Workshop **OSS2022**

Unconventional transport in superconducting & magnetic systems with spin-orbit coupling

14-17 November 2022 Vietri sul Mare, Italy

OSS
Oxide Superspin
Core-to-Core Programme
JSPS EPSRC CCES-IBS CNR-SPIN

Book of Abstracts

SPIN

Dipartimento di Fisica E.R. Caianiello

UNIVERSITÀ DEGLI STUDI DI SALERNO

EPSRC

AIM

OSS2022 is organized within the Core-to-Core Oxide SuperSpin International Network involving experimental and theoretical groups in UK, Japan, South Korea, and Italy. The aim of OSS2022 is to bring together members of the Network along with leading scientists in the field of advanced materials and interface research to discuss frontier research in the area of novel superconductivity at oxide superconductor interfaces with magnetic materials.

Through a better understanding of materials processing and properties, one can envision achieving full control over superconducting symmetry at oxide interfaces and to be able to gain access to the fundamental mechanisms underlying the science of advanced oxide interfaces and unconventional superconductivity.

The workshop will cover both theoretical and experimental aspects of the field, with a focus on structural, magnetic and electronic properties of superconducting heterostructures, correlated electron matter, topological insulators and semimetals, surface states of topological systems and their interplay with conventional orders.

Conference Chairs

A. Vecchione (Chair), CNR-SPIN Salerno

Y. Maeno (Co-Chair), Kyoto University

T. Noh (Co-Chair), Seoul National University

J. Robinson (Co-Chair), University of Cambridge

Program Committee

Y. Asano, Hokkaido University

M. Cuoco (Chair), CNR-SPIN Salerno

C. Kim, Seoul National University

J. Robinson (Co-Chair), University of Cambridge

S. Yonezawa, Kyoto University

Scientific and Organizing Committee

S.B. Chung, University of Seoul

R. Fittipaldi, CNR-SPIN Salerno

F. Forte, CNR-SPIN Salerno

P. Gentile, CNR-SPIN Salerno

G. Mattoni, Kyoto University

M. Lettieri, CNR-SPIN Salerno

C. Noce, University of Salerno

A. Romano, University of Salerno

Technical Support Committee

S. Abate, CNR-SPIN Salerno

B. Amoruso, University of Salerno

C. D'Apolito, University of Salerno

V. Di Marino, University of Salerno

A. Loffredo, Cnr-Spin Salerno

R. Sacco, Cnr-Spin Salerno

OSS2022 Program

Time	Monday 14th	Tuesday 15th	Wednesday 16th	Thursday 17th
	Session 1 Unconventional superconductivity in Sr_2RuO_4	**Session 3** Superconducting spintronics and magnetism	**Session 5** Nonequilibrium magnetic and spin-orbit coupled systems	**Session 6** Novel phases at oxide interfaces and in 2D materials
	Chair: Antonio Vecchione	**Chair: Jason Robinson**	**Chair: Jennifer Fowlie**	**Chair: Changyoung Kim**
08:45 – 09:00	Welcome (Jason Robinson & Directors Dep. Phys. Salerno & CNR-SPIN)			
09:00 – 09:30	Yoshiteru Maeno	Sachio Komori	Gil-Ho Lee	Jinkwon Kim
09:30 – 10:00	Aline Ramirez	Alex Chan	Stefano Bonetti	Sukbum Chung
10:00 – 11:00	**Coffee Break**			
11:00 – 11:30	Kenji Ishida	Katharina Franke	Beena Kaliski	Carmine Autieri
11:30 – 12:00	Yuri Fukaya	Linde Olde Olthof	Teruo Ono	Angelo di Bernardo
12:00 – 12:30	Vadym Grinenko	Remko Fermin	Dongwook Go	Nicolas Gauquelin
12:30 – 14:30	**Lunch Break**			
	Session 2 Unconventional transport effects in superconductors	**Session 4** Topological superconductivity	**Excursion**	**Session 7** Frontiers in quantum materials and quantum phases
	Chair: Katharina Franke	**Chair: Yoshi Maeno**		**Chair: Mario Cuoco**
14:30 – 15:00	Jennifer Fowlie	Keiji Yada		Dirk Wulferding
15:00 – 15:30	Maria Teresa Mercaldo	Szabolcs Csonka		Philip Hofmann
15:30 – 17:00	**Coffee break & poster viewing**	**1-minute poster presentations & coffee break**		**Coffee Break & Poster viewing**
17:00 – 17:30	Alexander Golubov	Marco Aprili		Angela Wittmann
17:30 – 18:00	Elke Scheer	Yajian Hu		Enrico Giannini
18:00 – 18:30	Hisa Matsuki	Masatoshi Sato		Satoshi Kashiwaya
19:00	Free time	Free time	**Conference Dinner**	*Closing remarks*

Each talk is dedicated 25 minutes plus 5 minutes for discussion.

INVITED SPEAKERS

POSTERS

Tunnelling process into YSR states visualized by shot-noise scanning tunnelling microscopy

U. Thupakula[1], V. Perrin[1], A. Palacio-Morales[1], L. Cario[2], P. Simon[1], F. Massee[1] and M. Aprili[1]*

[1]*Laboratoire de Physique des Solides (CNRS UMR 8502), Bâtiment 510, University Paris-Sud/University Paris-Saclay, 91405 Orsay, France*
[2]*University of Nantes, CNRS, Institut des Matériaux Jean Rouxel, IMN, F-44000 Nantes, France*

Isolated electronic states generated by single atom impurities, such as acceptor and donor states in semiconductors and in-gap states in superconductors, are ideal building blocks for bottom-up constructed devices. Particularly chains and islands of magnetic impurities in superconductors have attracted considerable attention recently as they may host Majorana fermions. One of the challenges in this endeavour is to understand the intrinsic lifetime of the localised states, also known as Yu-Shiba-Rusinov (YSR) states, which is expected to be limited by the inelastic coupling with the continuum. Up to now STM studies of YSR states have focused on spectroscopy at atomic scale by measuring the average tunneling current as a function of the bias voltage. However current fluctuations gives us the possibility to explore the dynamics and the total charge transferred by a single tunneling event.

After a brief introduction to shot-noise scanning tunneling microscopy [1], I will show that electron tunneling into superconducting 2H-$NbSe_2$ mediated by YSR states is ordered as function of time, as evidenced by a reduction of the noise [2]. Moreover, our results show the concomitant transfer of charges e and 2e, indicating that incoherent single particle and coherent Andreev processes operate simultaneously. From the quantitative agreement between experiment and theory we obtain a lifetime $1/\tau = 1$ μeV $\ll k_BT$ demonstrating that shot-noise can probe energy and time scales inaccessible by conventional spectroscopy whose resolution is thermally limited.

[1] F. Massee et al. Review of Scientific Instruments 89, 093708 (2018).
[2] U. Thupakula, V. Perrin, A. Palacio-Morales, L. Cario, M. Aprili, P. Simon, and F. Massee, Phys. Rev. Lett. 128, 247001 (2022).

Competing sources of Berry curvature and charge reconstruction at the oxide interface

Carmine Autieri

International Research Centre Magtop, Institute of Physics, Polish Academy of Sciences, Aleja Lotników 32/46, PL-02668 Warsaw, Poland

In oxide heterostructures, different materials are integrated into a single artificial crystal, resulting in a breaking of inversion symmetry across the heterointerfaces [1]. A notable example is the interface between polar and nonpolar materials, where valence discontinuities lead to otherwise inaccessible charge and spin states. This approach paved the way for the discovery of numerous unconventional properties absent in the bulk constituents. However, control of the geometric structure of the electronic wave functions in correlated oxides remains an open challenge. Here, we create heterostructures consisting of ultrathin $SrRuO_3$, an itinerant ferromagnet hosting momentum-space sources of Berry curvature, and $LaAlO_3$, a polar wide-band-gap insulator. Transmission electron microscopy reveals an atomically sharp $LaO/RuO_2/SrO$ interface configuration, leading to an excess charge being pinned near the $LaAlO_3/SrRuO_3$ interface. We demonstrate through magneto-optical characterization, theoretical calculations and transport measurements that the real-space charge reconstruction drives a reorganization of the topological charges in the band structure, thereby modifying the momentum-space Berry curvature in $SrRuO_3$. Our results illustrate how the topological and magnetic features of oxides can be manipulated by engineering charge discontinuities at oxide interfaces [2,3].
Finally, we propose a theoretical model to assess the anomalous Hall effects in the presence of sign competing sources of the Berry curvature. We find that the resulting Berry curvature exhibits a non-monotonous angular dependence when the magnetization is reversed. This behavior leads to anomalies in the Hall conductance at values of magnetic fields for which the magnetization switches its orientation.

[1] T. C. van Thiel, J. Fowlie, C. Autieri, N. Manca, M. Šiškins, D. Afanasiev, S. Gariglio, and A. D. Caviglia, ACS Materials Lett. 2, 389–394 (2020).
[2] D. J. Groenendijk, C. Autieri, T. C. van Thiel, W. Brzezicki, N. Gauquelin, P. Barone, K. H. W. van den Bos, S. van Aert, J. Verbeeck, A. Filippetti, S. Picozzi, M. Cuoco and A. D. Caviglia, Phys. Rev. Research 2, 023404 (2020).
[3] T. C. van Thiel, W. Brzezicki, C. Autieri, J. R. Hortensius, D. Afanasiev, N. Gauquelin, D. Jannis, N. Janssen, D. J. Groenendijk, J. Fatermans, S. Van Aert, J. Verbeeck, M. Cuoco, and A. D. Caviglia, Phys. Rev. Lett. 127, 127202 (2021).

Terahertz electric-field driven magnetism in $SrTiO_3$

M. Basini[1], M. Pancaldi[1], B. Wehinger[2], M. Udina[3], T. Tadano[4], M. C. Hoffmann[5], A. V. Balatsky[2,6,7], S. Bonetti[1,2, *]

[1]Department of Physics, Stockholm University, Sweden
[2]Dept. of Molecular Sciences and Nanosystems, Ca' Foscari University of Venice, Italy
[3]Department of Physics and ISC-CNR, "Sapienza" University of Rome, Italy
[4]Research Center for Magnetic and Spintronic Materials, National Institute for Materials Science, Japan
[5]Linac Coherent Light Source, SLAC National Accelerator Laboratory, USA
[6]NORDITA, Sweden
[7]Department of Physics, University of Connecticut, United States
†Present address: Elettra-Sincrotrone Trieste S.C.p.A., Italy
‡ Present address: European Synchrotron Radiation Facility, France

The emergence of collective order in matter is among the most fundamental and intriguing phenomena in physics. In recent years, the ultrafast dynamical control and creation of novel ordered states of matter not accessible in thermodynamic equilibrium is receiving much attention. Among those, the theoretical concept of dynamical multiferroicity has been introduced to describe the emergence of magnetization by means of a time-dependent electric polarization in non-ferromagnetic materials. In simple terms, a large amplitude coherent rotating motion of the ions in a crystal induces a magnetic moment along the axis of rotation. However, the experimental verification of this effect is still lacking. Here, we provide evidence of room temperature magnetization in the archetypal para-electric perovskite $SrTiO_3$ due to this mechanism. To achieve it, we resonantly drive the infrared active soft phonon mode with intense circularly polarized terahertz electric field, and detect a large magneto-optical Kerr effect. A simple model, which includes two coupled nonlinear oscillators whose forces and couplings are derived with ab-initio calculations using self-consistent phonon theory at a finite temperature, reproduces qualitatively our experimental observations on the temporal and frequency domains. A quantitatively correct magnitude of the effect is obtained when one also considers the phonon analogue of the reciprocal of the Einstein – de Haas effect, also called the Barnett effect, where the total angular momentum from the phonon order is transferred to the electronic one. Our findings show a new path for designing ultrafast magnetic switches by means of coherent control of lattice vibrations with light.

Spin Pumping Long-Range Spin-Triplet Currents into Superconducting Nb Through Cr/Fe Interfaces

Alex K. Chan[1], Murat Cubukcu[2], Sachio Komori[3], Alexander Vanstone[1], Juliet Thompson[3], Garry Perkins[1], Mark Blamire[3], Jason Robinson[3], Matthias Eschrig[4], Hidekazu Kurebayashi[5], Lesley Cohen[1]

[1]Physics, Blackett Laboratory, Imperial College London, London, United Kingdom
[2]National Physical Laboratories, Teddington, Middlesex, United Kingdom
[3]Materials Science and Metallurgy, University of Cambridge, Cambridge, United Kingdom
[4]Physics, Univeristy of Greifswald, Greifswald, Germany
[5]Electronic and Electrical Engineering, University College London, London, United Kingdom

Understanding the conditions required to create long-range spin-polarised supercurrents, carried by triplet Cooper pairs, is a crucial aspect of superconducting spintronics. In recent years, theoretical and experimental works have shown it is possible to form long-range triplet supercurrents (LRTS) through a spatially varying magnetization at a superconducting/ferromagnetic (S/F) interface [1,2]. By including a spatially varying magnetisation, singlet-to-triplet conversion can occur via the proximity effect along with spin-mixing and spin-rotation processes. For example, experimental evidence for the generation of LRTS has been found in Nb/Cr/Fe/Cr/Nb Josephson junctions [3]. The Cr interdiffuses into Fe to create a spatially inhomogeneous magnetic layer. Independently, studies on spin pumping by ferromagnetic resonance (FMR) into Pt/Nb/Py/Nb/Pt stacks showed signatures of LRTS [4,5]. The presence of Pt - a strong spin-orbit-coupling layer - was necessary to observe the key signature of a broadening of the FMR linewidth. However, this empirical claim has remained contentious in the literature [6,7]. We set out to demonstrate conclusively the ability to spin pump LRTS into a superconductor and only when the conditions for proximity induced triplet Cooper pairs to form are satisfied in the presence of a magnetic field. In this presentation, we discuss our results on various Nb/Cr/Fe/Cr/Nb and Nb/Fe/Nb multilayer films [8], which demonstrate in-plane uniaxial anisotropy. The anisotropy is present despite the Fe being amorphous. We study their Gilbert damping behaviour above and below the superconducting critical temperature T_c. We observe key signatures of LRTS, an enhancement of the Gilbert damping below T_c, only when certain criteria are met: when Cr is present and when the external field is applied in the films' hard axes. A triplet channel can only open when the interfacial spin layer is unsaturated. We show a strong positive correlation between the strength of such a triplet channel and the anisotropy strength. The possible source of anisotropy is explored, and further discuss the implications for future experiments.

[1] J. Linder and J. W. A. Robinson, Nat. Phys. 11, 307 (2015).
[2] M. Eschrig, Phys. Today 64, 43 (2011).
[3] J. W. A. Robinson, N. Banerjee and M. G. Blamire, Phys. Rev. B 89, 104505 (2014).
[4] K-R. Jeon, C. Ciccarelli, H. Kurebayashi et al., Phys. Rev. B 99, 024507 (2019).
[5] K-R. Jeon, X. Montiel, S. Komori, et al., Phys. Rev. X 10, 031020 (2020).
[6] M. A. Silaev, Phys. Rev. B 102, 180502 (2020).
[7] M. Muller, L. Liensberger, L. Flacke, et al., Phys. Rev. Lett. 126, 087201 (2021).
[8] A. K. Chan, M. Cubukcu, X. Montiel et al., arXiv:2202.01520 (2022).

Theory of superconductivity in doped quantum paraelectrics

Suk Bum Chung

Department of Physics and Natural Science Research Institute, University of Seoul, Seoul, 02504, Republic of Korea
School of Physics, Korea Institute for Advanced Study, Seoul, 02455, Republic of Korea

Recent experiments on Nb-doped $SrTiO_3$ have shown that the superconducting energy gap to the transition temperature ratio maintains the Bardeen-Cooper-Schrieffer (BCS) value throughout its superconducting dome. Motivated by these and related studies, we show that the Cooper pairing mediated by a single soft transverse-optical phonon is the most natural mechanism for such a superconducting dome given experimental constraints, and present the microscopic theory for this pairing mechanism. Furthermore, we show that this mechanism is consistent with the T^2 resistivity in the normal state. Lastly, we discuss what physical insights $SrTiO_3$ provides for superconductivity in other quantum paraelectrics such as $KTaO_3$.

[1] Yue Yu, Harold Y. Hwang, S. Raghu, and Suk Bum Chung, npj Quantum Materials 7, 63 (2022).

Cooper pair splitting and Andreev molecule in Superconductor - Parallel InAs nanowire hybrid

Olivér Kürtössy[1], Zoltán Scherübl[1], Gergő Fülöp[1], Thomas Kanne[2], Jesper Nygard[2], Peter Makk[1], Szabolcs Csonka[1]*

[1]Department of Physics, Institute of Physics, Budapest University of Technology and Economics, and MTA-BME Superconducting Nanoelectronics Momentum Research Group
[2]Center for Quantum Devices, Niels Bohr Institute, University of Copenhagen, 2100 Copenhagen, Denmark

Hybrid nanostructures consisting of two parallel InAs nanowires connected by an epitaxially grown superconductor (SC) shell recently became available [1]. The defect-free SC-semiconductor interface and the vicinity of two quasi-one-dimensional channels can be utilized to enhance crossed Andreev reection (CAR) between quantum dots (QD) formed in the separate wires. These properties allow not only a highly-efficient spatial separation of entangled electrons in the so-called Cooper pair splitting process (CPS) [2], but can lead to the strong hybridization of the QDs resulting in an Andreev molecule [3], as a milestone towards more exotic states, like Majoranna or parafermions [4].
We report the experimental realization of both CPS and Andreev molecule in different parallel nanowire-based nanocircuits (see Fig. 1). We characterize the electrostatic and the CAR-mediated interaction between parallel QDs. The electron transport in both systems is analyzed theoretically showing good agreement with the measurements.

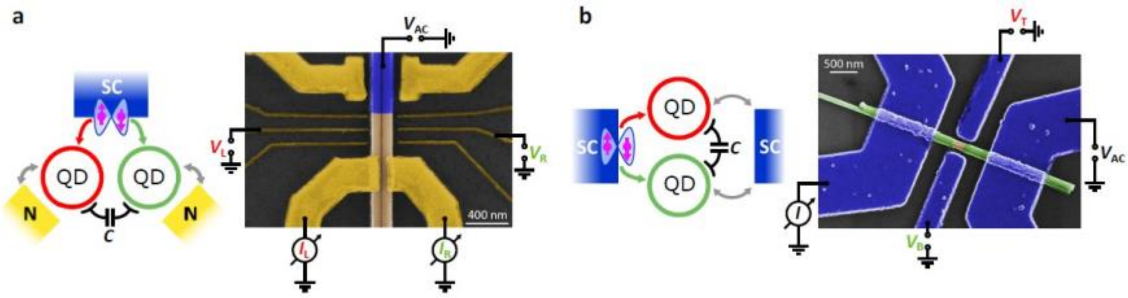


Fig. 1 a) Cooper-pair splitter and b) Andreev molecule setup based on parallel InAs wires

[1] T. Kanne et al., Adv. Funct. Mat. 32, 9, 9 (2021).
[2] O. Kürtössy et al., arXiv:2203.143977 (2022), accepted npj Quantum Materials.
[3] O. Kürtössy et al., Nano Lett. 21, 7929-7937 (2021).
[4] J. Klinovaja, and D. Loss, Phys. Rev. B 90, 045118 (2014).

