlling a whole new family of correlated physics in moire van der Waals heterostructures.

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Twofold symmetry of c-axis resistivity in kagome superconductor CsV_3Sb_5 with in-plane rotating magnetic field

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In transition metal compounds, due to the interplay of charge, spin, lattice and orbital degrees of freedom, many intertwined orders exist with close energies. One of the commonly observed states is the so-called nematic electron state, which breaks the in-plane rotational symmetry. This nematic state appears in cuprates, iron-based superconductor, etc. Nematicity may coexist, affect, cooperate or compete with other orders. Materials with a kagome lattice structure can host a rich variety of exotic states. Here we show the anisotropic in-plane electronic state and superconductivity in a recently discovered kagome metal CsV_3Sb_5 by measuring c-axis resistivity with the in-plane rotation of magnetic field. We observe a twofold symmetry of superconductivity in the superconducting state and a unique in-plane nematic electronic state in normal state when rotating the in-plane magnetic field. Interestingly these two orders are orthogonal to each other in terms of the field direction of the minimum resistivity. Our results shed new light in understanding non-trivial physical properties of CsV_3Sb_5.

References

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Interplay between charge order and superconductivity in the Kagome metals AV_3Sb_5 (A= K, Rb)

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The kagome metal AV_3Sb_5 (A=K, Rb, Cs) hosts chiral charge order, nontrivial band topology and a superconducting ground state with unconventional characteristics, providing an ideal platform to investigate the interplay between different electronic states on the kagome lattice. We have studied the evolution of charge order and superconductivity in KV_3Sb_5 and RbV_3Sb_5 under hydrostatic pressure using electrical resistivity, synchrotron powder X-ray diffraction experiments and first-principles calculations. Our experimental results show two superconducting domes under pressure in these two compounds, while the first superconducting dome arises from the competition between superconductivity and charge order, and the evolution of the second superconducting dome is associated with structural phase transitions.

References

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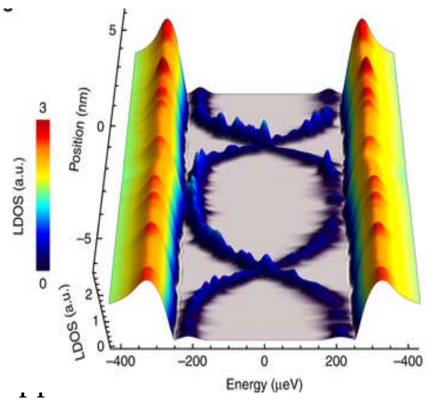
The COST Action Nanocohybri

The COST Action Nanocohybri is open to scientists from 27 European countries and collaborators all over the world. Nanocohybri kicked-off in November 2017 and will likely last until end of April 2022. Nanocohybri organizes networking activities aimed to fulfil the objectives of the Action. Nanocohybri organizes meetings, promotes exchanges through short term visits and provides opportunities for young researchers to present work related to the Action in other meetings. The Management Committee approves activities following COST excellence and inclusiveness policy. All details, including time and budgetary frames as well as eligibility issues are available at the Action's webpage.

The next major meetings of the Action will be organized in Spring 2022, details will be soon announced in the webpage.



Topological superconductivity in monolayer of Pb covering Co-Si islands, see Nat Comm 8, 2040 (2017).

e amount of fundamental nducting systems and the control magnetic flux, vices. Much of the topical arried out all over Europe nsional systems, hybrids and magnets or e engineering for current ntific and methodological similar and there is an important potential for cross-fertilization. The challenge is to make the understanding achieved and control the main superconducting parameters in devices to produce radically new behaviour. The Action has three working groups.

- Working group 1 (WG1). Low dimensional and hybrid systems. WG1 deals with two-dimensional and ultra-thin film superconductors. Nanofabrication techniques include lithography, controlled constrictions, exfoliation and systems capable to produce devices composed of layers of different materials. Characterization is made through photoemission spectroscopy, tunnelling microscopy, micro-Raman, quantum transport or ultrafast optics. New imaging techniques available at large-scale infrastructures (such as X-ray holography at synchrotron radiation sources) are also used. Theory analyses quantum transport from numerical studies using standard systems for superconductivity and ab-initio calculations. WG1 is lead by Brigitte Leridon.

- Working group 2 (WG2). Novel devices from hybrid interfaces. The involved groups aim to integrate materials where the Cooper pair wave function has a sign change into devices, for example cuprates or topological insulators and other materials with topologically non-trivial surface states into Josephson junction circuits. We also study superconductor/ferromagnetic hybrids in detail, looking at novel modulated phases. Techniques include microscopic bandstructure calculations and measurements of the Josephson effect using transport experiments. We use advanced microscopies, including SQUID-on-a-tip and magnetic force. WG2 is lead by Alexander I. Buzdin.

- Working group 3 (WG3). Hybrids with nanoscale vortex pinning and nanofabrication for high magnetic fields. We explore vortex pinning and current transport at low temperatures and high magnetic fields, in cuprate as well as in pnictide superconductors. We control fabrication techniques allowing to make pinning on demand and to study the collective behaviour of the vortex lattice in presence of patterned arrays of nanostructures. We also address the influence of structural or electronic distortions (such as nematicity), particularly close to quantum criticality, in the enhancement of superconducting parameters. Working methods include microscopy, correlated with transport calculations in superconductors, three-axis nanoSQUID and vortex manipulation. WG3 is lead by Dieter Kölle.