SRO214

Strontium Ruthenate

25 years of a puzzling superconductor

Zurich
May 9-11, 2019

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PAULI CENTER
for Theoretical Studies

OSS
Oxide Superspin
Core-to-Core Programme

Workshop Program

Thursday

Location: HIT E51

09:00-09:10	Opening
09:10-12:30	**New Experimental Techniques: Straining and Microstructures**
	chair: Fuchun Zhang
09:10 - 10:00	Andrew Mackenzie *Overview of some recent experimental advances in Sr_2RuO_4*
10:00 - 10:30	Annika Black-Schaffer *Odd-frequency superconductivity in Sr_2RuO_4 measured by Kerr effect*
10:30 - 11:00	Coffee break
11:00- 11:30	Philipp Moll *Sr_2RuO_4 on the mesoscale: A FIB approach*
11:30-12:00	Kyle Shen *Thin film engineering of superconductivity in ruthenates*
12:00-12:30	Clifford Hicks *Evaluation of chiral superconductivity in Sr_2RuO_4, including new results from muSR under uniaxial stress*
12:30-14:00	Lunch break
14:00-17:20	**Pairing Symmetry**
	chair: Dirk Manske
14:00-14:50	Yoshiteru Maeno *Paradigm shift toward the clarification of the superconductivity in Sr_2RuO_4*
14:50-15:20	Shunichiro Kittaka *Thermodynamic study of the pairing symmetry in Sr_2RuO_4*
15:20-15:50	Coffee break
15:50-16:20	Elena Hassinger *Directional thermal conductivity of Sr_2RuO_4: Evidence for vertical line nodes*
16:20-16:50	Aline Ramires *The order parameter of Sr_2RuO_4: A microscopic perspective*
16:50-17:20	Brad Ramshaw *Multi-component superconducting order parameter observed with resonant ultrasound spectroscopy*
17:30 - …..	Poster Session

SRO21⁺4

Friday

Location: HIT E51

08:30-12:20	**Mechanisms and Microscopic Approach**
	chair: Andrea Damascelli
08:30-09:20	Steve Kivelson *Some principles of the theory of unconventional superconductivity*
09:20-09:50	Ronny Thomale *Towards a microscopic theory of unconventional superconductivity in Sr_2RuO_4*
09:50-10:20	Markus Braden *Magnetic excitations and their possible role in the superconducting pairing in Sr_2RuO_4*
10:20-10:50	Coffee break
10:50-11:20	Vidya Madhavan *Fourier transform scanning tunneling spectroscopy measurements of Sr_2RuO_4*
11:20-11:50	Hae-Young Kee *Role of Spin-Orbit Coupling in Sr_2RuO_4*
11:50-12:20	Felix Baumberger *Electronic correlations and enhanced spin-orbit coupling in Sr_2RuO_4 determined from high-resolution laser-based ARPES*
12:20-14:00	Lunch break
14:00-17:20	**Spin Configuration**
	chair: Antoine George
14:00-14:50	Kenji Ishida *NMR and NQR Studies on Sr_2RuO_4*
14:50-15:20	Stuart Brown *Reduced ^{17}O NMR Knight shifts in the superconducting state of stressed and unstressed Sr_2RuO_4*
15:20-15:50	Coffee break
15:50-16:20	Suk-Bum Chung *Cooper pair spin current in Sr_2RuO_4*
16:20-16:50	Shingo Yonezawa *Superconducting anisotropy of Sr2RuO4 under in-plane magnetic field and current*
16:50-17:20	Muhammad S. Anwar *Superconducting proximity effect in Sr_2RuO_4 based devices*
17:20-18:00	Discussions
18:00-……	Apero & Poster Session