Towards superconducting spintronics based on van-der-Waals systems

A. Spuri, R. Hartmann, W. Belzig, E. Scheer, A. Di Bernardo

Department of Physics, University of Konstanz, Universitätstraße 10,
78457 Konstanz, Germany

The realization of Cooper pairs of electrons with parallel-aligned spins (i.e., spin-triplet pairs) has been demonstrated for a variety of three-dimensional (3D) superconductor/ ferromagnet (S/F) heterostructures. Several studies have shown that, using a stack of non-collinear Fs [1-2] or Fs that are magnetically inhomogeneous [3-4], it is possible to convert the spin-singlet pairs of a conventional S into fully-polarized spin triplets – this has paved the way for the research field currently known as superconducting spintronics [5].

Van-der-Waals (vdW) heterostructures host a variety of unconventional phases, both superconducting and magnetic, which can be explored to realize two-dimensional (2D) superspintronic devices with novel functionalities and types of control compared to devices based on 3D S/F hybrids. The conversion of spin singlets into spin triplets across a 2D S/F vdW interface represents, however, the first step towards superconducting spintronics based on vdW hybrids.

In this talk, I will show recent magnetotransport experiments that we have performed on few-layer-thick S (e.g., NbS_2, $NbSe_2$) flakes coupled to F flakes via vdW interactions. To extend the range of properties of our vdW systems, we use not only conventional 2D vdW Fs, but also F flakes that are cleaved from ionic F single crystals through a new approach developed in my research group.

In addition to discussing the properties of these F flakes, which are completely dissimilar from their corresponding 3D F single crystals, I will present magnetotransport data showing the first indirect evidence for spin-triplet generation across a 2D S/F vdW interface.

[1] T. S. Khaire et al., Phys. Rev. Lett. 104, 137002 (2010).
[2] X. L. Wang et al., Phys. Rev. B 89, 140508 (R) (2014).
[3] J.W.A. Robinson et al., Science 329, 59 (2010).
[4] A. Di Bernardo et al., Nat. Commun. 6, 8053 (2015).
[5] J. Linder, and J. W. A. Robinson, Nat. Phys. 11, 307 (2015).

Superconducting triplet currents generated by an effective spin-orbit coupling in a spin-textured ferromagnetic disk

Remko Fermin[1], Dyon van Dinter[1], Naor Scheinowitz[1], Michel Hubert[1], Bart Woltjes[1], Mikhail Silaev[2], Jan Aarts[1], Kaveh Lahabi[1]

[1]Leiden University, Leiden Institute of Physics, Niels Bohrweg 2, 2333 CA, Leiden, The Netherlands
[2]University of Jyväskylä, Department of Physics, Survontie 9, C 40500, Jyväskylä, Finland

Since the discovery of the long-range superconducting proximity effect, the interaction between spin-triplet Cooper pairs and magnetic structures such as domain walls and vortices has been the subject of intense theoretical discussions, while the relevant experiments remain scarce. We have developed nanostructured Josephson junctions with a highly controllable spin texture, based on disk- and ellipse-shaped Nb/Co bilayers. We use the vortex magnetization of the cobalt in disk-shaped junctions to induce long-range triplet (LRT) superconductivity in the ferromagnet. Surprisingly, the LRT correlations emerge in highly localized (sub-80 nm) channels at the rim of the ferromagnet, despite its trivial band structure. We show that these robust rim currents arise from the magnetization texture acting as an effective spin–orbit coupling, which results in spin accumulation at the bilayer–vacuum boundary. The ellipse-shaped samples exhibit a bistable magnetic texture: the ellipse can either be prepared as uniformly magnetized or as a pair of vortices at zero applied field. We use this bistability to create a new type of non-volatile Josephson junction, since the two states yield considerably different critical currents, thereby enabling reliable electrical readout of the element. Our approach, that combines micromagnetic modeling with microstructured SF-hybrids, presents a novel route towards studying effective spin-orbit coupling of magnetic textures, LRT generation and, realizing superconducting memory applications.

Superconductivity and magnetism in infinite-layer nickelate heterostructures

J. Fowlie[1,2], M. Hadjimichael[3], M. M. Martins[4], D. Li[1,2], M. Osada[1,2], B. Y. Wang[1,2], K. Lee[1,2], Y. Lee[1,2], Z. Salman[4], T. Prokscha[4], J.-M. Triscone[3], H. Y. Hwang[1,2] and A. Suter[4]

[1]*Department of Applied Physics, Stanford University, USA*
[2]*Stanford Institute for Materials and Energy Sciences, SLAC National Lab, USA*
[3]*Department of Quantum Matter Physics, University of Geneva, Switzerland*
[4]*Laboratory for Muon Spin Spectroscopy, Paul Scherrer Institute, Switzerland*

Nickel and copper are nominally very similar in chemistry so the search for superconductivity in nickelates is a story almost as old as the quest to understand the high temperature superconductivity of the cuprates.
In this talk, I will introduce the recent discovery of superconductivity in infinite-layer nickelates [1] and the ever-growing family of nickelate superconductors. I will touch on some of the materials challenges involved before summarizing the key physics we have learned so far including results from x-ray scattering [2] that identify a Mott-Hubbard-like character to the infinite-layer nickelate electronic structure as well as a significant rare earth 5d influence at the Fermi level. In particular I will focus on muon spin rotation [3] that reveals local magnetism in these materials that 1) onsets at rather high temperature, 2) is independent of the rare earth 4f electrons, 3) appears to be robust to doping 4) is antiferromagnetic and possibly short-range-ordered in nature and 5) coexists with superconductivity at low temperatures.
Finally, I will come back to the comparison between nickelates and cuprates and discuss how the disparities in the magnetic properties may be understood.

[1] D. Li et al., Nature 572, 624 (2019).
[2] H. Lu et al., Science 373, 213 (2021).
[3] J. Fowlie et al., Nature Physics 18, 1043 (2022).

Diode effect in Josephson junctions with a single magnetic atom

Martina Trahms[1], Larissa Melischek[2], Jacob F. Steiner[2], Bharti Mahendru[1], Idan Tamir[1], Nils Bogdanoff[1], Olof Peters[1], Gael Reecht[1], Clemens B. Winkelmann[3], Felix von Oppen[2], Katharina J. Franke[1]

[1]*Fachbereich Physik, Freie Universität Berlin, Germany*
[2]*Fachbereich Physik and Dahlem Center for Complex Quantum Systems, Freie Universität Berlin, Germany*
[3]*Université Grenoble Alpes, CNRS, Institut Néel, Grenoble, France*

Nonreciprocal charge transport describes the dependence of the current on biasing direction and is the basic principle of every diode. Here, we create atomic-scale Pb-Pb Josephson junctions in a scanning tunneling microscope. By insertion of single magnetic adatoms the junction adopts nonreciprocal current behavior. We show that the nonreciprocity of the retrapping current, which separates the dissipative current branch from the low-resistance branch upon biasing reduction, depends on the Yu-Shiba-Rusinov (YSR) states inside the superconducting energy gap. Aided by theoretical modelling, we ascribe the non-reciprocity to quasiparticle currents flowing via Yu-Shiba-Rusinov (YSR) states inside the superconducting energy gap.

Spin-susceptibility for orbital-singlet Cooper pair in the three-dimensional Sr_2RuO_4 superconductor

Yuri Fukaya[1,2], Tatsuki Hashimoto[1,3], Masatoshi Sato[1], Yukio Tanaka[4], Keiji Yada[4]

[1]*Yukawa Institute for Theoretical Physics, Kyoto University, Japan*
[*2]*CNR-SPIN, c/o University of Salerno, Italy*
[3]*Department of Mechanical Engineering, Stanford University, USA*
[4] *Department of Applied Physics, Nagoya University, Japan*

Pairing symmetry in Sr_2RuO_4 superconductor [1] is one of the mysterious issues in solid-state physics. The spin-triplet chiral *p*-wave state was believed to be the most suitable one due to the supported experiments [2]. However, recent observations in NMR experiments indicated the possibility of spin-singlet pairings due to the reduction of the spin susceptibility with an in-plane magnetic field [3].
A recent theoretical study suggested the interorbital E_g Cooper pair with time-reversal symmetry breaking in the three-dimensional Sr_2RuO_4 model [4]. This interorbital pairing is described by spin-triplet/orbital-singlet/*s*-wave, and it has the $d_{zx}+id_{yz}$-like energy gap structure with the Bogoliubov Fermi surface [4,5].
To determine the spin structure of the Cooper pair, the temperature dependence of spin susceptibility is a good way. Since the electronic structure at the Fermi level in Sr_2RuO_4 is described by the t_{2g}-orbitals, it is necessary to investigate the spin susceptibility with orbital-dependent Cooper pairs [6].
We study the temperature dependence of the spin susceptibility with the orbital-singlet Cooper pairs in the three-dimensional Sr_2RuO_4 model constructed by Ref. [4] below T_c [7]. Then we focus on both orbital-singlet spin-triplet/*s*-wave and spin-singlet/*p*-wave states for each irreducible representation in the D_{4h} point group.
In spin-triplet/*s*-wave pairings, that is the pseudospin-singlet ones represented in the band basis, spin susceptibility is reduced with the decrease of the temperature, irrespective of the direction of the applied magnetic fields. However, in the case of spin-singlet/*p*-wave states, the pseudospin-triplet **d**-vector in the band basis is not completely aligned in the *xy*-plane (along the *z*-axis) owing to the strong atomic spin-orbit coupling. As a result, spin susceptibility for spin-singlet/*p*-wave pairings also decreases around 5-10 percent for the temperature along the *z* (*x*) axis. Our results can fit the recent NMR experiments [3].

[1] Y. Maeno et al., Nature (London) 372, 532 (1994).
[2] K. Ishida et al., Nature (London) 396, 658 (1998).
[3] A. Pustogow et al., Nature (London) 574, 72 (2019). K. Ishida, et al., J. Phys. Soc. Jpn. 89, 034712 (2020). A. Chronister, et al., Proc. Natl. Acad. Sci. 118, e2025313118 (2021).
[4] H. G. Suh et al., Phys. Rev. Research 2, 032023(R) (2020).
[5] D. F. Agterberg et al., Phys. Rev. Lett. 118, 127001 (2017). P. M. R. Brydon, et al., Phys. Rev. B 98, 224509 (2018).
[6] C. M. Puetter and H.-Y. Kee, Europhys. Lett. 98, 27010 (2012).
[7] Y. Fukaya et al., Phys. Rev. Research 4, 013135 (2022).

Study of the metal to insulator phase transition in Ca_2RuO_4 under different stimulus

N. Gauquelin*

Electron Microscopy for Materials Research (EMAT), Department of Physics, University of Antwerp, BE-2020 Antwerpen, Belgium and NANOlab Center of Excellence, University of Antwerp, BE-2020 Antwerpen, Belgium

Mott materials have raised a lot of interest in physics in the last decades due to their insulator to metal transition. This transition relies on a change of the electronic states by filling the band-gap of an insulator to turn it into a more conductive metallic state. This band filling can be realized in different ways by either applying pressure or strain (bandwidth-control), changing the temperature nearby the Mott transition (temperature-control) or doping the system away from half filling (density-control using electric field or current).

The interest in Ca_2RuO_4 (CRO) in contrast to the more common VO_2 or Fe_3O_4 is that this can be achieved with low E-field. CRO is a Mott-insulator at room temperature and on heating through T_{MI}=83°C it undergoes an insulator-to-metal transition accompanied by an abrupt structural change. The structural transition leads to a remarkable orbital reconstruction from a preferential out-of-plane orbital occupancy of the 4d states (xz,yz) to a dominant orbital configuration with in-plane character (xy). This redistribution at lower temperature turns the system into an orbitally ordered state.

Recent advances in electron microscopy instrumentation such as aberration-correctors, direct electron detectors, electron monochromators and in-situ sample holders have given us the unique opportunity to get structural information and electronic information at the nanometer scale under applied pressure, electric field, current, temperature and even gas atmospheres. This makes it possible to visualize almost directly the development of new phases triggered by those stimulus as they develop at the nanometer (even sometimes atomic) scale.

In this presentation, measurement of the structure of a Ca_2RuO_4 single crystal piece across its insulator to metal transition using temperature, electric field and current will be presented. Effects of the application of pure electric field and current in the different crystallographic directions ([100], [010] and [001]) will be discussed and compared to the temperature-dependent measurements.

Isotope tuning of the superconducting dome of strontium titanate

Enrico Giannini, Dorota Pulmannová, Willem Rischau and Dirk van der Marel

Department of Quantum Matter Physics, University of Geneva, Switzerland

$SrTiO_3$ is one of the most widely investigated, and still one of the most puzzling perovskite materials, exhibiting unique features that defy the conventional understanding of superconductivity in a doped semiconductor. In the semiconducting state, zero-point quantum fluctuations prevent the ferroelectric order from stabilizing at any finite temperature, and the resulting exceptionally large dielectric permittivity allows metallic conductivity to appear at unusually low doping. In the electron-doped material, superconducting pairs form at carrier densities as low as $3 \cdot 10^{17}$ cm^{-3}, and violate the conventional BCS scenario. The proximity to a ferroelectric instability and the diluted superconductivity are theoretically suggested, and experimentally proven to be related, but the origin of pairing and the overall transport behavior are still not understood. Isotope substitutions (^{18}O for ^{16}O) beyond a critical threshold suppress quantum fluctuations and stabilize ferroelectricity (as well as Ca-substitutions for Sr, strain, and pressure). Concurrently, superconductivity is enhanced in doped $SrTi^{18}O_3$ and the superconducting critical temperature is tuned by isotope substitutions in a way that is opposite in sign, and significantly larger in amplitude than predicted by the conventional BCS theory.
Moreover, an isotope-induced shift of the superconducting dome to lower carrier concentrations is observed. Upon electron doping the critical threshold of ^{18}O substitutions is increased, and a Quantum Critical Line exists in the phase diagram. In the normal state, a coexistence of metallicity and ferroelectric-like order is pointed out by Raman spectroscopy. All these observations agree with a quantum critical scenario in which superconducting pairing is mediated by fluctuations of the ferroelectric soft mode. This talk reviews and discuss the recent experimental results that support a description of superconductivity in doped-$SrTiO_3$ as being driven by low-energy soft-phonon excitations close to a Quantum Critical Point.

Orbitronics:
Exploiting orbital angular momentum for next-generation electronics

Dongwook Go

Peter Grünberg Institut and Institute for Advanced Simulation, Forschungszentrum Jülich

Spintronics is one of the candidates that can achieve the key goals of the next generation information technology; high speed, scalability, and low-energy consumption. The discovery of spin-orbit torque a decade ago revolutionized the field and opened a promising route for electric control of magnetism. This has led to commercial device applications, e.g. spin-orbit torque random access memory. To enhance the efficiency, various novel ideas have been proposed; spin-momentum locking from Rashba states, topological surface states, oxide heterostructures, antiferromagnets, etc. Because these rely on strong spin-orbit interaction to electrically induce nonequilibrium spin density or current, the choice of materials is limited to heavy elements which are scarce on earth and often incompatible with mass production.

Recently, we proposed a fundamentally new direction by using orbital angular momentum (OAM) and its current. The orbital degree of freedom has been barely exploited so far because of the expectation that strong crystal field would suppress a coherent superposition. In spite of quenching of equilibrium orbital angular momentum, we have found that it is possible to electrically induce excitations of OAM and its current in nonequilibrium induced by an external electric field. We have shown that the efficiency of orbital current generation via orbital Hall effect far exceeds that of the spin current generation. Moreover, since the mechanism is independent from spin-orbit interaction, we have a broader choice of materials including light materials. In the last few years, numerous experiments have found evidences of the orbital current, have demonstrated its potential impact on spintronic devices, and have led to the birth of orbitronics in which we aim to build new type of devices by using electronic orbital information.

All these developments are the tip of an iceberg and can potentially lead to a new paradigm of quantum transport phenomena. A new perspective from orbitronics may shed light not only on spintronics but also other important areas of condensed matter physics such as topological matters. In this talk, I will present the state-of-the-part and recent development in orbitronics and outlook and future directions of this new emerging field.

Testing pairing symmetry using *s* + *p*-wave superconductor junctions

A. A. Golubov[1], B.J. Geurts[2], T.H. Kokkeler[1,3], Y. Tanaka[4]

[1] *Faculty of Science and Technology, University of Twente, The Netherlands*
[2] *Faculty of Electrical Engineering, Mathematics and Computer Science, University of Twente, The Netherlands*
[3] *Donostia International Physics Center (DIPC), 20018 Donostia-San Sebastian, Spain*
[4] *Department of Applied Physics, Nagoya University, Nagoya 464-8603, Japan*

We derive a boundary condition for the Nambu-Keldysh Green's function in diffusive normal metal - unconventional superconductor junctions applicable for mixed parity pairing [1]. Applying this theory to a 1d model of *s* + *p*-wave superconductor, we calculate local density of states (LDOS) in the diffusive normal metal (N) and charge conductance of a junction between N and *s* + *p*-wave superconductor. When the *s*-wave component of the pair potential is dominant, LDOS has a gap like structure at zero energy and the dominant pairing in N is even-frequency spin-singlet *s*-wave. On the other hand, when the *p*-wave component is dominant, the resulting LDOS has a zero energy peak and the dominant pairing in N is odd-frequency spin-triplet *s*-wave. The results show the robustness of the anomalous proximity effect specific to spin-triplet superconductor junctions.

Using the developed approach, multi-terminal (SNN) junctions are investigated where the superconducting potential is a mixture between *s*-wave and *p*-wave potentials [2]. The ways are proposed to determine whether S has a mixed pair potential and to distinguish between *s* + chiral and *s* + helical *p*-wave superconductors. It is found that a difference in conductance for electrons with opposite spins arises if both an *s*-wave and a *p*-wave components are present, even in the absence of a magnetic field. It is shown that a setup containing two SN junctions provides a clear difference in spin conductance between the *s* + chiral *p*-wave and *s* + helical *p*-wave symmetries.

