CEMS Topical Meeting Online

Quantum Technology meets Quantum Matter

Japan Standard Time (UTC+9)

Thursday, 17 September

9:00–9:10 **Opening**

9:10–9:50

Katja Nowack (Cornell)

"Local magnetic measurements of unconventional superconductors"

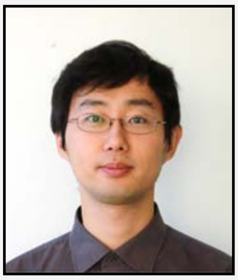
9:50–10:30

Sergey Uchaikin (IBS)
Arjan van Loo (RIKEN)

"Axion search with Josephson parametric amplifiers"

10:30–10:40 **Break**

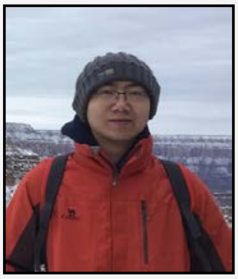
10:40–11:20



Sen Yang (CUHK)

"Study pressure driven phase transitions via NV centers in diamond"

11:20–12:00



Fan Yang (Stanford)

"Imaging nematic transitions in iron-pnictide superconductors with a quantum gas"

Friday, 18 September

9:00–9:40

Naoto Tsuji (RIKEN)

"Spin freezing crossover in multi-orbital systems and SYK strange metal"

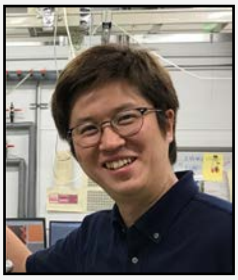
9:40–10:20

Sadashige Matsuo (RIKEN)

"Control of the DC and AC Josephson effects on the ballistic InAs nanowires"

10:20–10:30 **Break**

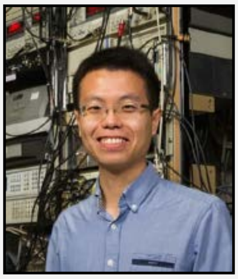
10:30–11:10



Hiroshi Imada (RIKEN)

"Single-molecule investigation of charge and energy dynamics by photon-STM"

11:10–11:50



Kai Yang (IBM)

"Atomic-scale magnetic resonance of quantum spins on a surface"

11:50–12:00 **Closing**

https://cems.riken.jp/topicalmeeting/003_qt_meets_qm/

RIKEN CEMS

Organizer: Eisuke Abe (eisuke.abe@riken.jp)

Local magnetic measurements of unconventional superconductors

Katja Nowack[1]

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A defining property of a superconductor is its response to an applied magnetic field. In this talk, I will discuss how we use scanning superconducting quantum interferences devices (SQUIDs) to study the local magnetic response in two different types of superconductors. First, I will discuss measurements on focus ion beam (FIB) defined microstructures fabricated from single crystals of the heavy-fermion superconductor $CeIrIn_5$. Using scanning SQUID we observe that the superconducting transition temperature, T_c, varies throughout the structure in a complex pattern. This pattern arises due to the interplay of a non-trivial strain field from the differential thermal contraction of the substrate and microstructure and the sensitivity of T_c in $CeIrIn_5$ to the strength and direction of strain. Devices with different geometry show that the spatial modulation of T_c can be tailored in agreement with predictions based on finite element simulations. These results offer a new approach to manipulate strain-sensitive electronic order on micrometer length scales in strongly correlated matter. Second, I will show how we use scanning SQUID to perform local magnetic measurements of ionic gated superconducting MoS_2 devices. This allows us to observe for the first time the diamagnetic response of any few layer van der Waals superconductor despite the extremely small sample volume. I will discuss how we can extract the superfluid density and other characteristics of the superconducting state from our measurements.

Axion search with Josephson parametric amplifiers

Sergey Uchaikin[1] and Arjan Ferdinand van Loo[2]

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Axions are hypothetical particles that have been proposed as a solution to the strong CP problem of quantum chromodynamics. Axions with a mass between 10^{-3} meV and 1 meV may also be promising cold dark matter candidates. The observed density of axions in the universe should be in the range of 10^{11}–10^{14} per cm^3. These axions can be detected by their conversion to microwave photons in high magnetic fields inside a high-quality cavity due to the inverse Primakoff effect. Microwave signals from axions are expected to be very small, and to register them a very low-noise amplifier such as a Josephson parametric amplifier is necessary.