Saturday

Location: HIL E6

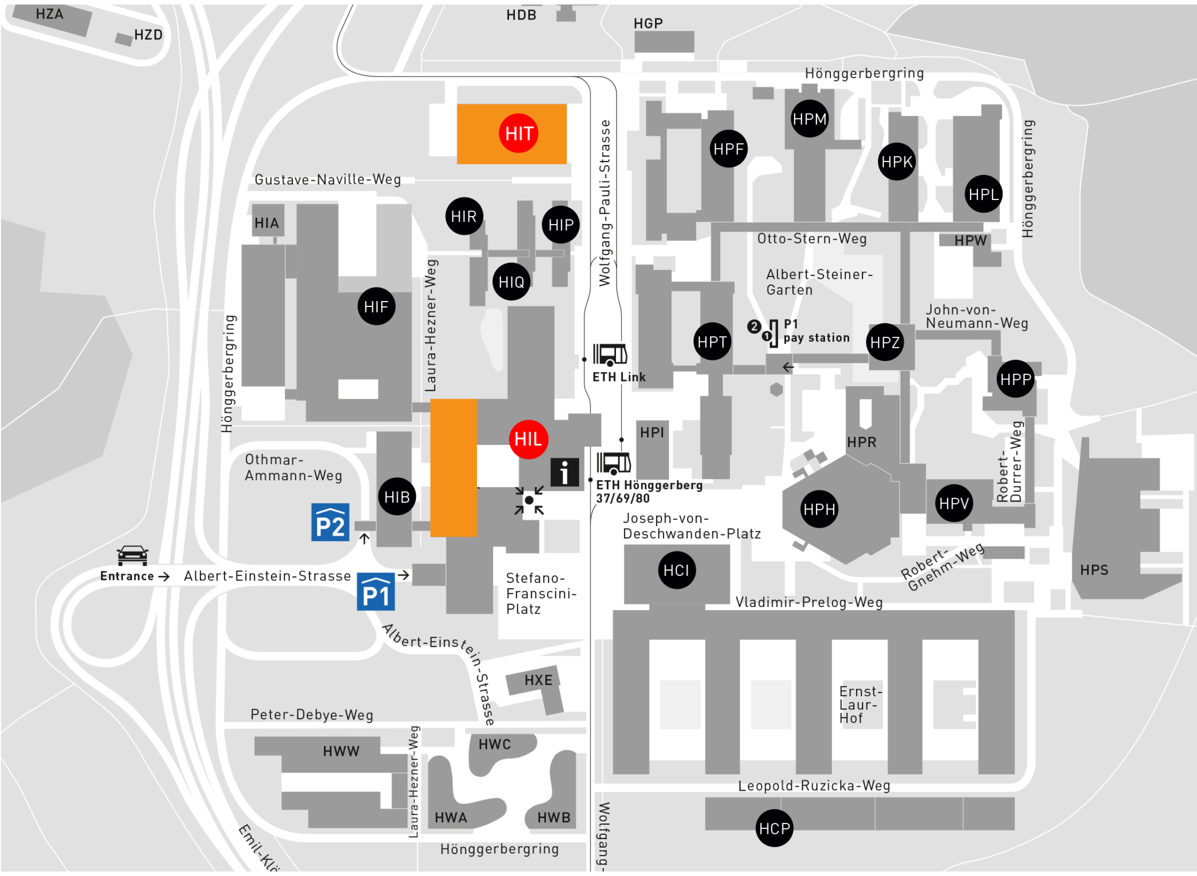
09:00-12:20	**Topology**
	chair: Andreas Schnyder
09:00-09:50	Catherine Kallin *Topology, edge currents and related issues in Sr2RuO4*
09:50-10:20	Daniel Agterberg *Topologically protected Bogoliubov Fermi surfaces*
10:20-10:50	Coffee break
10:50-11:20	Adrien Bouhon *Bulk-boundary correspondence for the chiral superconducting state at edges and domain walls*
11:20-11:50	Ying Liu *Superconductivity in bulk and mesoscopic Sr_2RuO_4*
11:50-12:20	Satoshi Kashiwaya *Josephson and tunneling effects of Sr_2RuO_4*
12:20	Conclusion

Venue

Thursday & Friday:
In the building HIT, room E51
Address: Wolfgang-Pauli Strasse 27, 8093 Zurich

Saturday:
Building HIL, room E6
Stefano-Franscini-Platz 5, 8093 Zurich

Hönggerberg Campus Map



Organization:
Manfred Sigrist (ETH Zurich)
Mark H Fischer (University of Zurich)

Conference Secretary:
Denise Pin (pin@itp.phys.ethz.ch)

Posters

Superconducting gap anisotropy induced by topological singularities - thermodynamic and spin transport properties

Bastian Zinkl
ETH Zürich

Imaging superconducting microstructures with scanning SQUID microscopy

Matt Ferguson
Cornell University

Deviation from the Fermi-Liquid Transport Behavior in the Vicinity of a Van Hove Singularity

Frantisek Herman
ETH Zürich

Tuning Sr2RuO4 with Uniaxial Stress

Mark Barber
MPI Dresden

Anomalous Nonlocal Conductance as a Fingerprint of Chiral Majorana Edge States

Satoshi Ikegaya
MPI Stuttgart

The 3 Kelvin phase in the eutectic Sr_2RuO_4-Ru

Hirono Kaneyasu
University of Hyogo

The effect of c-axis pressure on Sr2RuO4

Fabian Jerzembeck
MPI Dresden

Superconducting Sr2RuO4 film grown by pulsed laser deposition

Jinkwon Kim
Seoul National University

spin valve device on spin-triplet superconducting Sr2RuO4 for observing super spincurrent