Further, we propose new approach to distinguish *p*-wave from *s*-wave symmetry by measuring conductance a four terminal junction consisting of S and N terminals [3]. The N-terminals are used to manipulate the energy distribution functions of electrons in the junction in order to control the charge transport. It is shown that the differential conductance of junctions containing *p*-wave and s-wave superconductors is distinctly different, thus providing experimental test to detect potential p-wave superconductivity.

[1] Y. Tanaka, T.H. Kokkeler, and A.A. Golubov, Phys. Rev. B 105, 214512 (2022).
[2] T.H. Kokkeler, Y. Tanaka, and A.A. Golubov, arXiv:2208.06657.
[3] T.H. Kokkeler, A.A. Golubov, and B.J. Geurts, Supercond. Sci. Technol. 35, 084005 (2022).

TRSB superconductivity of Sr_2RuO_4: recent progress on muon spin rotation/relaxation (μSR) experiments under uniaxial stress

Vadim Grinenko

Tsung-Dao Lee Institute, Shanghai Jiao Tong University, Pudong, Shanghai 200240, China

Muon spin rotation (μSR) and polar Kerr effect measurements provide evidence for a time-reversal symmetry breaking (TRSB) superconducting state in Sr_2RuO_4 [1,2]. In our previous μSR studies of Sr_2RuO_4, we observed that T_{TRSB} and T_c split under ⟨100⟩ uniaxial stresses, thereby supporting a hypothesis of TRSB superconductivity [3]. Together with the observation that T_{TRSB} and T_c track each other under hydrostatic stress and also under an introduction of disorder [4], this observation suggests a symmetry-protected even-parity chiral superconducting state, $d_{xz}\pm id_{yz}$. However, so far, the splitting of the transitions under uniaxial ⟨100⟩ stress has been seen only in μSR measurements. In contrast with expectations for a chiral state, a second anomaly was not resolved either in heat capacity [5] nor in elastocaloric effect [6] measurements under ⟨100⟩ uniaxial stress. These contradictory results call for a search for additional evidence that TRSB phase transition is indeed present below T_c under uniaxial stress.

I will present μSR data under an applied magnetic field, demonstrating that the vortex lattice modifies significantly in the TRSB state compared to the superconducting state above T_{TRSB} when transitions are split under ⟨100⟩ stress. Our data can be interpreted as an indication of vortex clustering at low temperatures and transition to a homogeneous vortex lattice above T_{TRSB}. The strongest disorder in the vortex distribution is observed at T_{TRSB}. The vortex clustering is expected in two-component superconductors due to the presence of two different coherence lengths associated with two distinct phase transitions [7].

Also, we performed zero-field μSR measurements under uniaxial stress applied along a ⟨110⟩ lattice direction. We have obtained preliminary evidence for suppression of T_{TRSB} below T_c at a rate much higher than the suppression rate of T_c. This result indicates that condensation energy associated with the TRSB state might be very small compared to that associated with the superconductivity overall. Our data provide a possible consistency between μSR and thermodynamic probes and additional evidence for the phase transition at T_{TRSB} characterised by divergent coherence length.

[1] J. Xia et al., Phys. Rev. Lett. 97, 167002 (2006).
[2] G. M. Luke et al., Nature 394, 558 (1998).
[3] V. Grinenko, et al., Nat. Phys. 17, 748–754 (2021).
[4] V. Grinenko, et al., Nat Commun 12, 3920 (2021).
[5] Y.-S. Li et al., Proc. Nat. Acad. Sci. USA 118, e2020492118 (2021).
[6] Y.-S. Li et al., Nature 607, 276–280 (2022).
[7] E. Babaev and M. Speight, Phys. Rev. B *72*, 180502(R) (2005).

In-operando electronic structure of quantum materials devices

Philip Hofmann

Department of Physics and Astronomy, Aarhus University, Ny Munkegade 120, 8000 Aarhus C, Denmark, philip@phys.au.dk

In electronic devices such as a field effect transistor, materials are exposed to electrostatic doping and the presence of a transport current. This does not affect the basic properties of a conventional material such as silicon. Quantum materials, on the other hand, can fundamentally change their properties under these conditions because their ground states are dictated by a delicate and fragile balance between several interactions on a similar energy scale. Examples of this are electrically driven charge density waves, insulator-to-metal transitions in Mott insulators or the breakdown of superconductivity with an applied current density.

One of the most important tools for studying quantum materials in equilibrium is angle-resolved photoemission spectroscopy (ARPES), as this gives direct access to the sample's spectral function. Very recently, ARPES has also been applied to non-equilibrium situations such as doping [1,2,3] or transport currents [4] in simple *in-operando* electronic devices [5]. In this talk, I will review these developments and illustrate the power of non-equilibrium experiments by ARPES on simple devices made from two-dimensional materials. Finally, I will present first ARPES results on the current-induced insulator to metal transition in the Mott insulator Ca_2RuO_4.

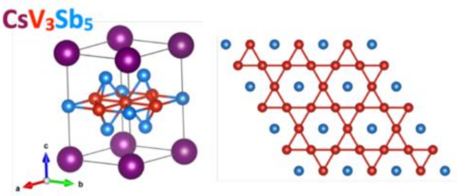
[1] F. Joucken et al., Nano Lett. 19, 2682 (2019).
[2] P. V. Nguyen et al., Nature 572, 220 (2019).
[3] R. Muzzio et al., Phys. Rev. B 101, 201409(R) (2020).
[4] D. Curcio et al., Phys. Rev. Lett. 125, 236403 (2020).
[5] Ph. Hofmann, AVS Quantum Science 3, 02110 (2021).

Polar Kerr effect study on the time-reversal symmetry-breaking in the charge density wave of CsV_3Sb_5

Yajian Hu[1,4], Soichiro Yamane[1], Giordano Mattoni[1,3], Keito Obata[1], Yongkai Li[2], Yugui Yao[2], Zhiwei Wang[2], Yoshiteru Maeno[1,3], and Shingo Yonezawa[1]

[1]Department of Physics, Kyoto University, Kyoto 606-8502, Japan
[2]School of Physics, Beijing Institute of Technology, Beijing 100081, P. R. China
[3]Toyota Riken - Kyoto Univ. Research Center (TRiKUC), Kyoto 606-8501, Japan
[4]RIKEN Center for Emergent Matter Science (CEMS), Saitama 351-0198, Japan

The Kagome metals AV_3Sb_5 (A = K, Rb, Cs) have attracted tremendous interest because they host non-trivial band topology and exotic phenomena, such as charge density wave (CDW) and superconductivity. CsV_3Sb_5 shows a CDW transition at $T_{CDW} \sim 94$ K with unconventional features, such as rotation-symmetry breaking. A superconducting transition occurs at $T_c \sim 2.6$ K, making CsV_3Sb_5 a great platform to study the interplay between the nontrivial band topology and unconventional superconductivity [2].
One of the central issues of CsV_3Sb_5 regards the time-reversal symmetry-breaking (TRSB) in the CDW state. Various experiments show TRSB behaviour, for instance, chiral anisotropy, anomalous Hall effect and increasing relaxation rate in zero-field μSR measurements. Theories suggest that the TRSB originates from the charge bond order and orbital loop-currents. However, several contradicting experimental results are also reported, such as [3,4]. Therefore, further study of the TRSB and CDW is crucial.
In this work [1], we study CsV_3Sb_5 by magneto-optic Kerr effect. Polar Kerr angle θ_K is measured using a home-made all-fiber Sagnac interferometer setup based on Ref. [5], at low temperature, with and without magnetic field. Under magnetic field, θ_K shows a jump at T_{CDW}. This jump can be flipped by magnetic field and the jump size is proportional to magnetic field. At zero field, we have detected non-zero Kerr angle below T_{CDW}. The sign of Kerr angle changes when the sample is cooled under opposite magnetic field. The field-training effect suggests spontaneous TRSB in the CDW state. In this talk, we will present and discuss our latest results and the TRSB in this material.



[1] This work: arXiv:2208.08036
[2] T. Neupert et al., Nature Phys. 18, 137 (2022).
[3] H. Li et al., Phys. Rev. B 105, 045102 (2022).
[4] D. Saykin et al., arXiv:2209.10570 (2022).
[5] J. Xia et al., Phys. Rev. Lett. 97, 167002 (2006).
*This work is supported by JSPS core-to-core program (No. JPJSCCA20170002). We acknowledge J. Xia, J. Wang and C. Farhang in Univ. of California Irvine for the instrumentation support.

NMR measurements on Sr_2RuO_4 near upper critical field

K. Ishida[1], K. Kinjo[1], M. Manago[1†], S. Kitagawa[1], Z. Q. Mao[2],
S. Yonezawa[1], and Y. Maeno[1‡]

[1] *Department of Physics, Kyoto University, Kyoto, Japan*
[2] *Department of Physics, Pennsylvania State University, PA, USA*
[†] *Present address: Department of Physics and Material Science, Shimane University, Shimane, Japan*
[‡] *Present address: Toyota Riken-Kyoto University Research Center (TRiKUC), Kyoto, Japan*

Since the discovery of the superconductivity of Sr_2RuO_4 [1], its superconductivity has been attracted much attention. Because the normal-state electronic state is understood by the correlated fermi-liquid picture and its fermi surface is well-characterized [2], Sr_2RuO_4 was considered to be one of the best platforms to study unconventional superconductivity. However, the superconducting state of Sr_2RuO_4 still remains undetermined.
Recently, precise NMR measurements with the radio-frequency pulse energy small enough to avoid overheating showed a clear decrease in the NMR Knight shift [3]. This indicates that the chiral spin-triplet scenario, which has been considered a promising candidate for a long time, is ruled out. The full determination of the SC state of Sr_2RuO_4 is entering a new stage.
The observation of the first-order superconducting-normal phase transition below 0.7 K indicates that Pauli departing effect is dominant in Sr_2RuO_4[4]. In addition, recent field-angle dependent specific-heat measurements [5] suggested that some anomalies exist in the high-field superconducting region. In order to clarify the anomalies in the low-temperature high-filed superconducting region of Sr_2RuO_4, we performed ^{17}O-NMR measurement under in-plane magnetic fields. Sr_2RuO_4 has two crystallographically non-equivalent oxygen sites, i.e. RuO_2-plane site and apical O site. We focused on the NMR measurements at the apical O site. We observed anomalous splitting NMR spectrum in the superconducting phase above 1.2 T, where the suppression of four-fold oscillation was reported in the field-angle-dependent specific-heat measurement.
In this presentation, I will show the experimental results of the present NMR measurements and suggest the occurrence of the Fulde-Ferrell-Larkin-Ovchinnikov state near the upper critical field [6], together with the review of our NMR results so far.

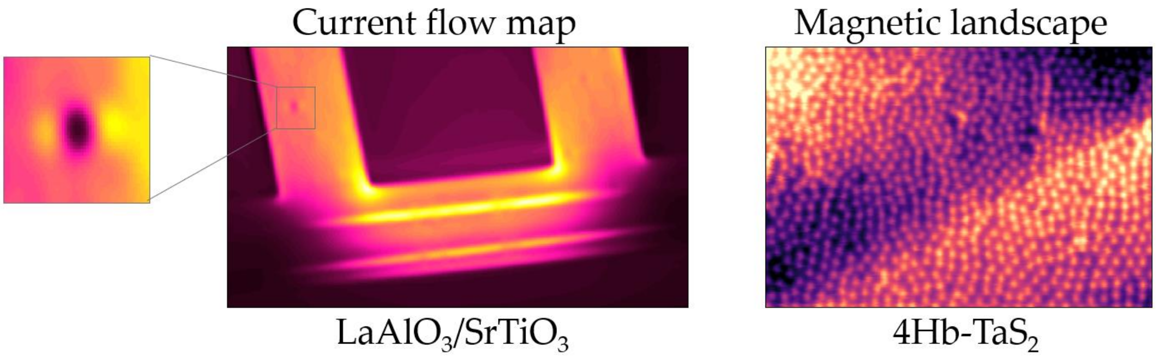
[1] Y. Maeno et al., Nature 372, 532-534 (1994).
[2] A. P. Machkenzie and Y. Maeno, Rev. Mod. Phys. 75, 657 (2003).
[3] A. Pustogow et al., Nature 574, 72-75 (2019).
[4] S. Yonezawa et al., Phys. Rev. Lett. 110, 077003 (2013).
[5] S. Kittaka et al., J. Phys. Soc. Jpn. 87, 093703 (2018).
[6] K. Kinjo et al., Science 376, 397- 400 (2022).

Imaging quantum materials with scanning SQUID microscopy

Beena Kalisky

Department of Physics and BINA Institute of Nanotechnology and Advanced Materials, Bar-Ilan University

Competition or cooperation between different electronic orders with similar energy scales often gives rise to new or unexpected behaviors. Detecting traces of such orders requires versatile probes, which can probe different aspects of the system, such as conductivity, superconductivity and magnetism. In my talk, I will describe two systems where our local view uncovered surprising mesoscopic effects. In the oxide interface $LaAlO_3/SrTiO_3$, we imaged the current flow close to a metal-insulator transition. We found that the critical behavior is controlled by structural domain patterns in the substrate, rather than by universal scaling laws. In the transition metal dichalcogenide 4Hb-TaS_2 we show that the superconducting state hosts a spontaneous vortex phase, where vortices appear in the absence of an external field. I will show evidence that this spontaneous vortex phase is caused by unconventional magnetism in the normal state.



Point contact spectroscopy of nodal line semimetal $CaAg_{0.9}Pd_{0.1}P$

Naoki Matsubara, Shota Nagasaka, Rikizo Yano, Kazushige Saigusa, Yusaku Shinoda, Yoshihiko Okamoto, Koshi Takenaka, and Satoshi Kashiwaya

Department of Applied Physics, Nagoya University, Nagoya 464-8603, Japan.

Recently, there has been a great interest in the electronic states of topologically nontrivial semimetals in which zero-gap states appear at specific points in momentum space. Nodal line semimetals are peculiar in that the zero-gap states appear along a ring. CaAgP is one of the promising candidates for nodal line semimetals [1]. Unlike other candidates, the Dirac ring of CaAgP appears solely near the Fermi level, which makes CaAgP the ideal platform to study the electronic states of the nodal line semimetal. In addition to the unique bulk states, the topologically protected surface states emerge as drumhead-like dispersion inside the Dirac ring [2]. The presence of surface states has been identified by the emergence of high-mobility electron carriers. Moreover, the onset of superconductivity with Tc of 1.7-1.8 K has been detected by Pd-doping ($CaAg_{0.9}Pd_{0.1}P$) [3].
Here we focus on the superconductivity of $CaAg_{0.9}Pd_{0.1}P$. Since our previous study has revealed the correlation between the surface carrier density and T_c [4], we expect that the flat dispersive surface carrier with high carrier density originates the superconductivity. Observing the superconducting gap by point contact spectroscopy of normal-insulator-superconductor junctions can provide direct evidence of the surface superconductivity and unconventional pairing states [5]. The normal contact was formed by a silver paste, and the measurements were performed by a usual three-terminal method. The temperature dependence of resistance shown indicates the onset of superconductivity at 1.8 K. The conductance spectra obtained below Tc showed dome-shaped peaks inside the superconducting gap similar to those observed on Sr_2RuO_4. This fact indicates the appearance of Andreev bound states at the surface, and thus the surface superconductivity of $CaAg_{0.9}Pd_{0.1}P$ is proved to have an unconventional pairing state [6]. Differently from the cases of Sr_2RuO_4, we detected asymmetry in the conductance spectra which symmetrically respond to the applied magnetic field. Since the origin of the asymmetry can be attributed to the chirality of the pair potential in $CaAg_{0.9}Pd_{0.1}P$, we conclude that $CaAg_{0.9}Pd_{0.1}P$ is a chiral superconductor.

[1] Y. Okamoto, et al., J. Phys. Soc. Jpn. 85, 0123701 (2016).
[2] A. Yamakage, et al., J. Phys. Soc. Jpn. 85, 013708 (2016).
[3] Y. Okamoto, et al., Physical Review B 102, 115101 (2020).
[4] R. Yano, et al., unpublished.
[5] S. Kashiwaya, et al., Physica E. 55, 25 (2014).
[6] R. Yano, et al. submitted.

Superconducting Ruddlesden-Popper Oxide Thin Films with Suppressed Extended Defects

Jinkwon Kim[1,2,3*], Junsik Mun[4], Youngdo Kim[2,3], Carla M. Palomares García[5], Lingfei Wang[2,3], Miyoung Kim[4], Changyoung Kim[2,3], Jason W. A. Robinson[5], Yoshiteru Maeno[6], Tae Won Noh[2,3], Darrell. G. Schlom[1,7,8]

[1]*Department of Material Science and Engineering, Cornell University, Ithaca, NY 14853, USA*
[2]*Center for Correlated Electron Systems, Institute for Basic Science (IBS), Seoul 08826, Korea*
[3]*Department of Physics and Astronomy, Seoul National University, Seoul 08826, Korea*
[4]*Department of Materials Science and Engineering and Research Institute of Advanced Materials, Seoul National University, Seoul 08826, Korea*
[5]*Department of Materials Science & Metallurgy, University of Cambridge, Cambridge CB3 0FS, United Kingdom*
[6]*Department of Physics, Kyoto University, Kyoto 606-8502, Japan*
[7]*Kavli Institute at Cornell for Nanoscale Science, Ithaca, New York 14853, USA*
[8]*Leibniz-Institut für Kristallzüchtung, Max-Born-Straße 2, 12489 Berlin, Germany*

Ruddlesden-Popper (RP) oxides ($A_{n+1}B_nO_{3n+1}$, n = 1, 2, ...) have attracted enormous attention for their potential for novel electronic and energy device applications, such as nonvolatile magnetic memories, tunable microwave antennas, energy harvesters, and quantum computers [1]. However, the practical utilization of A_2BO_4 thin films has been limited by extended defects, particularly out-of-phase boundaries (OPBs) [2]. Despite OPBs being ubiquitously observed in A_2BO_4 thin films, their suppression is still challenging due to the inhomogeneous interfaces.

In this study, we suppressed OPBs in RP oxide thin films by atomic-scale interface engineering. As model systems, the unconventional superconductor Sr_2RuO_4 (bulk T_c ~ 1.5 K) and $La_{2-x}Sr_xCuO_4$ (bulk T_c ~ 39 K) thin films were grown by pulsed laser deposition (PLD) and molecular beam epitaxy (MBE) [3,4]. Delicate analysis of the film-substrate interface was derived by scanning transmission electron microscopy (STEM). By controlling film-substrate interfaces, the OPBs were significantly suppressed for both thin films. Notably, these OPB-free Sr_2RuO_4 and $La_{2-x}Sr_xCuO_4$ thin films exhibited highly enhanced superconductivity compared with the film with huge OPB densities. Our defect engineering on A_2BO_4 thin film growth will provide valuable guidelines for eliminating various types of defects in other complex oxides and facilitate next-generation quantum devices.