Eun-Kyo Koh
Seoul National University

Nematic fluctuations in Sr_2RuO_4 and $Ba_{1-x}St_xNi_2As_2$, and the role of uniaxial strain

Samuel Lederer
Cornell University

Layer-by-layer Study of the Interplay between Spin-orbit Interaction and Structural Distortions in Sr2RuO4

Andrea Damascelli
University of British Columbia

Abstracts

Overview of some recent experimental advances in Sr2RuO4

Andrew P Machenzie
Max Planck Institute for Chemical Physics of Solids

I will review a number of exciting experimental developments in the study of normal and superconducting state physics in Sr2RuO4, notably as a result of the relatively newly developed capabilities to perform a wide range of measurements under uniaxial pressure. On some topics it will be more of a preview, in the sense that I will give first mention to topics that will be covered in more depth in other talks and posters at the conference.

Odd-frequency superconductivity in Sr2RuO4 measured by Kerr effect

Annica Black-Schaffer
Uppsala University

In this talk I will show that essentially all multi-band superconductors host bulk odd-frequency superconductivity. Applying these results to the chiral topological superconductor Sr2RuO4, we find that an intrinsic Kerr effect is evidence for this odd-frequency state. We use both general two- and three-orbital models, as well as a realistic tight-binding description of Sr2RuO4 to demonstrate that odd-frequency pairing arises due to finite hybridization between different orbitals in the normal state, and is further enhanced by finite inter-orbital pairing. If time permits, I will also show that odd-frequency pairing is ubiquitous in the heavy-fermion superconductor UPt3 and that a finite Kerr rotation in its B phase is only present if odd-frequency pairing also exists.

Sr_2RuO_4 on the mesoscale: A FIB approach

Philip J.W. Moll
EPF Lausanne

Recent advances in ion beam microstructure fabrication have enabled high levels of control over single crystalline material on the sub-micrometer length scale. Starting from single crystals of high purity, the superconductivity of Sr_2RuO_4 can be probed on small length scales. In a collaborative project with the group of Katja Nowack (Cornell), we explore the influence of spatially modulated strain fields on the transition temperature. Key is a thermal differential contraction between a ~100x20x2μm^3 Sr_2RuO_4 slice carved by FIB and the sapphire substrate it is mounted on. The bi-axial stress induces a non-trivial strain pattern within the slice, and the resulting T_c landscape can be mapped by scanning SQUID measurements. These experiments showcase the feasibility of engineering correlation landscapes in a 3D crystal, and to specifically address questions of order parameter symmetry by a symmetry analysis of the emerging T_c patterns.

Thin film engineering of superconductivity in ruthenates

Kyle Shen
Cornell University

Sr_2RuO_4 has been revealed to be extremely sensitive to strain, and thus uniquely suited to manipulating its superconducting state. Epitaxial strain in thin films, induced by a deliberately mismatched substrate, is a promising avenue to applying various kinds of strain to Sr_2RuO_4, for instance, which either break or preserve C_4 symmetry. Here I will discuss some of our recent work where we have used epitaxial strain and stabilization to drive a Lifshitz transition in the Fermi surface topology and investigate how epitaxial strain affects the superconducting transition temperature. I will also describe some of our recent efforts in epitaxial strain enhancement of superconductivity in other related ruthenate thin films.

Evaluation of chiral superconductivity in Sr_2RuO_4, including new results from muSR under uniaxial stress

Clifford Hicks
Max Planck Institute for Chemical Physics of Solids

I will review the evidence supporting and in contradiction to a hypothesis of chiral superconductivity in Sr_2RuO_4, meaning $p_x \pm ip_y$ or $d_{xz} \pm id_{yz}$, from uniaxial stress experiments. Muon spin rotation measurements show evidence for a splitting between T_c and onset of TRSB superconductivity, as predicted for chiral superconductivity. However the expected cusp in the strain dependence of T_c is not resolvable in measurements so far, including high-resolution scanning SQUID susceptometry measurements, and no second heat capacity anomaly is observable in heat capacity data under uniaxial stress.

Paradigm shift toward the clarification of the superconductivity in Sr_2RuO_4

Yoshiteru Maeno
Department of Physics, Graduate School of Science, Kyoto University, Japan

A very recent NMR report on Sr_2RuO_4 indicates that the Knight shift decays in the superconducting states in the “3-K phase” under uniaxial stress, as well as in the “1.5-K phase” without stress [1]. The invariant NMR Knight shift in previous reports [2] was likely due to Joule heating of the samples by the RF pulses [1, 3]. Such new information urges us to re-examine the interpretations of a variety of experimental results on Sr_2RuO_4. In this talk, we will review the validity of interpretations in previous experiments, which were based on the spin-triplet chiral *p*-wave scenario. We discuss issues and possible resolutions in this new paradigm.

[1] A. Pustogow *et al.*, arXiv.1904.00047.
[2] Y. Maeno, *et al.*, J. Phys. Soc. Jpn. **81**, 011009 (2012).
[3] K. Ishida, private communications.

Thermodynamic study of the pairing symmetry in Sr_2RuO_4

S. Kittaka
Institute for Solid State Physics, University of Tokyo

Identification of the order parameter of Sr_2RuO_4 has remained a challenge. Although it has been considered as a good candidate for a chiral *p*-wave superconductor [1], there exist several experimental facts that cannot be explained in the framework of the spin-triplet scenario [2]. In particular, a first-order superconducting transition under an in-plane magnetic field below roughly $0.5T_c$ [3-5], along with strong limitation of the upper critical field H_{c2}, is reminiscent of the Pauli-paramagnetic effect that is not allowed in the anticipated spin-triplet scenario. The superconducting gap structure is also controversial because various gap structures including vertical and horizontal line node gaps have been proposed so far [6-10].

In the present work [11], we investigated the gap structure from field-angle-resolved measurements of the specific heat [12]. We revealed that a fourfold oscillation in the specific heat measured under an in-plane rotating field does not change sign down to the lowest temperature of $0.04T_c$ in the low-field region. In addition, we revealed that the low-field specific heat increases in proportion to $H^{1/2}$ with no multigap structure at 0.06 K, in sharp contrast to the previous reports [8]. These results are clearly incompatible with the anticipated chiral-*p*-wave scenario. On the basis of microscopic theoretical calculations, the observed specific-heat behavior can be explained by Doppler-shifted quasiparticles around horizontal line nodes on the Fermi surface, whose in-plane Fermi velocity is highly anisotropic, together with the occurrence of the Pauli-paramagnetic effect [12, 13]. The presence of horizontal line nodes is compatible with recent observation of a substantial spin gap at Q=(1/3, 1/3, L) below T_c from inelastic neutron scattering measurements [14]. These findings, along with recent results of NMR Knight-shift measurements [15], indicate that the pairing symmetry in this system is most likely to be a spin singlet possessing horizontal line nodes.

[1] Y. Maeno, S. Kittaka, T. Nomura, S. Yonezawa, and K. Ishida, J. Phys. Soc. Jpn. **81**, 011009 (2011).
[2] A. P. Mackenzie *et al*., npj Quantum Mater. **2**, 40 (2017).
[3] S. Yonezawa *et al*., Phys. Rev. Lett. **110**, 077003 (2013).
[4] S. Yonezawa *et al*., J. Phys. Soc. Jpn. **83**, 083706 (2014).
[5] S. Kittaka *et al*., Phys. Rev. B **90**, 220502(R) (2014).
[6] K. Izawa *et al*., Phys. Rev. Lett. **86**, 2653 (2001).
[7] M. A. Tanatar *et al*., Phys. Rev. Lett. **86**, 2649 (2001).
[8] K. Deguchi *et al*., Phys. Rev. Lett. **92**, 047002 (2004).
[9] K. Deguchi *et al*., J. Phys. Soc. Jpn. **73**, 1313 (2004).
[10] E. Hassinger *et al*., Phys. Rev. X **7**, 011032 (2017).
[11] S. Kittaka *et al*., J. Phys. Soc. Jpn. **87**, 093703 (2018).
[12] T. Sakakibara, S. Kittaka, and K. Machida, Rep. Prog. Phys. **79**, 094002 (2016).
[13] K. Machida *et al*., Phys. Rev. B **99**, 064510 (2019).
[14] K. Iida *et al*., arXiv:1904.01234.
[15] A. Pustogow *et al*., arXiv:1904.00047.