[1] D. G. Schlom et al., J. Am. Ceram. Soc. 91, 2429 (2008).
[2] M. A. Zurbuchen et al., J. Mater. Res. 22, 1439 (2007).
[3] J. Kim et al., Nano Lett. 21, 4185 (2021).
[4] J. Kim et al., under review.

Magnetic exchange through oxide superconductors

Sachio Komori

Department of Physics, Nagoya University, Japan

In ferromagnetic insulator/superconductor/ferromagnetic insulator (FI/S/FI) superconducting spin-valves, the superconducting transition temperature of S is controllable through the magnetization alignment of the two FI layers. Conversely, the magnetization alignment can be controlled by superconductivity due to an interplay between the magnetic exchange energy and the superconducting condensate, i.e., the superconducting condensation energy induces a modification of the magnetization alignment to minimize the magnetic exchange field that breaks Cooper pairs in S [1,2].
For the case of an s-wave (isotropic) S, magnetic exchange field decays in S over the length scale of the superconducting coherence length. However, in a d-wave (anisotropic) S, magnetic exchange field is found to be long-ranged, penetrating tens of coherence lengths due to the quasiparticle nodal states [2].
In this talk, I will present my postdoc works in Cambridge [2,3] and recent works in Nagoya on oxide S/FI interfaces demonstrating unconventional coupling between superconductivity and magnetism.

[1] Y. Zhu et al., Nature Mater. 16, 195 (2017).
[2] A. Di Bernardo et al., Nature Mater. 18, 1194 (2019).
[3] S. Komori et al., Phys. Rev. Lett., 121, 077003 (2018).

Steady Floquet–Andreev states in graphene Josephson junctions

Gil-Ho Lee

Department of Physics, Pohang University of Science and Technology, Pohang, Republic of Korea

Engineering quantum states through light-matter interaction has created a new paradigm in condensed matter physics. A representative example is the Floquet-Bloch state, which is generated by time-periodically driving the Bloch wavefunctions in crystals. Previous attempts to realise such states in condensed matter systems have been limited by the transient nature of the Floquet states produced by optical pulses, which masks the universal properties of non-equilibrium physics. Here, we report the generation of steady Floquet Andreev (F-A) states in graphene Josephson junctions by continuous microwave application and direct measurement of their spectra by superconducting tunnelling spectroscopy [1]. We present quantitative analysis of the spectral characteristics of the F-A states while varying the phase difference of superconductors, temperature, microwave frequency and power. The oscillations of the F-A state spectrum with phase difference agreed with our theoretical calculations. Moreover, we confirmed the steady nature of the F-A states by establishing a sum rule of tunnelling conductance, and analysed the spectral density of Floquet states depending on Floquet interaction strength. This study provides a basis for understanding and engineering non-equilibrium quantum states in nano-devices.

[1] S. Park et al., Nature 603, 421–426 (2022).

Still puzzling: unconventional superconductivity of Sr_2RuO_4

Yoshiteru Maeno

Toyota Riken – Kyoto U. Research Center (TRiKUC), Kyoto Univ., Kyoto 606-8501, Japan

Sr_2RuO_4 exhibits unconventional superconductivity of an archetypal strongly correlated electron system [1]. Concerning its superconducting symmetry, it had long been considered that the spin-triplet, odd-parity *p*-wave superconducting state, which breaks the time-reversal symmetry, was promising, albeit with some controversial results [2].

In 2019, however, a new development overturned some past experimental results, and spin-singlet-like behavior has become conclusive [3]. Furthermore, the development of uniaxial strain-applying devices has stimulated research to explore changes in superconductivity by controlling the symmetry and dimensionality of the Fermi surface [4]. However, there are still unnatural aspects in the currently favored interpretation of spin-singlet chiral *d*-wave superconductivity, and the focus is on solving this puzzle.

Unlike many other unconventional superconductors, the normal state of Sr_2RuO_4 is a typical Fermi liquid. Nevertheless, to elucidate its superconducting state, it seems essential to go beyond the framework of traditional unconventional superconductivity and incorporate the features of pairing in multi-orbital systems [5]. In this talk, I will summarize the key recent facts and unresolved issues to guide the audience to the four talks that follow.

1. Y. Maeno, H. Hashimoto, K. Yoshida, S. Nishizaki, T. Fujta, J.G.Bednorz, and F. Lichtenberg, Nature 372, 532 (1994). "Superconductivity in a layered perovskite without copper".
2. A.P. Mackenzie, T. Scaffidi, C.W. Hicks, Y. Maeno, npj Quantum Materials 2, 40-1-9 (2017). "Even odder after twenty-three years: the superconducting order parameter puzzle of Sr_2RuO_4".
3. A. Pustogow, Yongkang Luo, A. Chronister, Y.-S. Su, D. A. Sokolov F. Jerzembeck, A. P. Mackenzie, C. W. Hicks, N. Kikugawa, S. Raghu, E. D. Bauer, S. E. Brown, Nature 574, 72 (2019). "Constraints on the superconducting order parameter in Sr_2RuO_4 from oxygen-17 nuclear magnetic resonance".
4. V. Grinenko, S. Ghosh., R. Sarkar, J-P Orain, A. Nikitin, M. Elender, D. Das, Z. Guguchia, F. Brückner, M.E. Barber, J. Park, N. Kikugawa, D.A. Sokolov, J.S. Bobowski, T. Miyoshi, Y. Maeno, A.P. Mackenzie, H. Luetkens, C.W. Hicks, H-H. Klauss, Nature Physics 17, 748 (2021). "Split superconducting and time-reversal symmetry-breaking transitions in Sr_2RuO_4 under stress".
5. H.G Suh, H. Menke, P.M.R. Brydon, C. Timm, A. Ramires, and D.F. Agterberg, Phys. Rev. Res. 2, 032023(R) (2020). "Stabilizing even-parity chiral superconductivity in Sr_2RuO_4".

Infinite magnetoresistance in superconducting spin switch with spin-orbit coupling

Hisakazu Matsuki[1]*, Guang Yang[1,2], Greg Mazur[1], Nadia Stelmashenko[1], Lesley Cohen[3] and Jason W. A. Robinson[1]*

[1]*Department of Materials Science & Metallurgy, University of Cambridge, 27 Charles Babbage Road, Cambridge, CB3 0FS, UK*
[2]*School of Integrated Circuit Science and Engineering, Beihang University, Beijing, 100191, China*
[3]*The Blackett Laboratory, Imperial College London, London SW7 2AZ, England, UK*

At a thin-film superconductor (S) interface with a ferromagnetic insulator (FI), the magnetic exchange field of the FI can spin-split the superconducting density of states [1-3] and suppress the superconducting critical temperature (T_c) [4]. In a FI/S/FI superconducting spin switch, the suppression of T_c is reduced for an antiparallel (AP) configuration between the two FI layer magnetisations due to a net cancellation effect of the magnetic exchange fields acting on the S layer. Conversely, for parallel (P) magnetisations, the exchange fields add enhancing the suppression of T_c i.e., $\Delta T_c = T_c$ (AP) – T_c (P) > 0. For S materials with weak spin-orbit coupling (SOC) such as Al the spin splitting in S can exceed several Tesla [2,3] and ΔT_c can reach tens of mK [4]. It has also been shown that by dusting an atomic layer of Au at the Al/EuS interface, it is possible to quench the spin splitting in Al due to SOC in Au [5]. Here we report EuS/Nb/EuS superconducting spin switches in which the superconducting layer of Nb has strong SOC and a T_c down to a thickness of only 2 nm. By optimising the Nb/EuS interface we obtain record-breaking values of ΔT_c that exceed 1.5 K with a $\Delta T_c/T_c$ (P) ratio of nearly 100%. The results indicate physics that goes beyond the standard quasiclassical picture of S/FI proximity effects in which superconducting spin-switch performance is boosted by the large values of T_c in the nearly nm-thick layer of Nb in conjunction with strong SOC.

[1] P. Fulde, Adv. in Phys. 22, 667 (1973).
[2] X. Hao, J. S. Moodera, R. Meservey, Phys. Rev. Lett. 67, 1342 (1991).
[3] E. Strambini et al., Phys. Rev. Mat. 1, 054402 (2017).
[4] B. Li et al. Phys. Rev. Lett. 110, 097001 (2013).
[5] P. Wei et al., Phys. Rev. Lett. 122, 247002 (2019).

Orbitronics effects in spin-singlet superconductors

Maria Teresa Mercaldo*

Dipartimento di Fisica, Università di Salerno, ITALY

We consider a multi-orbital spin-singlet superconductor without inversion symmetry, e.g. due to crystalline asymmetry as well as to electric fields or mechanical strain. The lack of inversion symmetry yields non-trivial orbital-Rashba couplings in the system that affects the electronic orbital texture at the surface leading to a dramatic impact on the superconductivity. We demonstrate that, by varying the strength of the orbital-Rashba couplings, the superconducting phase can be either suppressed, or undergo a $0-\pi$ transition, with the π-phase being marked by non-trivial sign change of the superconducting order parameter between different bands [1-2]. The occurrence of orbital dependent phase frustration can naturally account for the observation of the suppression of the critical supercurrent without change in the critical temperature, observed in recent experiments [3-4].
Furthermore, in superconductors that lack inversion symmetry, the flow of supercurrent can induce a non-vanishing magnetization, a phenomenon also known as Edelstein effect. We find that the supercurrent-induced orbital magnetization is more than one order of magnitude greater than that due to the spin, and it is shown to be also sign tunable [5].
Exploring further the role of spatial symmetry breaking, we show that in two-dimensional spin-singlet superconductors with low degree of spatial-symmetry content, a vortex state at zero magnetic field can be energetically stable [6]. This vortex is marked by neutral supercurrents flowing around the core with counterpropagating Cooper pairs with opposite orbital moments.
The overall findings unveil a rich scenario to design heterostructures with superconducting orbitronics effects for the achievement, for instance, of all-electric superconducting devices.

This work is supported by the EU's Horizon 2020 research and innovation program under Grant Agreement nr. 964398 (SUPERGATE).

[1] M. T. Mercaldo, P. Solinas, F. Giazotto, and M. Cuoco, Phys. Rev. Applied 14, 034041 (2020).
[2] M. T. Mercaldo, F. Giazotto, and M. Cuoco, Phys. Rev. Research 3, 043042 (2021).
[3] G. De Simoni, et al., Nat. Nanotechnol. 13, 802 (2018).
[4] L. Bours, M. T. Mercaldo, M. Cuoco, E. Strambini, and F. Giazotto, Phys. Rev. Research 2, 033353 (2020).
[5] L. Chirolli, M.T. Mercaldo, C. Guarcello, F. Giazotto, and M. Cuoco, Phys. Rev. Lett. 128, 217703 (2022).
[6] M. T. Mercaldo, C. Ortix, F. Giazotto, and M. Cuoco, Phys. Rev. B 105, L140507 (2022).

Raising the T_c of *p*-wave superconductors through magnetic coupling with a conventional superconductor

Linde Olde Olthof*, Lina Johnsen, Jason Robinson, Jacob Linder

Department of Materials Science & Metallurgy, University of Cambridge
Center for Quantum Spintronics, Norwegian University of Science and Technology
* labo2@cam.ac.uk

Unconventional superconductors are of high interest due to their rich physics, for example, *p*-wave superconductivity associated with topological edge states. A practical obstacle in studying such systems is the very low critical temperature T_c that is required to realize a *p*-wave superconducting phase in a material. In this talk,

1. I will predict theoretically that the T_c of an intrinsic p-wave superconductor can be significantly enhanced by coupling to a conventional s-wave or d-wave superconductor with a higher critical temperature via an atomically thin ferromagnetic layer.
2. I will show that this T_c boost is tunable via the direction of the magnetization in the ferromagnet.
3. I will show that the enhancement in T_c can also be achieved using the Zeeman effect of an external magnetic field, although this has its own issues.

Superconducting Diode Effect in Rashba Superlattice

Hideki Narita[1], Ryo Kawarazaki[1], Yuta Miyasaka[1], Yuhei Ikeda[2], Ryusuke Hisatomi[1], Akito Daido[2], Yoichi Shiota[1], Takahiro Moriyama[1], Youichi Yanase[2,3], Alexey V. Ognev[5], Alexander S. Samardak[5], and Teruo Ono[1,4,5]*

[1]*Institute for Chemical Research, Kyoto University, Gokasho, Uji, Kyoto, 611-0011, Japan*
[2]*Department of Physics, Graduate School of Science, Kyoto University, Kitashirakawa, Sakyo, Kyoto 606-8502, Japan*
[3]*Institute for Molecular Science, Okazaki,444-8585, Japan*
[4]*Center for Spintronics Research Network, Institute for Chemical Research, Kyoto University, Gokasho, Uji, Kyoto, 611-0011, Japan*
[5]*Laboratory of Spin-Orbitronics, Institute of High Technologies and Advanced Materials, Far Eastern Federal University, Vladivostok 690922, Russia*
* E-mail: ono@scl.kyoto-u.ac.jp

The diode effect is fundamental to electronic devices and is widely used in rectifiers and AC-DC converters. However, conventional diodes have an energy loss due to finite resistance. We found the superconducting diode effect (SDE) in Nb/V/Ta superlattices with a polar structure, which is the ultimate diode effect exhibiting a superconducting state in one direction and a normal state in the other [1-3]. SDE can be considered as the nonreciprocity of the critical current for the metal-superconductor transition. We also found the reverse effect, i.e., the nonreciprocal critical magnetic field under the application of the supercurrent [4]. We also found that the polarity of the superconducting diode shows a sign reversal as a magnetic field is increased, which can be considered as the crossover and phase transitions of the finite-momentum pairing states predicted theoretically [5]. SDE in Nb/V/Ta superlattices needs an application of an external magnetic field to break the time reversal symmetry, which is a disadvantage in applications. We recently succeeded in demonstrating SDE in a zero-field by introducing ferromagnetic layers in superlattices [6]. The polarity of the SDE is controlled by the magnetization direction of the ferromagnetic layer, leading to development of novel non-volatile memories and logic circuits with ultralow power consumption.

This work was partly supported by JSPS KAKENHI Grant Numbers (18H04225, 18H01178, 18H05227, 20H05665, 20H05159, 21K18145), the Cooperative Research Project Program of the Research Institute of Electrical Communication, Tohoku University, the Collaborative Research Program of the Institute for Chemical Research, Kyoto University, and the Russian Ministry of Science and Higher Education under Megagrant No. 075-15-2021-607.

[1] F. Ando et al., J. Magn. Soc. Japan 43, 17 (2019).
[2] F. Ando et al., Nature 584, 373 (2020).
[3] F. Ando et al., Jpn. J. Appl. Phys. 60, 060902 (2021).
[4] Y. Miyasaka et al., Appl. Phys. Express 14, 073003 (2021).
[5] A. Daido et al., Phys. Rev. Lett. 128, 037001 (2022).
[6] H. Narita et al., Nat. Nanotechnol. 17, 823 (2022).

Deconstructing Sr_2RuO_4: Insights from a microscopic perspective

Aline Ramires

Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland

The nature of the superconducting order parameter in Sr_2RuO_4 has been topic of active debate since recent spin-susceptibility measurements revealed that it should be a spin-singlet state [1]. Together with the evidence for broken time-reversal symmetry [2,3] and a jump in the shear modulus c66 at the superconducting transition temperature [4,5], the available experiments point towards an even-parity chiral superconductor with Eg symmetry. This state has consistently been dismissed based on the quasi-two-dimensional electronic structure of this material. In this talk, I discuss how the orbital degree of freedom can encode the two-component nature of the Eg order parameter, allowing for a local orbital-antisymmetric spin-triplet state that can be stabilized by on-site Hund's coupling [6]. In addition, I will highlight recent strain and pressure experiments and show how this specific order parameter seems to naturally reconcile the surprising behaviour of the evolution of the critical temperature under strain along different directions. In particular, we can semi-quantitatively account for the asymmetric splitting of the critical temperatures for compressive strain along the 100 direction, and the reduction of the critical temperatures for compressive strain along the 001 and 110 directions with a single free parameter [7].

*This work was supported by the Swiss National Science Foundation (Grant No. 186043).

[1] A. Pustogow et al., Nature 574, 72 (2019).
[2] J. Xia et al., Phys. Rev. Lett. 97, 167002 (2006).
[3] V. Grinenko et al., Nature Physics 17, 748 (2021).
[4] S. Benhabib et al., Nature Physics 17, 194 (2021).
[5] S. Ghosh et al., Nature Physics 17, 199 (2021).
[6] H. G. Suh et al., Phys. Rev. Research 2, 032023 (2020).
[7] S. Beck et al., arXiv:2111.13506 (2021).

Bulk-boundary correspondence in point-gap topological phases

Masatoshi Sato

Center for Gravitational Physics and Quantum Information,
Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8582m Japan

A striking feature of non-Hermitian systems is the presence of two different types of topologies. One generalizes Hermitian topological phases, and the other is intrinsic to non-Hermitian systems, which are called line-gap topology and point-gap topology, respectively. Whereas the bulk-boundary correspondence is a fundamental principle in the former topology, its role in the latter has not been clear yet. In this talk, I discuss the bulk-boundary correspondence in the point-gap topology in non-Hermitian systems. After revealing the requirement for point gap topology in the open boundary conditions, we clarify that the bulk point-gap topology in open boundary conditions can be different from that in periodic boundary conditions. We give a complete classification of the open boundary point-gap topology with symmetry and show that the non-trivial open boundary topology results in robust and exotic surface states [1].

[1] D. Nakamura, T. Bessho, M. Sato, arXiv:2205.1563

Gate control of the critical current of superconducting nanowires

Jennifer Koch, Leon Ruf, Roman Hartmann, Elke. Scheer, Angelo Di Bernardo

University of Konstanz, Konstanz, Germany

Gate-controlled superconducting devices have become of great interest for the development of energy-efficient hybrid superconductor/semiconductor computing architectures. The idea behind this technology stems from the recent discovery that the supercurrent in nanowires can be controlled electrically with the application of a gate voltage down to a complete suppression of the supercurrent, hence the observation that the superconducting state can be switched off by an electrostatic gate voltage [1]. While the phenomenology has been confirmed by different researchers in various device realizations and for many different superconductors [2-11] and also the opposite effect, namely an enhancement of the supercurrent by the action of a gate has been stated [12], the physical mechanism behind is under debate. The discussion is based on the observation of leakage currents between the gate electrode and the current-carrying device.