Directional thermal conductivity of Sr_2RuO_4: Evidence for vertical line nodes

Elena Hassinger
MPI Dresden

Sr_2RuO_4 is an unconventional superconductor where a chiral p-wave order parameter has been discussed for many years. For this order parameter, symmetry does not require that the associated gap has nodes, yet specific heat, ultrasound and thermal conductivity measurements establish the existence of line nodes in the superconducting gap structure of Sr_2RuO_4. Theoretical scenarios have been proposed to account for the existence of accidental nodes within a p-wave state. To examine such scenarios, it is essential to know whether the line nodes are vertical (parallel to the tetragonal c-axis) or horizontal (perpendicular to the c axis). Here we report thermal conductivity measurements on high- quality single crystals of Sr_2RuO_4 down to 50 mK for currents parallel and perpendicular to the c-axis. We find that the residual conductivity along the c-axis in the T = 0 limit, is the same fraction of the normal state conductivity as for thermal transport in the basal plane. The immediate interpretation of this is that the line nodes in Sr_2RuO_4 are vertical. As well, the strong increase of the residual conductivity along c in very low in-plane fields is in agreement with a d-wave scenario. We discuss our findings in view of recent experimental results and theoretical calculations.

The order parameter of Sr_2RuO_4: A microscopic perspective

Aline Ramires
ICTP-SAIFR/IFT-UNESP

The character of the superconducting phase of Sr_2RuO_4 is topic of a longstanding discussion. The classification of the symmetry allowed order parameters has relied on the tetragonal symmetry of the lattice and on cylindrical Fermi surfaces, usually taken to be featureless, not including the non-trivial symmetry aspects related to their orbital content. Here we show how the careful account of the orbital degree of freedom leads to a much richer classification of order parameters. We analyse the stability and degeneracy of these new order parameters from the perspective of the concept of superconducting fitness and propose a new best candidate for the order parameter of Sr_2RuO_4, which can consistently account for essentially all the observed phenomenology of this material.

Multi-component superconducting order parameter observed with resonant ultrasound spectroscopy

Brad Ramshaw
Cornell University

All superconductors show a discontinuity in their compressional ("bulk") elastic moduli at T_c. Shear elastic moduli, on the other hand, are usually continuous through T_c because symmetry prevents the coupling of most superconducting order parameters to shear strain. In a tetragonal superconductor, however, there are superconducting order parameters that can couple to shear strain - these are known as two-component or "vector" order parameters, of the E_g or E_u point-group representations. The most famous proposed two-component order parameter is the p_x+ip_y state in Sr_2RuO_4, and thus Sr_2RuO_4 should exhibit discontinuities in its shear moduli through T_c. We have performed the first measurement of all six elastic moduli through T_c Sr_2RuO_4, and found that the shear modulus c_{66} shows a clear discontinuity at the phase transition, identifying the superconducting order parameter as two-component. While p_x+ip_y remains the most likely candidate, $d_{xz,yz}$ remains possible, along with other *p*-wave states which may be ruled out by other measurements. We also obtain dynamic information about the order parameter through the ultrasonic attenuation, which exhibits a clear peak below T_c in the compressional moduli, while the shear attenuation decrease below T_c. Taken together this information should strongly constrain the order parameter symmetry in Sr_2RuO_4.

Towards a microscopic theory of unconventional superconductivity in Sr_2RuO_4

Ronny Thomale
Julius-Maximilians- Universität Würzburg

Despite its low T_c, Sr_2RuO_4 has been one of the most important seed materials and inspiration for contemporary research on unconventional superconductivity, encompassing triplet pairing, Majorana zero modes in vortices, chiral Majorana edge states, and chiral topological bulk order. In order to appropriately take into account the enhanced diversity of experimental evidence, the theoretical modelling of superconductivity in Sr_2RuO_4 necessitates refinement at several levels. This includes the consideration of spin-orbit coupling, uniaxial strain, and the systematic treatment of Fermi surface instabilities and electronic flucutations beyond the mere weak coupling domain. I review the state of the art of several current frontiers along these lines, and how functional renormalization group has the potential to reach an accurate description of electron pairing in Sr_2RuO_4 in the physically relevant parametric window of intermediate interaction strength.

Magnetic excitations and their possible role in the superconducting pairing in Sr_2RuO_4

Markus BRADEN
II. Physikalisches Institut, Universität zu Köln (Germany)