The so far suggested mechanisms include a direct field effect [1-4], leakage-current-induced phase and charge fluctuations [5-7,13] and direct [8] or phonon-mediated [9] heating to field emission [8,10,11,14].

In this talk I will first review the current experimental observations and the suggested possible mechanisms before discussing our novel observations on nanowires of Nb and $Nb_{0.18}Re_{0.82}$. The findings point at an important role of the disorder and the sample preparation route for the performance of the device.

[1] G. de Simoni et al., Nature Nanotechnol. 13, 802 (2018).
[2] F. Paolucci et al., Nano Lett. 18, 4195 (2018).
[3] F. Paolucci et al., Phys. Rev. Applied 11, 024061 (2019).
[4] P. Orus et al, Sci Rep. 11, 17698 (2021).
[5] T. Elalaily et al., Nano Lett. 21, 9684 (2021).
[6] J. Basset et al., Phys. Rev. Research 3, 043169 (2021).
[7] D. Haxell et al., arXiv:2204.05619v1
[8] M. F. Ritter et al., Nature Commun. 12, 1266 (2021).
[9] M. F. Ritter et al, Nature Electronics 5, 71 (2022).
[10] H. D. Alegria et al, Nature Nanotechnol. 16, 404 (2021).
[11] I. Golokolenov et al., Nat. Commun. 12, 2747 (2021).
[12] M. Rocci et al., Nano Lett 21, 216 (2021).
[13] A. Amoretti et al., arXiv:2202.00687v1.
[14] C. Catto et al., arXiv:2105.08322v2.

Tuning Spin Current Injection at Ferromagnet-Nonmagnet Interfaces by Molecular Design

Angela Wittmann ,[1,2] Guillaume Schweicher ,[2,3] Katharina Broch,[4] Jiri Novak,[5] Vincent Lami,[6] David Cornil,[7] Erik R. McNellis,[1] Olga Zadvorna,[2] Deepak Venkateshvaran,[2] Kazuo Takimiya,[8] Yves H. Geerts,[3] Jérôme Cornil,[7] Yana Vaynzof,[6] Jairo Sinova,[1] Shun Watanabe,[9] and Henning Sirringhaus[2]

[1]*Johannes Gutenberg-Universität, Germany*
[2]*University of Cambridge, United Kingdom*
[3]*Université Libre de Bruxelles, Belgium*
[4]*Universität Tübingen, Germany*
[5]*Masaryk University, Brno, Czech Republic*
[6]*Heidelberg University, Germany*
[7]*University of Mons, Belgium*
[8]*RIKEN Center for Emergent Matter Science, Wako, Japan*
[9]*The University of Tokyo, Japan*

Organic semiconductors have been found to have a comparably large spin diffusion time and length [1]. This makes them ideal candidates for spintronic devices.
Here we study the efficiency of spin injection at ferromagnetic resonance (FMR) from a ferromagnetic material into an adjacent non-magnetic material. The spin mixing conductance g_{eff} can be quantified by measuring the linewidth broadening of the FMR absorption of the ferromagnet due to an increase in Gilbert damping caused by spin injection into the adjacent non-magnetic material. We use this technique to systematically study spin injection from a metallic ferromagnet permalloy, $Ni_{80}Fe_{20}$, into dinaphtho[2,3-b:2′,3′-f]thieno[3,2-b]thiophene (DNTT), one of the best performing small molecule organic semiconductors to date. We show that both, spin injection efficiency at the interface as well as the spin diffusion length can be tuned sensitively by the interfacial molecular structure and side chain substitution of the molecule [2] (see Fig.1). The vast possibilities of molecular design for small molecules combined with the tunability of the spin mixing conductance open the possibility of synthesizing tailor-made molecular materials with well-controlled spin injection properties.

[1] I. Bergenti et al., Phil. Trans. R. Soc. A 369, 3054 (2011).
[2] A. Wittmann et al., Phys. Rev. Lett. 124, 027204 (2020).

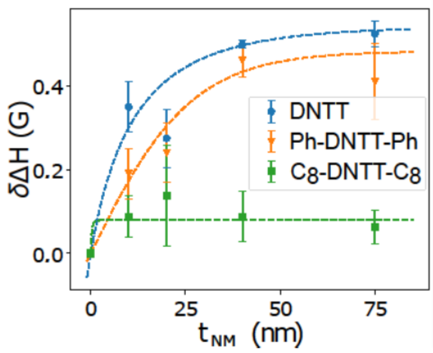


Figure 1 Linewidth broadening as a function of organic layer thickness for three derivatives of DNTT

Emergent nematicity and electronic scattering processes in metallic kagome superconductors

Dirk Wulferding[1*], Seungyeol Lee[2], Youngsu Choi[2], Soohyun Cho[3], Qiangwei Yin[4], Zhijun Tu[4], Chuncheng Gong[4], Hechang Lei[4], Saqlain Yousuf[2], Jaegu Song[2], Hanoh Lee[2], Tuson Park[2], and Kwang-Yong Choi[2]

[1]*IBS-Center for Correlated Electron Systems, Seoul National University, Korea*
[2]*Department of Physics, SKKU Suwon, Korea*
[3]*Shanghai Institute of Microsystem and Information Technology, Shanghai, China*
[4]*Department of Physics, Renmin University Beijing, China*

Recently, metallic systems with flat electronic bands and Dirac points have gathered immense attention, as they are prone to numerous exotic and topological electronic phases and related instabilities. Particularly, the discovery of superconductivity in the layered metallic kagome compounds AV_3Sb_5 (A=Cs,K,Rb) has ignited a massive research effort to elucidate the nature and the pairing mechanism of this potential topological superconductor [1,2]. Of special relevance may be a neighboring charge-density-wave phase – yet, its true role in establishing superconductivity in AV_3Sb_5 remains unresolved until now.
We present a detailed temperature and polarization resolved Raman scattering study on CsV_3Sb_5 single crystals [3]. Our highly resolved angular dependence study sheds a light on the symmetry of CDW-related excitations and of selected phonons, which allude to an emergent $C2$ symmetry breaking that becomes more pronounced upon approaching T_c. This symmetry-breaking together with phonon anomalies at T_{CDW} signify a nematic phase through a concerted interplay of electronic correlations and electron-phonon coupling within the exotic CDW phase. We also uncover an intrinsic electronic scattering contribution with a distinct temperature dependence, that is different from defect- and impurity-promoted scattering events.

[1] B. R. Ortiz et al., Phys. Rev. Materials 3, 094407 (2019).
[2] B. R. Ortiz et al., Phys. Rev. Lett. 125, 247002 (2020).
[3] D. Wulferding et al., Phys. Rev. Research 4, 023215 (2022).

Topological property of interorbital pairing in multi-orbital superconductors

Fukaya Yuri[1], Paola Gentile[1], Mario Cuoco[1], Satoshi Ando[2], Yuya Hiramatsu[2], Satoshi Ikegaya[2], Shun Tamura[2], Yukio Tanaka[2] and Keiji Yada[2*]

[1]*CNR-SPIN, c/o Universit ́a di Salerno, Italy*
*[*2]Department of Applied Physics, Nagoya University, Japan*

Topological phase of matter is now a central issue in condensed matter physics since its theoretical proposal and experimental discoveries of many candidate materials. Among them, topological superconductivity (TSC) has attracted much attention in the context of its application to quantum computation. In its early works, simple model is used to understand the basic properties of TSC. While on the other hand, the various degrees of freedom of the system such as sublattice or orbital degree of freedom may give rise to new functionality of TSC.

Here, we study the topological properties of multi-orbital superconductors with perovskite structure such as two-dimensional interface of $LaAlO_3/SrTiO_3$ and Sr_2RuO_4. In these materials, t_{2g}-orbitals of 3*d*/4*d*-electron system is dominant in its low-energy excitations. Then, interorbital pairing is formed when the interorbital interaction is responsible for the pairing interaction.

In the case of two-dimensional interface of $LaAlO_3/SrTiO_3$, A_1 or B_1 pairing is stable under the interorbital interactions depending on the chemical potential and the ratio of the interorbital interactions [1]. When the interorbital B_1 pairing is realized, topological nodes protected by the one-dimensional winding number appears. Then, the Majorana flat band emerges in the (110) edge. Furthermore, higher harmonics becomes dominant in the current-phase relationship of the Josephson junction of B_1 pairing state. This is because of the nontrivial *d*-vector texture in the band basis of this pairing.

As for Sr_2RuO_4, interorbital E_g pairing has been proposed for the new candidate [2]. In this pairing, line-node-like Bogoliubov Fermi surfaces appear in the gap structure even though the pairing is onsite. Due to this "line nodes", nearly-zero-energy surface state appears on the (001) surface. However, because of the pseudo Zeeman field, which is the origin of the Bogoliubov Fermi surface, the surface states are not true zero energy states and have splitting energy. Nevertheless, the calculated surface density of states has pronounced zero-energy peak since the magnitude of this pseudo Zeeman field is much smaller than that of the bulk energy gap. While the nearly-zero-energy surface states on the (001) surface is not topologically protected, the surface states on (100) surface is protected by two-dimensional Chern number. Even in the same E_g irreducible representation, the Chern number depends on the basis function. When the *d*-vector is along the *z*-direction in spin-orbital basis, the topological nodal point with monopole charges exist. Then, the topological phase transition occurs in k_z space.

[1] Y. Fukaya et al., Phys. Rev. B 97, 174522 (2018).
[2] H. G. Suh et al., Phys. Rev. Research 2, 032023(R) (2020).

POSTERS

Surface State of Inter-Orbital Pairing State in Sr_2RuO_4 Superconductor

S. Ando, S. Ikegaya, S. Tamura, K. Yada, Y. Tanaka

Department of Applied Physics, Nagoya University

The symmetry of the superconducting pair potential in Sr2RuO4 is an important and unclear problem in the condensed matter Physics. Conventionally, the symmetry of the pair potential had been predicted to be the chiral p-wave (px+ipy) from early polarized neutron scattering [1], NMR [2], and muon-spin resonance measurement [3]. However, recent NMR [4] nd polarized neutron scattering measurements [5] revealed that the spin susceptibility for the in-plane field is suppressed largely under the superconducting state. This fact seems to be inconsistent with the behavior of the px+ipy superconducting state.
To solve this problem, an Eg symmetry spin-triplet/orbital-singlet/s-wave pair potential, where the Cooper pair consists of two electrons in the different orbitals is proposed, theoretically, [6] as one of the possibility.

In this study, we confirm that this pair potential is transformed into a chiral d-wave pair potential and a pseudo-Zeeman field in the band basis for a low-energy range. Because of the chiral d-wave pair potential, the surface states appear near zero energy in the momentum range enclosed by the nodal lines of the chiral d-wave pair potential for each band at the (001) surface [7]. Nevertheless, the pseudo-Zeeman field gives band splitting of the surface states, and its splitting energy is much smaller than the SC energy gap. The local density of states at the (001) surface of the SC state has a pronounced peak structure at zero energy because of the surface states near zero energy when the order of the resolution is lower than the splitting energy [8].

[1] J. A. Duffy, et al., Phys. Rev. Lett. 85, 5412 (2000).
[2] K. Ishida, et al., Nature 396, 658 (1998).
[3] G. M. Luke, et al., Nature 394, 558 (1998).
[4] A.N. Petsch, et al., Phys. Rev. Let. 125, 217004 (2020).
[5] A. Pustogow, et al., Nature 574, 72 (2019).
[6] H. G. Suh, et al., Phys. Rev. Res. 2, 032023 (2020).
[7] S. Kobayashi et al., Phys. Rev. B 92, 214514 (2015).

[8] S. Ando et al., arXiv:2210.02136

A_2B_3 quintuple layer crystals grown by optical floating zone technique

Raja Arumugam[1], Anita Guarino[1], Geetha Balakrishnan[2], Rosalba Fittipaldi[1], Antonio Vecchione[1]

[1]CNR-SPIN c/o University of Salerno, I-84084, Fisciano, Salerno, Italy
[2]Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom

In recent years, binary chalcogenide A_2B_3 (A=Bi, Sb; B=Se, Te) materials with quintuple layered structure become a hot topic for the scientific community, due to their excellent topological properties. The development of a sample growth method to obtain materials with on-demand band gap, involving the use of Bi_2Se_3, Bi_2Te_3 and Sb_2Te_3 compounds, is of utmost importance allowing to selectively excite electrons from the bulk valence band or from a surface Dirac band. In this framework, from the parent Bi_2Se_3 samples with Sb/Te substitution can be grown to tune the bandgap in the 200-300 meV range and to pin the Fermi level from the midgap down inside the trivial bulk valence band. Proper concentrations of Se and Sb have been substituted in the Te and Bi sites, respectively. $Bi_2Te_{3-x}Se_x$ and $Bi_xSb_{2-x}Te_3$ topological insulator single crystals were grown using optical floating zone technique in our lab. The grown crystals are shown in figure 1. These types of crystal are crystallized in a rhombohedral crystal system with R-3m space group, as assessed by X-ray diffraction. The composition and microstructure of the grown crystals were determined, with a scanning electron microscope, through energy dispersive spectroscopy (EDX) and electron back scattered diffraction (EBSD) analysis.

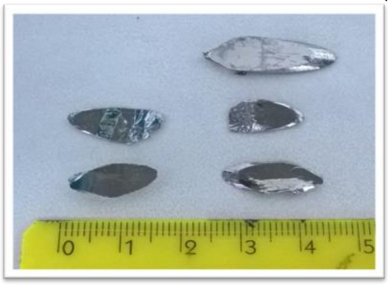


Fig: $Bi_2Te_{3-x}Se_x$ and $Bi_xSb_{2-x}Te_3$ crystals

[1] X. Tang et al., A comprehensive review on Bi_2Te_3-based thin films: Thermoelectrics and beyond, Interdisciplinary, 1, 88-115, (2022).
[2] Dong-xia qu et al., Quantum oscillations and Hall anomaly of surface states in the topological insulator Bi_2Te_3, Science, 329, 821-824, (2010).

Growth and characterization of Pr-doped Ca_2RuO_4 single crystals

M. Cannavacciuolo[1], Mariateresa Lettieri[2], Rosalba Fittipaldi[2], Alfonso Romano[1] and Antonio Vecchione[2]

[1]*Dipartimento di Fisica "E.R. Caianiello", Università degli Studi di Salerno, Via Giovanni Paolo II, I-84084 Fisciano – Salerno (Italy)*
[2]*CNR-SPIN, Via Giovanni Paolo II, 84084 Fisciano – Salerno (Italy)*

In the last few decades there has been a growing interest in studying Mott insulators due to their ability to host novel quantum phenomena when external conditions are suitably varied. In this context, the antiferromagnetic Mott insulator Ca_2RuO_4 has recently received considerable attention due to the metal-insulator transition (MIT) induced by variations of pressure, electric field or by elemental substitutions. It has been found, for example, that praseodymium doping tends to suppress the MIT, with T_{MI} going down to about 85 K for $Ca_{(2-x)}Pr_xRuO_4$ with x = 0.07 [1].
In the present study, we focused on the synthesis of Pr-doped Ca_2RuO_4 single crystals to tune T_{MI} at about room temperature, and in particular $Ca_{(2-x)}Pr_xRuO_4$ crystals with x = 0.04 were realized. Such single crystals were successfully synthesized by floating zone technique with an excess of Ru in the starting material. Furthermore, X-ray diffraction and scanning electron microscopy (SEM) with Energy Dispersive Spectroscopy (EDS) allowed to infer the presence of Ru metal inclusions for a 30% excess of Ru in the starting mixture. The morphological and structural studies revealed the formation of a well aligned lamellar pattern of Ru inclusions. The lamellae are lined up along a certain direction and the separation between adjacent ones is of about 10 µm. Energy dispersive spectroscopy analysis demonstrates that the darker parts correspond to stoichiometric $Ca_{1.96}Pr_{0.04}RuO_4$ crystal, while the brighter ones are domains rich in Ru. In addition, X-ray diffraction pattern of cleaved $Ca_{1.96}Pr_{0.04}RuO_4$ crystals showed the (00l) Bragg reflections of doped Ca_2RuO_4 phase, and only the (100) reflection of the Ru phase.
As reported in the literature, the presence of Ru inclusions in ruthenate single crystals can play a role in tuning the physical properties of such materials [2,3]. Therefore, further investigations are in progress to assess the electric and magnetic properties of $Ca_{(2-x)}Pr_xRuO_4$ crystals with Ru inclusions.

[1] S. Riccò et al., Nature Communications 9, 4535 (2010).
[2] Y. Maeno et al., Physical Review Letters 81, 3765–3768 (1998).
[3] V. Granata et al., Journal of Alloys and Compounds 832, 154890 (2020).

Exploration of the superconducting pairing symmetry in NbRe films

C. Cirillo[1], F. Macià[2,3], J.M. Hernandez[2,3], Z. Makhdoumi Kakhaki[4], A. García-Santiago[2,3], and C. Attanasio[4]

[1]CNR-SPIN, c/o Università degli Studi di Salerno, Fisciano I-84084 Sa, Italy
[2]Department of Condensed Matter Physics, University of Barcelona, Barcelona, 08028, Spain
[3]Institute of Nanoscience and Nanotechnology (IN2UB), University of Barcelona, Barcelona, 08028, Spain
[4]Dipartimento di Fisica "E.R. Caianiello", Università degli Studi di Salerno, Fisciano I-84084 Sa, Italy

Non-centrosymmetric superconductors (NCS) are a fascinating class of materials, where exotic properties are observed. In particular, the lacking of the inversion symmetry in their crystal structure may produce an unconventional superconducting order parameter, featuring a mixture of spin-singlet and spin-triplet components [1]. This can in principle open the path for the generation and control of spin polarized supercurrents, with perspectives both in basic research and spin-based applications [2].
The pairing symmetry of the superconducting order parameter of non-centrosymmetric $Nb_{0.18}Re_{0.82}$ (NbRe) films was investigating by using different techniques. Tunneling spectroscopy on Al/Al_2O_3/NbRe tunnel junctions provides evidence for a single *s*-wave superconducting gap [3]. More recently, NbRe-based ferromagnetic (S/F) hybrids were also studied. In particular, preliminary spin pumping experiments by ferromagnetic resonance measurements were performed on NbRe/Co/NbRe trilayers in order to reveal the possible presence of spin-triplet superconducting correlations [4]. Measurements, acquired as a function of both frequency and temperature, reveal that the damping parameter is reduced at the superconducting transition. Results and future experiments are discussed.