The magnetic excitations in the unconventional superconductor Sr_2RuO_4 consist of several contributions, which reflect the distinct magnetic ordering schemes observed in closely related materials as well as the different electronic bands. Quasi-one-dimensional bands are associated with antiferromagnetic nesting fluctuations while quasi-two-dimensional bands with the van Hove singularity result in quasiferromagnetic correlations. Indirect evidence for ferromagnetic fluctuations is deduced from the metallic ferromagnet $SrRuO_3$, while isovalent Ca_2RuO_4 is a Mott insulator with antiferromagnetic magnons [1]. Due to the low transition temperature and the small expected value of the superconducting gap it is difficult to study the low-energy magnetic response in the superconducting state by inelastic neutron scattering (INS). We were able to follow the nesting magnetic signal of the quasi-one-dimensional bands across the superconducting transition down to very low energies. Even at E=0.325 meV, which lies well below the superconducting gap 2Δ values reported from tunneling experiments or deduced from BCS theory, there is no change in the magnetic response [2], which seems incompatible with the picture of a large gap on these Fermi-surface sheets. The quantitative analysis of the quasiferromagnetic fluctuations in Sr_2RuO_4 by INS is hampered by the smaller amplitude and the little structure in Q space of this signal. Only by use of polarized neutron scattering we can determine the strength and characteristics of the ferromagnetic response, which agrees with reports of specific heat, magnetic susceptibility and NMR. Incorporating this ferromagnetic response into the gap equation, however, does not stabilize a triplet pairing state [3]. Furthermore, the quasiferromagnetic response in Sr_2RuO_4 does not resemble the paramagnon scattering expected for a nearly ferromagnetic material, but it seems to arise from broad instabilities at low propagation vectors. In contrast recent INS on the ferromagnetic perovskite $SrRuO_3$ find the typical ferromagnetic magnon and paramagnon scattering below and above the Curie temperature [4]. The magnon stiffness and gap in $SrRuO_3$ is found to anomalously soften upon cooling well below the Curie temperature, which can be attributed to the impact of Weyl points [4].

[1] S. Kunkemöller, *et al.*, RL. **115**, 247201 (2015).
[2] S. Kunkemöller, *et al.*, PRL. **118**, 147002 (2017).
[3] P. Steffens, *et al.*, PRL. **122**, 047004 (2019).
[4] K. Jenni, *et al.*, arXiv:1902.04036 (2019).

Fourier transform scanning tunneling spectroscopy measurements of Sr_2RuO_4

Vidya Madhavan
University of Illinois at Urbana-Champaign

The single-layered ruthenate Sr_2RuO_4 has attracted a great deal of interest as a spin-triplet superconductor with an order parameter that may potentially break time reversal invariance and host half-quantized vortices with Majorana zero modes. While the actual nature of the superconducting state is still a matter of controversy, it has long been believed that it is condensed from a metallic state that is well described by a conventional Fermi liquid. In this talk I will show high resolution Fourier transform scanning tunneling spectroscopy (FT-STS) measurements on Sr_2RuO_4 both above and below T_c. In the normal state, we use a combination of FT-STS and momentum resolved electron energy loss spectroscopy (M-EELS) to probe interaction effects in the normal state of Sr_2RuO_4.The QPI data show signatures of the β-band with a distinctly quasi-one-dimensional (1D) character as well as the g-band at the energy range of the van-Hove singularity. The β-band dispersion reveals surprisingly strong interaction effects that dramatically renormalize the Fermi velocity, suggesting that the normal state of Sr_2RuO_4 is that of a `correlated metal' where correlations are strengthened by the quasi 1D nature of the bands. In addition, we observe kinks at energies of approximately 10meV, 38meV and 70meV. I will discuss comparisons with M-EELS data, which show that the two higher energy features arise from coupling with collective modes. I will further show BQPI data below T_c and discuss the ramifications of the data for the superconducting order parameter.

Electronic correlations and enhanced spin-orbit coupling in Sr_2RuO_4 determined from high-resolution laser-based ARPES

Felix Baumberger
Department of Quantum Matter Physics, University of Geneva & Swiss Light Source, PSI

We combine laser-based angle-resolved photoemission and dynamical mean-field theory calculations to study the interplay of electron-electron correlations and spin-orbit coupling (SOC) in the model Fermi liquid Sr_2RuO_4. Analyzing the experimental Fermi surface, we show that correlations enhance SOC by a factor of ~2 over the bare value. We further reveal that the real part of the self-energy of the β and γ sheet is momentum dependent and strongly non-linear down to low energies, in contrast to widely held believes about the phenomenology of Fermi liquids. Introducing a new method to determine orbital self-energies from quasiparticle states with multi-orbital composition, we demonstrate that the anisotropy of the self-energy does not imply momentum dependent many-body interactions. The non-linearity of the self-energy is reproduced by single-site dynamical mean field theory, which provides strong evidence for a dominantly electronic origin of 'kinks' in the quasiparticle dispersion of Sr_2RuO_4.

NMR and Study on Sr2RuO4

Kenji Ishida
Department of Physics, Graduate School of Science, Kyoto University

NMR experiments have been done in various unconventional superconductors, and gave information about superconducting (SC) pairing state and SC gap structure. We reported that the Knight shift at the Ru and O sites in Sr_2RuO_4 is invariant on passing through T_c.[1,2]. Quite recently, Pustogow and Luo *et al.* reported a reduction of the Knight shift at the O site measured with a small-energy RF pulse. We reexamined ^{17}O-NMR on our sample with similar small-energy RF pulses and reproduced their results. In the presentation, we will present new results obtained with the small energy RF pulses, and the heat-up effect after NMR RF pulses.