[1] E. Bauer and M. Sigrist, *Non-Centrosymmetric Superconductors: Introduction and Overview* (Springer, London, 2012).
[2] J. Linder and J. W. A. Robinson, Nature Physics 11, 307 (2015).
[3] C. Cirillo, G. Carapella, M. Salvato, R. Arpaia, M. Caputo, and C. Attanasio, Phys. Rev. B 94, 104512 (2016).
[4] C. Cirillo et al., in preparation.

Spin Hall effect and superconductivity in Nb-based A15 compounds

Giuseppe Cuono[1], Ghulam Hussain[1], Raghottam M. Sattigeri[1], and Carmine Autieri[1]

[1]*International Research Centre MagTop, Institute of Physics, Polish Academy of Sciences, Aleja Lotników 32/46, PL-02668 Warsaw, Poland*

The spin Hall effect (SHE) is the conversion of charge current to spin current and it has become an important topic in recent years due the possible technological applications, like spintronics, creating logic and storage devices based on manipulating both spin and current [1,2]. A large SHE has been predicted in the A15 family of superconductors, due to their bands that present crossings but with the inculsion of spin-orbit coupling (SOC) interaction form hybridization gaps [3].

We investigate the properties of Nb-based A15 compounds, namely Nb_3Ge, Nb_3Sn and Nb_3Sb by means of ab-initio calculations, Wannier interpolation method and model Hamiltonian.

We analyze the band structure and then we extract the tight-binding model through Wannier method and we calculate the spin Hall conductivity. We observe that one of the the spin-orbit splittings at the R point is at the Fermi level enhancing the SHE despite the moderate SOC of the elements of these compounds. Then we propose a minimal tight-binding model with t_{2g} Nb-orbitals reproducing the spin-orbit splittings at the R point in this class of compounds.

Finally, we calculate the phonon dispersion, the electron-phonon coupling parameters and the superconding critical temperature in these three Nb-based compounds.

[1] H. Ohno, M. D. Stiles, B. Dieny, Spintronics. Proc. IEEE Inst. Electr. Electron. Eng. 104, 1782 (2016).
[2] A. Fert, Nobel Lecture: Origin, development, and future of spintronics. Rev. Mod. Phys. 80, 1517 (2008).
[3] E. Derunova, Y. Sun, C. Felser, S. S. P. Parkin, B. Yan and M. N. Ali, Giant intrinsic spin Hall effect in W_3Ta and other A15 superconductors, Science Advances 5, 4 (2019).

Properties of the spin-polarized 2DEG at the LAO/ETO/STO interface

R. Di Capua[1,2], M. D'Antuono[1,2 *], M. Verma[3], M. Radovic[4], V. N. Strocov[4], C.Piamonteze[4], E. B.Guedes[4], N. C. Plumb[4], Y. Chen[2], G. M. De Luca[1,2], E. Di Gennaro[1,2], D. Stornaiuolo[1,2], D.Preziosi[5], B. Jouault[6], F. Miletto Granozio[2], A. Sambri[2],R. Pentcheva[3], G. Ghiringhelli[7,8] and M. Salluzzo[2]

[1]Dipartimento di Fisica, Università di Napoli "Federico II", Complesso Monte Sant'Angelo via Cinthia, I-80126 Napoli, Italy.
[2]CNR-SPIN, Complesso Monte Sant'Angelo via Cinthia, I-80126 Napoli, Italy.
[3]Dep. of Physics and Center for Nanointegration, University Duisburg-Essen Lotharstr, Germany.
[4]Photon Science Division, Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland.
[5]Université de Strasbourg, CNRS, IPCMS UMR 7504, 67034 Strasbourg, France.
[6]Laboratoire Charles Coulomb, 5221, CNRS, Université de Montpellier, France.
[7]Dipartimento di Fisica, Politecnico di Milano, Piazza L. da Vinci 32, I-20133 Milano, Italy.
[8]CNR-SPIN, Politecnico di Milano, Piazza Leonardo da Vinci 32, I-20133 Milano, Italy

The multi-orbital character of quasi-two-dimensional electron gases (q2DEGs) at the interface between oxide materials is at the origin of the rich physics of these systems and of the emergence of unconventional quantum phases in them. We will present the two-dimensional electron system (2DES) at the $LaAlO_3/EuTiO_3/SrTiO_3$ interface. It shows tunable superconductivity, spin-orbit coupling and ferromagnetism [1], offering the possibility to study the interaction among ground states that are rarely found combined in the same system, and opening to the possibility to interesting electronic applications. We explore the nature and properties of LAO/ETO/STO interface using a wide range of techniques, from electrical transport to angle-resolved photoemission spectroscopy. We will compare the experimental results with Density functional theory calculations, resolving the mechanism of orbital selective switching of the spin-polarization in this oxide q2DEG [2]. The joint experimental and theoretical approach is becoming essential to gain detailed understanding of novel heterostructures showing exceptional properties, and as a guide for future design of materials for advanced applications [3].

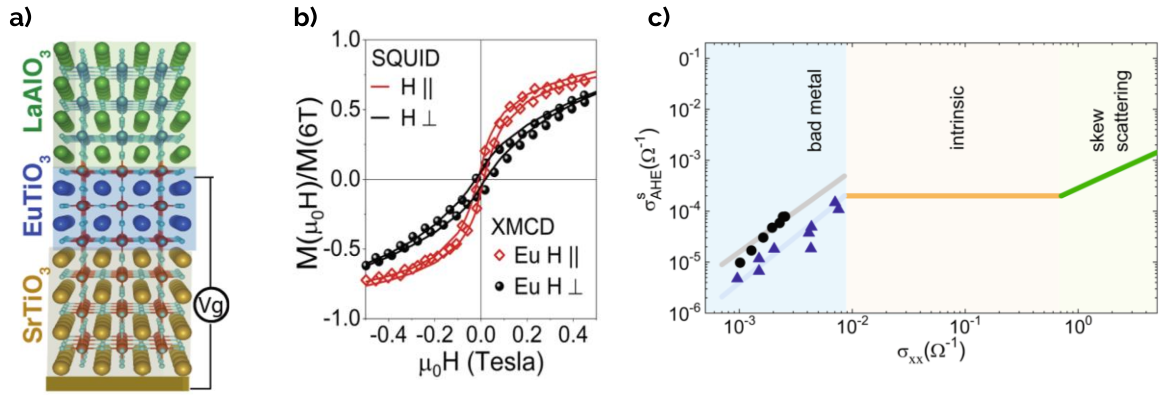


Figure 1: a) Sketch of the LAO/ETO/STO heterostructure. b) Eu- XMCD (scatter data) and SQUID magnetization (continuous lines) as function of the magnetic field parallel (red) and perpendicular (black) to the interface. The data are normalized to the saturation value. c) Anomalous Hall conductivity vs. longitudinal 2D conductivity. Full lines refer to the exponent α in the relation $\sigma_{AHE} \propto (\sigma_{xx})^{\alpha}$ with α = 1.8 (light blue, and gray, intrinsic anomalous Hall effect suppressed by disorder), α = 0 (orange, intrinsic anomalous Hall effect), α = 1(green, skew scattering).

[1]D. Stornaiuolo, et al. Nat.Mater. 15, (2016), 278–284.
[2] R. Di Capua, et al. npj Quantum Mater. 7, (2022), 41
[3] M. D'Antuono. et al., Nanotechnology 33 (2022) 085301

Huge Dzyaloshinskii-Moriya interactions in Re/Co[n]/Pt thin films

Amar Fakhredine[1], Carmine Autieri[2], and Andrzej Wawro[1]

[1] *Institute of Physics, Polish Academy of Sciences, Aleja Lotników 32/46, PL-02688 Warsaw, Poland*

[2] *International Research Centre MagTop, Institute of Physics, Polish Academy of Sciences, Aleja Lotników 32/46, PL-02688 Warsaw, Poland*

Spin-orbit coupling can lead to intriguing phenomena such as the magnetic anisotropy, the spin Hall effect, the Rashba effect and Dzyaloshinskii–Moriya (DMI) interaction. DMI is an antisymmetric indirect exchange interaction occurring between two spins. In magnetic materials with broken chiral symmetry, the structural handedness induces these chiral couplings which stabilize two- and three-dimensional localized structures with a fixed rotation sense and nanometre sizes defined as *skyrmions* [1]. Remarkably, skyrmions can be stabilized in ultrathin transition metal thin films, such as Cobalt if these are in contact with materials that exhibit high spin-orbit coupling. The discovery of skyrmions is promising for the industry of spintronic applications that offer ultra-small, ultrafast, and low-power devices. The control of the DMI strength in multilayered structures allows us to manipulate the different sizes and stability of these magnetic objects [2].

In this work, we illustrate a theoretical technique using DFT calculations to observe the DMI interactions in Re/Co[n]/Pt and report its interfacial and additive character [3]. The total DMI strength (d^{tot}[meV]) in the Re/Co[n]/Pt chiral multilayered system was calculated from the difference in energy between clockwise and anticlockwise configurations of the Co magnetic spin spirals which were further used to determine the micromagnetic DMI [4]. The investigated systems were composed of 5 atomic monolayers (ML) of Pt and 5 MLs of Re sandwiching the Co layer with a tuneable thickness ranging from 1 to 6 MLs. The micromagnetic DMI (named as D) was found as high as 5.78 mJ/m^2 for 3 layers of Co. This value of D is a considerably large. The layer resolved DMI strength at each Co layer shows the highest contributions from the two interfaces of the systems, namely Re/Co and Co/Pt, which add up to produce a huge additive outcome confirming that the DMI is an interfacial effect [5]. This also explains the dependence of the micromagnetic DMI on the number of Co layers since it appears due to the electron hybridization between magnetic moments in the 3d Co atoms and the strong spin-orbit coupling in 5d states of Pt and Re atoms.

This work was supported by the Polish National Science Centre under Project no. 2020/37/B/ST5/02299.

[1] Kiselev et al., Journal of Physics D: Applied Physics 44, 392001 (2011):
[2] M. Morshed et al.. Physical Review B 103, no. 17 (2021): 174414.
[3] J. Cho et al. Nat. Commun. 6, 8635 (2015).
[4] H. Soumyajyoti et al., Physical Review B 104, L180404 (2021).
[5] H. Yang et al., Physical Review Letters 115, 267210 (2015).

Particle-hole spectral asymmetry at the edge of multiorbital noncentrosymmetric superconductors

Yuri Fukaya[1], Keiji Yada[2], Yukio Tanaka[2], Paola Gentile[1], Mario Cuoco[1]

[1]*CNR-SPIN, c/o University of Salerno, Italy*
[2] *Department of Applied Physics, Nagoya University, Japan*

Andreev reflection [1] in spatially inhomogeneous superconductors (SCs) leads to the Andreev bound states with characteristic excitation energies below the superconducting gap [2]. The observation of these states, e.g., through scanning tunneling microscopy (STM) or angle-resolved photoemission spectroscopy (ARPES), is crucial to detect the nature of the superconducting phase and the underlying pairing symmetry [3].

A recent STM experiment in UTe_2 reported the energy asymmetric peaks that are detected inside the superconducting gap, and they concluded a sort of chiral behavior as they depend on the direction of the normal to the side surface of the step edge [4]. However, these phenomena observed in the UTe_2 SC [3] also indicate a sort of universal character that is inherently related to the nature of the superconducting state. Thus, it is not linked to the normal state properties, magnetic effects, or other microscopic details of the surface of the materials.

Bogoliubov quasiparticles are coherent electron-hole quantum superposition that typically exhibits a spectral distribution with particle-hole symmetry for time-reversal symmetric SCs. Here, in this study, we demonstrate that in two-dimensional noncentrosymmetric superconductors with interorbital *s*-wave spin-triplet pairing the energy profile of the density of states at the edge violates this paradigm [5]. We unveil the spin-orbital structure of multiple Andreev reflections that lead to anomalous “septet-pairing” states built out of mirror symmetric quasiparticles and configuration prohibited in the bulk. Due to the coupling of inversion symmetry breaking and the interorbital spin-triplet *s*-wave state, the resulting edge-bulk pairing mismatch generates the spectral function's asymmetric peaks. Remarkably, this asymmetric line shape distribution can be controlled by designing the spatial profile of the inversion symmetry breaking interaction. Our findings can qualitatively account for the phenomena observed at the surface of the UTe_2 SC and be exploited to single out the nature of pairing at oxide interface SCs.

[1] A. Andreev, Sov. Phys. JETP 19, 1228 (1964).
[2] S. Kashiwaya and Y. Tanaka, Rep. Prog. Phys. 63, 1641 (2000).
[3] Y. Tanaka, M. Sato, and N. Nagaosa, J. Phys. Soc. Jpn. 81, 011013 (2012).
[4] L. Jiao, S. Howard, S. Ran, Z. Wang, J. O. Rodriguez, M. Sigrist, Z. Wang, N. P. Butch, and V. Madhavan, Nature 579, 523 (2020).
[5] Y. Fukaya, K. Yada, Y. Tanaka, P. Gentile, and M. Cuoco, arXiv 2209.11077 (2022).

Proximity and diode effects in superconducting Nb/EuS

L. Gorzawski[1], H. Matsuki[1], S. Wang[1], N. Stelmashenko[1], A. Gutfreund[2], V. Plastovets[3], A. Buzdin[3], O. Milo[2], Y. Anahory[2], J. W. A. Robinson[1]

[1]*Department of Materials Science and Metallurgy, University of Cambridge, Cambridge, United Kingdom*

[2]*The Racah Institue of Physics, The Hebrew University of Jerusalem 91904, Israel*

[3]*The University of Bordeaux, LOMA UMR-CNRS 5798, F-33405 Talence, France*

In recent years there has been a series of exciting predictions and experimental discoveries relating to the interplay between superconductivity, magnetism and spin-orbit coupling (SOC) at superconductor/magnet interfaces. Next to mechanisms that enable magnetic control of spin and charge supercurrents [1-4], non-reciprocal charge transport through the "superconducting diode effect" is an area of fundamental and technological importance[5,6].

Our group has recently shown that the superconducting transition temperature (T_c) of Nb within a EuS/Nb/EuS spin switch is extremely sensitive to the magnetisation-orientation of the ferromagnetic EuS layers, achieving a difference in T_c between parallel and antiparallel magnetisations of up to 1.8 K. These results indicate a large magnetic exchange effect (MEF) in Nb of several Tesla, equivalent to MEFs reported in Al/EuS [7]. Furthermore, we have shown that the T_c transition-width of Nb on EuS remains sharp (< 50 mK) down to a Nb thickness of only 1.8 nm. Nb has strong SOC which, in conjunction MEF suggests that the Nb/EuS interface is an ideal platform for investigating the superconducting diode effect in which supercurrents preferentially flow in one direction, depending on the magnetisation-orientation of EuS i.e., a nonreciprocal behaviour of the critical supercurrent. This poster reports supercurrent measurements of Nb/EuS wires, showing evidence for a diode effect in which the forward direction is switchable by reversing the magnetization-orientation of the EuS. The exact origin of the diode effect is unclear, but is likely related to interfacial SOC [8] (conventional superconducting diode effect) or an exotic asymmetric flow of vortices [9].

[1] G. Yang et al., APL Materials 9, 050703 (2021).
[2] K Ohnishi et al., Applied Physics Letters 116, 130501 (2020).
[3] S. Komori et al., Science Advances 7, eabe0128 (2021).
[4] K-R Jeon et al., Physical Review X 10, 031020 (2020).
[5] Fuyuki Ando et al., Nature 584, 373–376 (2020).
[6] H. Narita, Nature Nanotechnology 17, 823–828 (2022).
[7] E. Strambini et al., Phys. Rev. Materials 1, 054402 (2017).
[8] F. Ando et al., Nature 584, 373–376 (2020).
[9] Y. Hou et al., arXiv preprint arXiv:2205.09276 (2022).

Spontaneous breaking of mirror symmetry beyond critical doping in Bi2212

Saegyeol Jung[1,2], Dongjoon Song[1,3,*], Changyoung Kim[1,2,#]

[1]*Center for Correlated Electron Systems, Institute for Basic Science, Seoul 08826, Republic of Korea*
[2]*Department of Physics and Astronomy, Seoul National University, Seoul 08826, Republic of Korea*
[3]*Stewart Blusson Quantum Matter Institute, The University of British Columbia, 2355 East Mall | Vancouver BC | V6T 1Z4 Canada*

In the phase diagram of cuprate high-temperature superconductors, the strange metal phase, one of the most exotic normal-state characteristics with a linear temperature dependence of the resistivity $\rho \sim T^{n}$ (n = 1) with n = 1 is located above the regions of underdoped pseudogap and overdoped FL-like phases with *T*-sublinear (n < 1 at $T < T^*$) and *T*-superlinear (n > 1 at $T < T_{up}$) resistivities, respectively. Various symmetry-breaking across the pseudogap boundary has been observed, which is consistent with the QCP scenario. Compared to this pseudogap region, the overdoped FL-like region has been investigated less systemically and it is unclear whether it is indeed a quantum disordered state or not. Here, we performed the rotational anisotropy second harmonic generation (RA-SHG) measurements on Pb-Bi2212 with p = 0.205 and T_{up} = 225 K to uncover a broken symmetry in the FL-like region beyond the pseudogap critical doping p_c. Taking our symmetry analysis from SHG and resistivity, we found there is spontaneous mirror symmetry breaking which occurs at T_{up}. This result may suggest T_{up} region beyond critical doping coincides with this mirror symmetry breaking order.

Challenges in identifying a topological Hall effect

Graham Kimbell[1,2], Paul Sass[3], Bart Woltjes[2], Eun Kyo Ko[4], Tae Won Noh[4], Weida Wu[3], Changyoung Kim[4], Mario Cuoco[5], and Jason Robinson[2]

[1]*University of Geneva, Switzerland*
[2] *University of Cambridge, UK*
[3]*Rutgers University, USA*
[4]*Seoul National University, Korea*
[5]*CNR-SPIN, Fisciano, Italy*

Skyrmions are topologically non-trivial chiral magnetic bubbles which can be observed with the ‘topological Hall effect’. 4 to 5 unit cell thick $SrRuO_3$ films show an extra Hall peak often attributed to the topological Hall effect from skyrmions [1,2].

This poster shows evidence that these peaks instead result from the superposition of two anomalous Hall effects from 4 and 5 unit cell thick regions, and more generally shows that a non-monotonic Hall signal is not unambiguous evidence of a topological Hall effect [3,4].

[1] J. Matsuno et al., Science Advances 2, e1600304 (2016).
[2] Y. Ohuchi et al., Nature Communications 9, 213 (2018).
[3] G. Kimbell et al., Phys. Rev. Materials 4, 054414, (2020).
[4] G. Kimbell et al., Communications Materials 3 (1), 1-18 (2022).

Correlated normal state fermiology and topological superconductivity in UTe_2

Hong Chul Choi,[1,2] Seung Hun Lee,[1,2,3,*] Bohm-Jung Yang[1,2,3,†]

[1]*Center for Correlated Electron Systems, Institute for Basic Science, Seoul 08826, Korea*
[2]*Department of Physics and Astronomy, Seoul National University, Seoul 08826, Korea*
[3]*Center for Theoretical Physics (CTP), Seoul National University, Seoul 08826, Korea*
**Email of the presenting author: sh2lee@snu.ac.kr*

UTe_2 is a promising candidate for spin-triplet superconductors, in which a paramagnetic normal state becomes superconducting due to spin fluctuations. The subsequent discovery of various unusual superconducting properties has promoted the use of UTe_2 as an exciting playground to study unconventional superconductivity, but fathoming the normal state fermiology and its influence on the superconductivity still requires further investigation. Here, we theoretically show that electron correlation induces a dramatic change in the normal state fermiology with an emergent correlated Fermi surface (FS) driven by Kondo resonance at low temperatures.

This emergent correlated FS can account for various unconventional superconducting properties in a unified way. In particular, the geometry of the correlated FS can naturally host topological superconductivity in the presence of odd-parity pairings, which become the leading instability due to strong ferromagnetic spin fluctuations. Moreover, two pairs of odd-parity channels appear as accidentally degenerate solutions, which can naturally explain the multicomponent superconductivity with broken time-reversal symmetry. Interestingly, the resulting time-reversal breaking superconducting state is a Weyl superconductor in which Weyl points migrate along the correlated FS as the relative magnitude of nearly degenerate pairing solutions varies. We believe that the correlated normal state fermiology we discovered provides a unified platform to describe the unconventional superconductivity in UTe_2.

Hallmarks of non-trivial topology in Josephson junctions based on oxide nanowires

Alfonso Maiellaro[1], Jacopo Settino[2], Claudio Guarcello[1,3], Francesco Romeo[1], and Roberta Citro[1,3]
[1]*Dipartimento di Fisica "E.R. Caianiello", Università di Salerno, Fisciano (SA), Italy*
[2]*Dipartimento di Fisica, Università della Calabria, Italy*
[3]*INFN, Sezione di Napoli, Gruppo collegato di Salerno, Italy*

Quasi-two-dimensional electron gases at the oxide interfaces have been recently proposed as a novel platform for topological superconductivity, but a hallmark of non-trivial topology has been elusive up to now. We show that an anomalous enhancement of the Josephson critical current with an applied magnetic field in oxide nanowires signals a crossover to a topological phase. The maximum of the current pattern corresponds to the appearance of Majorana bound states (MBSs) at the edges of the superconducting leads. Signatures of MBSs also include a fully transparent junction with a sawtooth profile in the current-phase relation. Our findings explain recent experimental observations [1,2] of unconventional Josephson phenomena in oxides and paves the way to recognize fingerprint of topology.

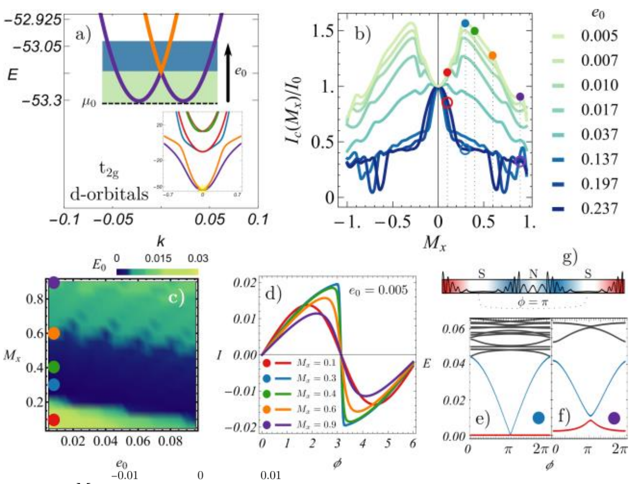


Fig. 1. a) Sketch of band structure nearby the Γ point in the Brillouin zone for $M_x = 0$. The six t_{2g} d-orbitals, i.e. d_{xy} (purple and orange), d_{zx} (red and blue) and d_{yx} (green and brown), are reported in the inset. The two-tone shaded area (green and blue) shows the working region of our simulations. b) Critical current in the SNS junction as a function of M_x for different fillings factor e_0. c) Phase diagram of the junction realized by plotting the lowest energy level of the half positive sector of the BdG spectrum for $\phi = \pi$ by varying M_x and e_0. Zero-energy region (blue region) corresponds to the emergence of MBS within each superconductor, the range of e_0-values corresponds to the green shaded area of panel a (low filling). d) CPRs evaluated at the pawns of panel c. e, f) Low-energy spectrum as a function of the superconducting phase difference ϕ for respectively $M_x = 0.3$, 0.9 as indicated by the corresponding pawns. It shows the presence of zero modes in the topological phase. The absence of MBSs in panel f is clearly traced back to panel c and d. g) Sketch of the MBSs wavefunctions in the topological region for $\phi = \pi$ blue and red areas indicate the Majorana polarization.

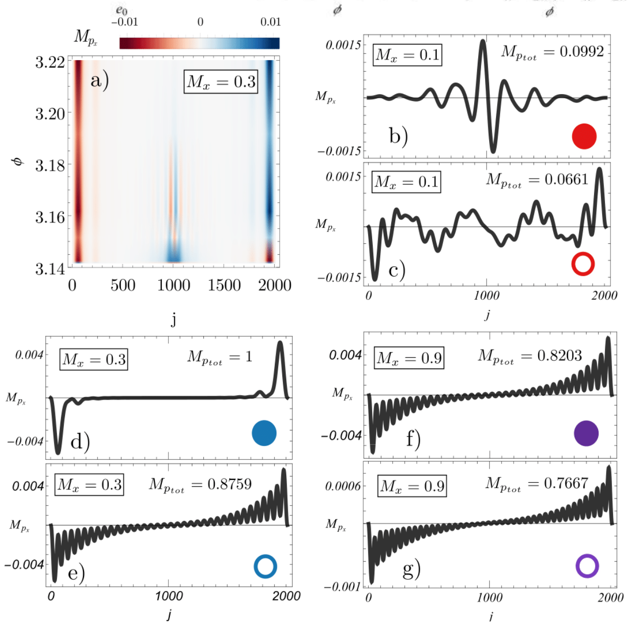


Fig. 2. a) M_{p_x} at $\phi = \pi$ shows the presence of four MBS. For $\phi = \pi + 0.05$ the inner Majoranas disappear, and the whole topological charge concentrates at the corners. b - g) Majorana polarization $\phi = \pi/40$ and for three M_x values (respectively the head, the maximum and the tail) of the lightest green and darkest blue curve of Fig. 1b, as indicated by the corresponding pawns. In the insets, $M_{p_{tot}}$ quantifies the topological charge of the exhibited modes.

[1] G. Singh et al. npj Quantum Matter 7, 2 (2022).
[2] J. Tiira et al., Nat Commun 8, 14984

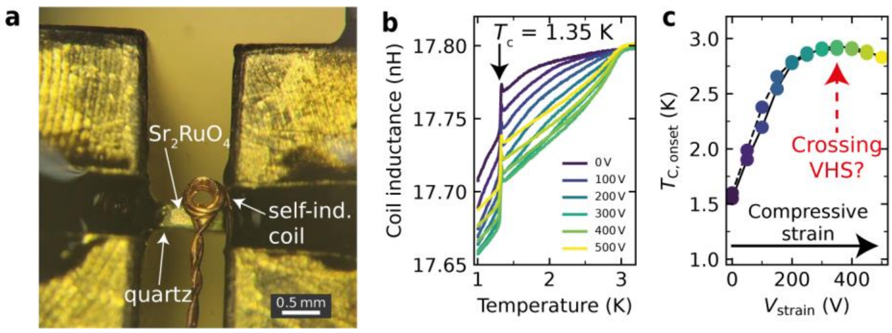
Control of Sr_2RuO_4 superconducting state with uniaxial pressure

Giordano Mattoni[1], Shoya Matsubara[2], M. Waqee-ur-Rehman[2], Shingo Yonezawa[2], Yoshiteru Maeno[1]

[1]*Toyota Riken-Kyoto University Research Center (TRiKUC), Kyoto University, Kyoto 606-8501, Japan*
[2]*Department of Physics, Graduate School of Science, Kyoto University, Kyoto 606-8502, Japan*

Since its discovery in 1994 [1], the superconducting state of Sr_2RuO_4 has sparked strong interest in the condensed matter community. One of the central issues is the unconventional character of its superconducting order parameter, which could have either a spin triplet or singlet character and a symmetry that existing theories and experiments cannot consistently explain [2]. Uniaxial pressure proved to be a powerful tool to study this problem as it allows tuning Sr_2RuO_4 band structure through a Van Hove singularity (VHS) while preserving its superconducting state that is highly sensitive to disorder [3, 4].

In this work, we further investigate Sr_2RuO_4 by applying uniaxial pressure to thin crystalline materials via an indirect method involving a quartz substrate that provides mechanical support. This method allows to pressurise Sr_2RuO_4 crystals in a specific crystalline direction, further extending the flexibility of this technique. We present preliminary results, that reproduce the enhancement of Sr_2RuO_4 superconducting transition temperature under uniaxial pressure, and discuss further developments.



[1] Y. Maeno, et al., Superconductivity in a layered perovskite without copper, Nature 372, 532-534 (1994).
[2] A.P. Mackenzie, et al., Even odder after twenty-three years: the superconducting order parameter puzzle of Sr_2RuO_4, npj Quantum Materials 2, 1-9 (2017).
[3] V. Sunko, et al., Direct observation of a uniaxial stress-driven Lifshitz transition in Sr_2RuO_4, npj Quantum Mater. 4, 46 (2019).
[4] V. Grinenko, et al., Split superconducting and time-reversal symmetry-breaking transitions in Sr_2RuO_4 under stress, Nat. Phys. 17, 748–754 (2021).

Complex intrinsic surface states of pyrite ferromagnetic topological semimetal CoS_2

Yuting Qian[1,2]

1. Center for Correlated Electron Systems, Institute for Basic Science
2. Department of Physics and Astronomy, Seoul National University

The ferromagnet CoS_2, a typical pyrite structure, was recently discovered to have multi-nodal structures. In this work, we observe many complex intrinsic surface states in CoS_2 and find the different origins of these various surface states. We find that CoS_2 not only exhibits a variety of topological nodal structures but also has an obstructed-atomic-limit feature. Thus, Fermi arc, drumhead, and obstructed atomic-center-induced surface states (OASs) are accessible in this system. Interestingly, OASs exhibit a clear Dirac-like crossing sitting at Fermi level protected by gilde mirror symmetry and some surface states spreading the whole Brillouin zone. Furthermore, combining first-principle calculation and experimental results, we observe that some additional spin-polarized surface states cannot be explained by the multi-nodal structures and OASs.
This unique surface states spreading throughout the whole Brillouin zone are dubbed crystal field-enforced surface states (CFSs), i.e., this is because the S octahedron surrounding each Co is broken at the surface. The broken S octahedron changes the crystal field applied to the surface Co atoms and splits Co *d*-orbitals into different ways. In addition, we find that due to the bulk nature of the CoS_2 crystal structure, at least one of the OASs and CFSs always appears regardless of the choice of surface termination. These diverse origins of intrinsic surface states are beneficial to plenty of potential applications and explain the novel physical properties recently discovered in experiments, such as high-performance electro-catalytic activity.

Quasiparticle density of states in a superconductor with Bogoliubov Fermi surfaces

T. Sato[1*], S. Kobayashi[2], and Y. Asano[1]

[1]*Department of Applied Physics, Hokkaido University, Japan*
[2]*RIKEN Center for Emergent Matter Science, Japan*

Subgap quasiparticle states usually exist locally at a surface of a topologically nontrivial superconductor, in a vortex core in magnetic field, and around impurities. Recent studies [1,2], however, have shown that Bogoliubov quasiparticles form the Fermi surfaces in a uniform multiorbital (multiband) superconductor that breaks time-reversal symmetry. Physical phenomena unique to a quasiparticle on the Bogoliubov Fermi surfaces (BFS) have not been studied. Our knowledge is limited to a fact that odd-frequency Cooper pairs coexist with quasiparticles on the BFS [3].

We theoretically investigate the subgap excitation spectra of a superconducting state with the BFS by calculating the density of states. We use the Luttinger-Kohn Hamiltonian to describe the normal state of J=3/2 electrons and time-reversal symmetry breaking pair potentials in the superconducting state. We solve the Gor'kov equation analytically. The density of states is calculated from the normal Green's function. The existence of the BFS is observed as the residual density of states at zero energy. We also find that the properties of the density of states strongly depend on the pseudospin structures in the normal state, those of the pair potentials, and the amplitude of the pair potential. By comparing the density of states with/without the BFS, we discuss effects of the odd-frequency Cooper pairs on the subgap spectra in the density of states.

[1] D. F. Agterberg, P. M. R. Brydon, and C. Timm, Phys. Rev. Lett. 118, 127001 (2017).
[2] P. M. R. Brydon, D. F. Agterberg, Henri Menke, and C. Timm, Phys. Rev. B 98, 224509 (2018).
[3] D. Kim, S. Kobayashi, and Y. Asano, J. Phys. Soc. Jpn. **90**, 104708 (2021).

The orbital decomposition of Yu-Shiba-Rusinov resonances in multiband superconducting Pb

Tom G. Saunderson[1], Emma Thill[2], Jacob Crosbie[2], Ming-Hung Wu[2] James F. Annett[2], Martin Gradhand[2,1]
[1]Institut für Physik, Johannes Gutenberg-Universität Mainz, 55128 Mainz, Deutschland
[2]H H Wills Physics Laboratory, University of Bristol, BS8 1TL, UK

As the fields of superconductivity, magnetism and spin-orbitronics collide exhibiting quasiparticle mediated spin Hall [1], orbital Rashba [2] and quasiparticle interference [3], it becomes increasingly clear that first-principles methods must catch-up to meet the demands of experimental techniques. Quasiparticle interference at impurities is a powerful tool for determining the structure of the superconducting gap in unconventional superconductors [4]. Additional analysis of pair-breaking induced by magnetic impurities in conventional superconductors supports the understanding of the superconducting state and the formation of Yu-Shiba-Rusinov bound states [5]. Extending those results to chains of magnetic impurities on a surface of superconductors with high spin-orbit coupling establishes one possible path towards Majorana Fermions [6].
Here, we present the implementation of the Bogoliubov-de Gennes (BdG) equation into a Green's function (KKR) first principles method [7], incorporating the description of substitutional impurities [8, 9, 10]. This method combines the full complexity of the underlying electronic structure and Fermi surface geometry of the normal state with an effective parametrisation of the superconducting state. It enables us to model impurities as well as interfaces. We present calculations for the bulk [8, 9] as well as the surface [10] of superconducting Pb in the presence of magnetic impurities and assess the orbital character of the ensuing Yu-Shiba-Rusinov bound states making contact to experimental observations.

[1] L. Chirolli et al., Phys. Rev. Lett. 128, 217703 (2022).
[2] K-R. Jeon et al., ACS Nano 2020, 14, 15874 (2020).
[3] E. Liebhaber et al., Nat. Commun. 13, 2160 (2022).
[4] Ø. Fischer et al., Rev. Mod. Phys. 79, 353 (2007).
[5] B. W. Heinrich et al., Prog. Surf. Sci. 93, 1 (2018).
[6] S. Nadj-Perge et al., Science 346, 1259327 (2014).
[7] T. G. Saunderson et al., Phys. Rev. B. 101, 064510 (2020).
[8] T. G. Saunderson et al., Phys. Rev. B. 102, 245106 (2020).
[9] T. G. Saunderson et al., Phys. Rev. B. 105, 014424 (2022).
[10] E. Thill and J. Crosbie et al., manuscript in preparation.

Study of 2D superconductivity at oxide interfaces by microwave resonators

Edouard Lesne, Yildiz G. Sağlam, Jacopo Settino*, Marios Koukanakis, Marc Gabay, Mario Cuoco**, Roberta Citro***, Gary A. Steele, Andrea D. Caviglia

Kavli Institute of Nanoscience, Delft University of Technology, P.O. Box 5046, 2600 GA Delft, The Netherlands

**Dipartimento di Fisica, Università della Calabria I-87036 Rende (CS), Italy*

***CNR-SPIN c/o Universitá degli Studi di Salerno, I-84084 Fisciano (SA), Italy*

****Dipartimento di Fisica "E. R. Caianiello", Universitá degli Studi di Salerno, I-84084 Fisciano (SA), Italy*

The emergent two-dimensional electron system (2DES) formed at the interface between $LaAlO_3$ (LAO) and $SrTiO_3$ (STO) insulating oxides has been a subject of great interest in condensed matter physics over the last decade. Recently, the (111)-oriented STO-based 2DES has attracted further attention due to its sixfold orbital and lattice symmetry whereby two consecutive planes form a dense honeycomb lattice of Ti 3d orbitals, a host candidate for topologically non-trivial electronic phases. Furthermore, it has been shown that the (111)-LAO/STO interface exhibits an electronic correlation-driven reconstruction of its band structure [1], and a two-dimensional superconducting ground-state [2], both tunable by electrostatic field effect.

To study the superconducting state at the LAO/STO(111) interface, we designed embedded superconducting coplanar waveguide (SCPW) resonators whose microwave resonance frequency can be tuned by electrostatic gating, manifesting a change of the 2DES' superfluid density through a large change of its kinetic inductance.

We find that the critical exponent for the scaling of the superfluid density versus temperature cannot be accommodated within a clean BCS scenario across the whole range of accessible doping level, at odd with a previous report at (001)-oriented LAO/STO superconducting 2DES [3].

We propose a theoretical scenario for which the phase space in the Brillouin zone close to the Fermi line is marked by two distinct regions, i.e. hot and cold, due to different electron pairing coupling and mass mismatch. Moreover, we assume the occurrence of long-range pairing interaction in the lattice, thus the attractive interaction is not simply separable, and the emergence of spatial modulations of the superconducting order parameter.

The problem can be conveniently described by an effective Eilenberger two-gap model (γ-model) [4], based on the 'renormalized BCS' model [5], that incorporates the Eliashberg corrections in the effective coupling constants.