[1] K. Ishida *et al.* Nature **396**, 658 (1998).
[2] K. Ishida *et al.* Phys. Rev. B **63**, 060507 (R) (2001).
[3] A. Pustogow and Y. Luo *et al.*, cond/mat 1904.00047

Reduced ^{17}O NMR Knight shifts in the superconducting state of stressed and unstressed Sr_2RuO_4

Stuart Brown
UCLA

The recent observation of a steep rise in transition temperature in stressed samples of Sr_2RuO_4, peaking at a factor 2.5 greater than the unstressed case, motivated our low temperature ^{17}O NMR studies under similar conditions. The normal state Knight shifts are consistent with stress-tuning through a van Hove singularity, and are interpreted as evidence for an associated Stoner enhancement along with a non-Fermi Liquid response. Deep in the superconducting state, a reduction of Knight shifts K is observed for all strains--including the unstrained case--indicating a drop in the spin polarization. The results are inconsistent with the chiral *p*-wave state. Constraints for the order parameter symmetry, in the context of other experimental findings, are discussed.

Superconducting anisotropy of Sr_2RuO_4 under in-plane magnetic field and current

Shingo Yonezawa
Department of Physics, Graduate School of Science, Kyoto University

The layered ruthenate Sr_2RuO_4 has been long studied for its unconventional superconducting nature but the debate on its superconducting order parameter has not yet been settled.
To have deeper insights, we studied the in-plane anisotropic superconducting behavior under in-plane magnetic field or current. We found that the upper critical field H_{c2} of Sr_2RuO_4 measured by means of resistivity, i.e. under applied current, exhibits two-fold symmetric behavior within the *ab* plane, although the crystal lattice has four-fold rotational symmetry. This is in clear contrast with the four-fold symmetric behavior observed in previous studies without current. After detailed examination, it is found that the two-fold behavior cannot be described by extrinsic field misalignment, nor by conventional vortex-flow resistivity. In addition, we found anomalous behavior in the in-plane field-angle dependence of specific heat of Sr_2RuO_4 above 1.2 T, suggestive of a subtle but noticeable change in the superconducting order parameter anisotropy near H_{c2}.
In this presentation, we describe these phenomena observed in Sr_2RuO_4 under a presence of in-plane magnetic field and in-plane electric current, and discuss its origin.

Superconducting proximity effect in Sr_2RuO_4 based device

M. S. Anwar
Department of Materials Science and Metallurgy, University of Cambridge

Now, it has been established that spin-triplet superconductivity can be emerged at an interface between a spin-singlet superconductor (S) and a ferromagnet (F) that can be utilized for superconducting spintronics. However, to generate spin-triplet correlations a magnetic inhomogeneity is required at S/F interface, which makes it difficult to functionalize such devices. Furthermore, the use of S may loss the spin-degree of freedom. These issues can be solved by using a spin-triplet superconductor (T) rather than a S. On the other hand, the proximity effect at T/F interface has not explored much. In this talk, I shall discuss our recent study of differential conductance of high and low barrier superconducting junctions fabricate by growing an epitaxial thin film of ferromagnetic $SrRuO_3$ on a Sr_2RuO_4 (as a T). It is found that spin-triplet correlations are induced into $SrRuO_3$ exhibits anisotropic response under externally applied magnetic fields. Furthermore, differential conductance vs bias voltage of $Au/SrTiO_3/SrRuO_3/Sr_2RuO_4$ tunnel junctions shows the V-shaped minigap. These observations may attribute to the p-wave superconducting correlation induced into $SrRuO_3$.

Anwar *et al.*, Nat. Commun. (2016) & arXiv:1903.02093(2019).

Title: Topology, edge currents and related issues in Sr_2RuO_4

Catherine Kallin
McMaster University

While the earlier combined experimental evidence in favour of triplet or odd-parity pairing and broken time reversal symmetry pointed to chiral p-wave order in the superconducting state of Sr_2RuO_4, recent experiments imply that this needs to be re-examined. Consequently, this talk will discuss both chiral p-wave and other orders. Chiral p-wave order on quasi-2d Fermi surfaces, as one has in Sr_2RuO_4 has topological order characterized by Chern numbers on each band. This talk will review the various signatures expected due to the topology of this order, as well as closely related signatures. In particular, the signatures for broken time-reversal symmetry will be examined in the context of existing experiments on Sr_2RuO_4, as the lack of time-reversal symmetry highly constrains the possible superconducting orders. Other orders that have been suggested for Sr_2RuO_4, or which appear competitive from microscopic calculations, including topological helical p-wave order and 3-dimensional realizations of chiral order, will also be discussed. Finally, the conditions for stability of half-quantum vortices will be briefly discussed, as Ying Liu will discuss related experiments.