Our work highlights the potential of such an approach to the fundamental study of unconventional superconductivity in complex materials, and more specifically in tackling the elusive pairing mechanism in superconducting strontium titanate.

[1] A. Monteiro et al., Physical Review B 99, 201102(R) (2019).
[2] A. Monteiro et al., Physical Review B 96, 020504 (2017).
[3] N. Manca et al., Physical Review Letters 122, 036801 (2019).
[4] V. G. Kogan, Phys. Rev. B - Condens. Matter Mater. Phys. 66, 1 (2002).
[5] E. J. Nicol and J. P. Carbotte, Phys. Rev. B 71, 054501 (2005).

Unconventional transport phenomena in fully-strained $Nd_2Ir_2O_7$ thin film

Jeongkeun Song[1,2], Taekoo Oh[1,2], Eun Kyo Ko[1,2], Ji Hye Lee[1,2], Woo Jin Kim[3,4], Yangyu Zhu[5], Bohm-Jung Yang[1,2], Yangyang Li[5]*, and Tae Won Noh[1,2]*

[1]*Department of Physics and Astronomy, Seoul National University, Seoul, 08826, Korea*
[2]*Center for Correlated Electron Systems, IBS, Seoul, 08826, Korea*
[3]*Stanford Institute for Materials and Energy Sciences, SLAC National Accelerator Laboratory,Menlo Park, CA 94025, United States.*
[4]*Department of Applied Physics, Stanford University, Stanford, CA 94305, United States.*
[5]*School of Physics, Shandong University, Jinan, 250100, China*

Antiferromagnetic (AFM) materials are attracting tremendous attention due to their spintronic applications and associated novel topological phenomena. However, detecting and identifying the spin configurations in AFM materials are quite challenging due to the absence of net magnetization. Herein, we report the practicality of utilizing the planar Hall effect (PHE) to detect and distinguish “cluster magnetic multipoles” in AFM $Nd_2Ir_2O_7$ (NIO-227) fully strained films.

By imposing compressive strain on the spin structure of NIO-227, we artificially induced cluster magnetic multipoles, namely dipoles and A_2- and T_1-octupoles. Importantly, under magnetic field rotation, each magnetic multipole exhibits distinctive harmonics of the PHE oscillation. Moreover, the planar Hall conductivity has a nonlinear magnetic field dependence, which can be attributed to the magnetic response of the cluster magnetic octupoles. Our work provides a strategy for identifying cluster magnetic multipoles in AFM systems and would promote octupole-based AFM spintronics.

Superconducting spin switches with ferromagnetic insulators

Hisakazu Matsuki[1*], Guang Yang[1,2], Greg Mazur[1], Nadia Stelmashenko[1], Lesley Cohen[3] and Jason W. A. Robinson[1*]

[1] *Department of Materials Science & Metallurgy, University of Cambridge, 27 Charles Babbage Road, Cambridge, CB3 0FS, UK*

[2] *School of Integrated Circuit Science and Engineering, Beihang University, Beijing, 100191, China*

[3] *The Blackett Laboratory, Imperial College London, London SW7 2AZ, England, UK*

The resistance of a thin superconductor (S) sandwiched between two ferromagnetic insulators (FI) is theoretically dependent on the magnetisation alignment of the FI layers. [1] Here, we report superconducting spin switches of EuS/Nb/EuS in which the thin film layer of Nb has strong spin orbit coupling and a sharp superconducting transition (T_c). By carefully controlling the growth of EuS/Nb/EuS, we obtain shifts in the superconducting transition [$\Delta T_c = T_{c\text{-}}(\text{AP}) - T_c(\text{P})$] between antiparallel (AP) and parallel (P) magnetisation alignments that exceed 1 K with $\Delta T_c/T_c > 50\%$. Further spin-switch optimisation including minimization of EuS roughness should enable an absolute spin-switch effect in which $\Delta T_c/T_c$ approaches unity.

[1] B. Li, et al. Phys. Rev. Lett. 110, 097001 (2013).

Controlling spin-valve effects in ferromagnet/superconductor structures via the ratio of orbital to spin moments

S. Wang, K. Dumesnil*, H. Bradshaw, N. Stelmashenko, J. W. A. Robinson

Department of Materials Science, University of Cambridge, 27 Charles Babbage Road, Cambridge, CB3 0FS, UK
**Institut Jean Lamour, CNRS-Université de* Lorraine*, UMR 7198, BP 239, 54506 Vandœuvre, France.*

The superconducting critical temperature (T_c) could be suppressed by the proximity coupling between a homogenous ferromagnet (F) and a thin film superconductor (S) [1]. This behaviour is modified when the magnetism is inhomogeneous [1,2,3], for example: due to a net reduction in the magnetic exchange field acting on the S layer, the magnitude of T_c in a superconducting spin-switch (F/S/F) is largest for an antiparallel magnetization-alignment of the F layers. Likewise, for a S/F bilayer, T_c can be enhanced at the coercive field due to a net reduction in the magnetic exchange field acting on the S layer.

Here, we examine how the superconductor proximity effect at superconductor/helimagnet interface is influenced by the ratio of orbital to spin moments in rare earth helimagnetic alloys. Through a better understanding of quantum coupling between f-orbital magnetism and s-d orbital superconductivity we aim to develop devices for superconducting quantum memory and logic.

The initiative will make it possible for the first investigation to examine how spin and orbital moments are coupled with s-d superconductivity within a composition-controlled epitaxial helimagnetic alloy. Preliminary results indicate (contrary to theory) that s-d superconductivity couples more strongly to orbital moments than spin moments. Success should enable the team to bid for a larger scale project with the EPSRC to develop prototype memory/logic devices.

[1] A. Buzdin, Rev. Mod. Phys. 77, 935-976 (2005).
[2] J. Linder & J. W. A. Robinson, Nature Physics 11, 307–315 (2015).
[3] G. Yang, C. Ciccarelli, J. W. A. Robinson, APL Materials 9, 050703 (2021).

Magnetism and Rashba spin-orbit coupling in proximity structures with superconductor/chiral molecule interfaces

J. Xu[1] , S. Anwar[1] , H. Matsuki[1] , S. Yochelis[2] , N. Stelmashenko[1] , A. Wittman[3] , Y. Paltiel[2], J. W. A. Robinson[1]

[1]Department of Materials Science & Metallurgy, University of Cambridge, 27 Charles Babbage Road, Cambridge, CB3 0FS, United Kingdom
[2]Applied Physics Department and the Center for Nanoscience and Nanotechnology, The Hebrew University of Jerusalem, 91904 Jerusalem, Israel
[3]Johannes Gutenberg-Universität Mainz, Institute of Physics, Staudingerweg, 55128 Mainz, Germany

Chiral molecules (CMs) such as alpha-helix polyalanine have chiral-induced spin-selectivity (CISS) properties meaning that a flow of electron charge through a layer of such molecules should be spin-filtered [1], generating a spin-polarized output charge current with potential application in spintronics. In proximity structures involving CMs absorbed onto the surface of an s-wave spin singlet superconductor (S), it has been shown that an unconventional s-wave spin-triplet superconducting state can form [2,3] with potentially strong spin-orbit coupling (SOC) at the S/CM interface. Here we systematically investigate proximity structures including metal/CM (M/CM) bilayers, S/M/CM trilayers, and structures with ferromagnetic layers (S/F/M/CM). The M/CM structures show evidence for Rashba SOC and induced magnetism at the M/CM interface. The superconducting structures may exceed the paramagnetic limit [4] and enable the generation of spontaneous vortices [5] in zero magnetic field.

[1] R. Naaman, Y. Paltiel, D.H. Waldeck, Nature Reviews Chemistry 3, 250 (2019).
[2] E. Katzir, et al., Phys. Rev. Lett. 108, 107004 (2012).
[3] M. Periyasamy et al., Appl. Phys. Lett. 117, 242601 (2021).
[4] L. A. B. Olde Olthof et al., Phys. Rev. B 103, L020504 (2021).
[5] L. A. B. Olde Olthof et al., Phys. Rev. B 100, 220505(R) (2019).

Developments of magneto-optic Kerr-effect measurement techniques for detecting time-reversal symmetry breaking

S. Yamane[A], Y. Hu[A], N. Kimura[A], K. Obata[A], G. Mattoni[A], Y. Li[B], Y. Yao[B], Z. Wang[B], J. Wang[C], C. Farhang[C], J. Xia[C], Y. Maeno[A], S. Yonezawa[A]

[A]*Dept. of Phys., Kyoto Univ., Toyota Riken-Kyoto Univ. Research Center (TRiKUC)*
[B]*Beijing Inst. of Tech.*
[C]*Dept. of Phys., Univ. California, Irvine*

The concept of topology has been becoming one of the principles in condensed matter physics, and its class is determined by the symme tries such as time-reversal symmetry [1]. Magneto-optical Kerr effect (MOKE) is a polarization change when the light is reflected from a magnetized material. It is well known that MOKE occurs in ferromagnetic material via the existence of spontaneous magnetic moment indicating time-reversal symmetries breaking (TRSB). On the other hand, MOKE can appear in some "non-magnetic" materials with TRSB order parameters like chiral superconductors. To confirm TRSB in such a novel superconductor, MOKE measurements with a nano-radian resolution of polarization change are required. Such high-resolution measurements can be achieved with a special experimental technique based on loop-less Sagnac interferometry [2, 3]. We have been constructing an all-fiber high-resolution MOKE setup (Fig.1). In this presentation, we describe our Kerr-effect measurements on SRO/STO113 thin film [3], eutectic Sr_2RuO_4-Ru [4, 5], and Kagome metal CsV_3Sb_5[6, 7].

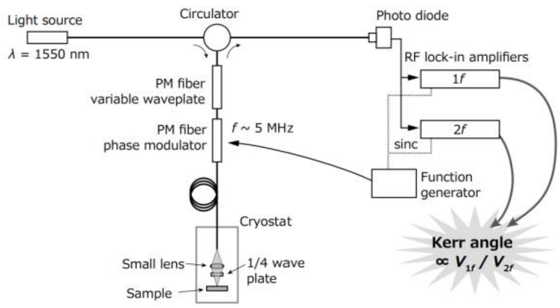


Figure 1: Illustration of our all-fiber high-resolution magneto-optical Kerr-effect setup

[1] C. L. Kane et al., Phys. Rev. Lett. 95, 146802 (2005).
[2] J. Xia et al., Phys. Rev. Lett. 97, 167002 (2006).
[3] J. Xia et al., Appl. Phys. Lett. 89, 062508 (2006).
[4] Y. Maeno et al., Phys. Rev. Lett. 81, 3765 (1998).
[5] H. Kaneyasu et al., PRB 100, 214501 (2019).
[6] B. Ortiz et al., Phys. Rev. Materials 3, 094407 (2019).
[7] Y. Hu, S. Yamane et al., arXiv:2208.08036 (2022).

LIST OF PARTICIPANTS

SURNAME NAME	AFFILIATION	EMAIL
AARTS Jan	Leiden University	aarts@physics.leidenuniv.nl
ANDO Satoshi Ando	Department of Applied Physics, Nagoya University	aodo.satoshi.p2@s.mail.nagoya-u.ac.jp
APRILI Marco	LPS-CNRS Paris	marco.aprili@u-psud.fr
ARUMUGAM Raja	CNR SPIN Salerno	raja.arumugam@spin.cnr.it
ATTANASIO Carmine	University of Salerno	cattanasio@unisa.it
AUTIERI Carmine	International Research Centre Magtop, Institute of Physics, Polish Academy of Sciences, Warsaw, Poland	autieri@magtop.ifpan.edu.pl
AVELLA Adolfo	Dipartimento di Fisica - Università di Salerno	a.avella@unisa.it
BONETTI Stefano	Ca' Foscari University of Venice	stefano.bonetti@unive.it
CANNAVACCIUOLO Marco	University of Salerno	mcannavacciuolo@unisa.it
CHAN Alex	Imperial College London	k.chan18@imperial.ac.uk
CHUNG Suk Bum	University of Seoul	sbchung0@uos.ac.kr
CSONKA Szabolcs	University of Budapest	csonka.szabolcs@ttk.bme.hu
CIRILLO Carla	CNR SPIN Salerno	carla.cirillo@spin.cnr.it
CITRO Roberta	University of Salerno	rocitro@unisa.it
CUOCO Mario	CNR-SPIN Salerno	mario.cuoco@spin.cnr.it
CUONO Giuseppe	International Research Centre MagTop, Institute of Physics, PAS Warsaw, Poland	gcuono@magtop.ifpan.edu.pl
D'ANTUONO Maria	University of Naples Federico II and CNR SPIN	maria.dantuono@unina.it
DI BERNARDO Angelo	University of Konstanz	angelo.dibernardo@uni-konstanz.de
DI GIORGIO Cinzia	University of Salerno	cdigiorgio@unisa.it

DINELLI Franco	CNR-INO	franco.dinelli@ino.it
FAKHREDINE Amar	Institute of Physics, Polish Academy of Sciences, Warsaw	amarf@ifpan.edu.pl
FERMIN Remko	Leiden University	fermin@physics.leidenuniv.nl
FITTIPALDI Rosalba	CNR SPIN Salerno	rosalba.fittipaldi@spin.cnr.it
FORTE Filomena	CNR SPIN Salerno	filomena.forte@spin.cnr.it
FOWLIE Jennifer	Stanford University	jfowlie@stanford.edu
FRANKE Katharina	Freie Universität Berlin	franke@physik.fu-berlin.de
FUKAYA Yuri	CNR SPIN Salerno	yuri.fukaya.15014@gmail.com
GENTILE Paola	CNR SPIN Salerno	paola.gentile@spin.cnr.it
GHADIMI Rasoul	SNU-CTP,IBS-CCES	Ghadimi.rasoul@gmail.com
GIANNINI Enrico	University of Geneva	enrico.giannini@unige.ch
GO Dongwook	Forschungszentrum Jülich	d.go@fz-juelich.de
GOLUBOV Alexander	University of Twente	a.golubov@utwente.nl
GORZAWSKI Laura	University of Cambridge	laura.gorzawski@uni-konstanz.de
GRINENKO Vadim	Tsung-Dao Lee Institute, Shanghai Jiao Tong University	vadim.a.grinenko@gmail.com
GUARCELLO Claudio	University of Salerno	cguarcello@unisa.it
GUARINO Anita	CNR SPIN Salerno	anita.guarino@spin.cnr.it
HOFMANN Philip	Aarhus University	philip@phys.au.dk
HU Yajian	Center of Emergent Matter Science, RIKEN	yajian.hu@riken.jp
ISHIDA Kenji	Department of Physics, Graduate School of Science, Kyoto University,	kishida@scphys.kyoto-u.ac.jp
JUNG Saegyeol	IBS-CCES, Seoul National University	wjdtoruf5829@snu.ac.kr
KALABOUKHOV Alexei	Chalmers University of Technology	alexei.kalaboukhov@chalmers.se
MAKHDOUMI KAKHAKI	University of Salerno	zmahdoumikakhaki@unisa.it

Zahra		
KALISKY Beena	Bar Ilan University	beena@biu.ac.il
KASHIWAYA Satoshi	Nagoya University	s.kashiwaya@nagoya-u.jp
KIM Changyoung	IBS-CCES, Seoul National University	changyoung@snu.ac.kr
KIM Jinkwon	Cornell University	kjink26@gmail.com
KIMBELL Graham	University of Geneva	Graham.Kimbell@unige.ch
KOMORI Sachio	Nagoya University	komori.sachio@h.mbox.nagoya-u.ac.jp
LEE GILHO	POSTECH	lghman@postech.ac.kr
LEE Sangjae	Seoul National University	sangjae.lee@snu.ac.kr
LEE Seung Hun	Seoul National University	sh2lee@snu.ac.kr
LETTIERI Mariateresa	CNR SPIN Salerno	mariateresa.lettieri@spin.cnr.it
MACKENZIE Andrew Peter	MPI for Chemical Physics of Solids, Dresden	mackenzie@cpfs.mpg.de
MAENO Yoshiteru	Kyoto University	maeno.yoshiteru.b04@kyoto-u.jp
MAIELLARO Alfonso	University of Salerno	amaiellaro@unisa.it
MATSUKI Hisakazu	University of Cambridge	hm584@cam.ac.uk
MATTONI Giordano	Kyoto University	mattoni@scphys.kyoto-u.ac.jp
MERCALDO Maria Teresa	Dipartimento di Fisica, Università di Salerno	mmercaldo@unisa.it
NICOLAS Gauquelin	EMAT, Department of Physics, University of Antwerpen	Nicolas.Gauquelin@uantwerpen.be
NOCE Canio	University of Salerno	cnoce@unisa.it
NOH Tae Won	IBS-CCES, Seoul National University	twnoh@snu.ac.kr
OLDE OLTHOF Linde	University of Cambridge	labo2@cam.ac.uk
ONO Teruo	Kyoto University	ono@scl.kyoto-u.ac.jp
QIAN Yuting	IBS-CCES, Seoul National University	yuting_qian@snu.ac.kr

RAMIRES Aline	Paul Scherrer Institute	aline.ramires@psi.ch
ROBINSON Jason	University of Cambridge	jjr33@cam.ac.uk
ROMANO Alfonso	Dipartimento di Fisica "E.R. Caianiello", Università di Salerno	alromano@unisa.it
SATO Masatoshi	Kyoto University	msato@yukawa.kyoto-u.ac.jp
SATO Takumi	Hokkaido University	takumis31@eis.hokudai.ac.jp
SAUNDERSON Tom G.	University of Mainz	tsaunder@uni-mainz.de
SCHEER Elke	University of Konstanz, Department of Physics	elke.scheer@uni-konstanz.de
SETTINO Jacopo	Dipartimento di Fisica, Università della Calabria	jacopo.settino@unical.it
SONG Jeognkeun	Seoul National University	jsong62@snu.ac.kr
STELMASHENKO Nadia	University of Cambridge, UK	nas19@cam.ac.uk
VECCHIONE Antonio	CNR SPIN Salerno	antonio.vecchione@spin.cnr.it
WANG Sijie	University of Cambridge	sw980@cam.ac.uk
WITTMANN Angela	Johannes Gutenberg University Mainz	a.wittmann@uni-mainz.de
WULFERDING Dirk	IBS-Center for Correlated Electron Systems, Seoul National University	dirwulfe@snu.ac.kr
XU Jiahui	University of Cambridge	Jx306@can.ac.uk
YADA Keiji	Nagoya University	yada@rover.nuap.nagoya-u.ac.jp
YAMANE Soichiro	Department of Physics, Graduate School of Science, Kyoto University	yamane.soichiro.73f@st.kyoto-u.ac.jp