Topologically protected Bogoliubov Fermi surfaces

Daniel F Agterberg
University of Wisconsin - Milwaukee

It is commonly believed that, in the absence of disorder or an external magnetic field, there are two possible types of nodal superconducting excitation gaps: the gap has point nodes or it has line nodes. Here, we show that, for an even-parity nodal superconducting state which spontaneously breaks time-reversal symmetry, the low-energy excitation spectrum generally does not belong to either of these categories; instead, it has extended Bogoliubov Fermi surfaces. These Fermi surfaces are topologically protected from being gapped by a non-trivial Z_2 invariant. In this talk, I will discuss the physical origin, topological protection, and energetic stability of these Bogoliubov Fermi surfaces.

Superconductivity in bulk and mesoscopic Sr_2RuO_4

Ling Liu
Pennsylvania State University

Since the discovery of its superconductivity 25 years ago, much of the work on Sr_2RuO_4has been focused on its pairing symmetry, motivated originally by a theoretical prediction that this low-temperature superconductor is an odd-parity, spin-triplet superconductor. Many experimental and theoretical results concerning this issue have been obtained in the intervening years. Nevertheless, the precise pairing state realized in Sr_2RuO_4 is yet to be resolved. Work carried out at Penn State has focused on the electrical transport and tunneling measurements on Sr_2RuO_4, in particular, the Josephson effect and related phase-sensitive measurements detecting the symmetry of the orbital part of the Cooper pair wave function. Samples used in our studies include very different forms of Sr_2RuO_4ranging from bulk single crystals, thin films, the eutectic phase of Ru-Sr_2RuO_4, to certain more complex devices involving very thin single crystals of a mesoscopic lateral size. In this talk I will present some details of our earlier phase-sensitive measurements on bulk Sr_2RuO_4 in view of recently reinvigorated interest in the pairing symmetry issue. I will also discuss our more recent work on doubly connected mesoscopic cylinders of Sr_2RuO_4prepared by a combination of conventional and unconventional nanofabrication techniques. It was predicted theoretically, within a spin-triplet superconductivity scenario, that a half-flux-quantum state will form in a doubly connected, mesoscopic sample of Sr_2RuO_4 in the presence of both out-of- and in-plane magnetic fields. Experimentally a half-step-height feature in the transition between two full-flux quantum states was indeed found in the cantilever magnetometry measurements and attributed to the existence of the predicted half-flux-quantum state. Our work was aimed at detecting evidence for the half-flux-quantum state using a different set of measurements and clarifying the effect of the in-plane magnetic field that was shown to be necessary to yield the half-height-step feature seen in the magnetometry measurements. I will present data on magnetoresistance oscillations of our cylinders in the presence of an in-plane magnetic field and discuss the implications of our results.

Josephson and tunneling effects of Sr_2RuO_4

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Strontium ruthenate (Sr_2RuO_4 :SRO) is accepted as one of the most promising candidates of the topological superconductors. The conductance spectra of the NIS (SRO/Au) tunneling junctions show the presence of broad zero-bias conductance peaks, which indicates the dispersive Andreev bound state formation at the out-of-plane edges of SRO due to topological superconductivity [1]. However, we cannot determine the time reversal symmetry using tunneling spectroscopy. Here we report the verification of the topological superconductivity based on the Josephson effect between SRO and *s*-wave superconductors with intent to discriminate between the chiral and helical states.

We fabricate two types of Josephson junctions: SRO/Nb corner junction [2] and Ru wholly rounded by SRO [3] by using 3K phase of SRO. In the case of SRO/Nb, we analyze the critical current as the function of applied magnetic field based on the theoretical formula developed by Kawai, et al [4]. The results exhibit the lack of cosine components in Josephson current. This result is consistent with the time-reversal preserving nature of SRO [5]. In the case of SRO/Ru, although we search for the spontaneous magnetic field generated at the interface between SRO/Ru using Al SQUID, no sign of the field generation has been detected down to 43mK [3]. The result contradicts to the anticipated generation of spontaneous magnetic field at the interface between chiral p-wave superconductor and s-wave superconductors. Comprehensive analyses of these results indicate that SRO is more reasonably considered as the helical *p*-wave superconductor rather than the chiral *p*-wave one.

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