Josephson parametric amplifiers consist of a microwave cavity containing Josephson junctions as their nonlinear element. These devices are capable of quantum-limited amplification of microwave signals. They were first developed in the context of circuit QED with the aim to increase the signal-to-noise ratio in experiments relating to superconducting qubits, but have since been employed in other contexts where efficient detection of weak microwave signals is important, such as the axion detection that is the topic of this talk.

Here, a JPA with an operation frequency around 2.3 GHz is installed in a running axion search experiment at the Center for Axion and Precision Physics Research. The goal of the experiment is to scan the JPA operation frequency range with KSVZ sensitivity.

Study pressure driven phase transitions via NV centers in diamond

Sen Yang[1]

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Strongly correlated systems are one of the most interesting and challenging fields in physics. To understand the physics of quantum phenomena such as superconductivity and magnetism, measurements with ultimate sensitivity is needed. Nitrogen vacancy (NV) centers in diamond are good candidates as a sensor in studying these phase transitions. We utilize nitrogen vacancy (NV) centers in diamond as a powerful, spatially-resolved vector field sensor for material research under pressure at cryogenic temperatures. Using a single crystal of $BaFe_2(As_{0:59}P_{0:41})_2$ as an example, we extract the superconducting transition temperature (T_c), the local magnetic field profile in the Meissner state and the critical fields (H_{c1} and H_{c2}). The method developed in this work will become a unique tool for tuning, probing and understanding quantum many body systems.

[1] King Yau Yip, Kin On Ho, King Yiu Yu, Yang Chen, Wei Zhang, S. Kasahara, Y. Mizukami, T. Shibauchi, Y. Matsuda, Swee K. Goh, Sen Yang, Science **366**, 1355 (2019).

[2] Kin On Ho, Man Yin Leung, Yaxin Jiang, Kin Pong Ao, Wei Zhang, King Yau Yip, Yiu Yung Pang, King Cho Wong Swee K. Goh, Sen Yang, Phys. Rev. Applied, **13**, 024041 (2020).

Imaging Nematic Transitions in Iron-Pnictide Superconductors with a Quantum Gas

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The SQCRAMscope is a recently realized Scanning Quantum CRyogenic Atom Microscope that utilizes an atomic Bose-Einstein condensate to measure magnetic fields emanating from solid-state samples [1]. Here, we combine the SQCRAMscope with an in situ microscope that measures optical birefringence near the surface of a sample to study iron-pnictide superconductors [2], where the relationship between electronic and structural symmetry-breaking resulting in a nematic phase is under debate. We conduct simultaneous and spatially resolved measurements of both bulk and surface manifestations of nematicity via transport and structural deformation channels, respectively. By performing local measurements of emergent resistivity anisotropy in iron pnictides, we observe sharp, nearly concurrent transport and structural transitions. More broadly, these measurements demonstrate the SQCRAMscope's ability to reveal important insights into the physics of complex quantum materials.

[1] F. Yang, A. J. Kollár, S. F. Taylor, R. W. Turner, & B. L. Lev, Phys. Rev. Applied **7**, 034026 (2017).
[2] F. Yang, S. F. Taylor, S. D. Edkins, J. C. Palmstrom, I. R. Fisher, B. L. Lev, Nat. Phys. **16**, 514 (2020).

Spin freezing crossover in multi-orbital systems and SYK strange metal

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Multi-orbital electron systems offer a playground of strong correlation physics, including orbital-selective Mott transitions, non-Fermi liquids, and unconventional superconductivity. Those physics can be successfully described by the multi-orbital Hubbard model, which finds various material applications such as Sr_2RuO_4 and iron-based superconductors. In the multiorbital Hubbard model with Hund's coupling, there is a competition between the Kondo effect (screening of local magnetic moments) and the Hund effect (formation of local moments), between which emerges a highly moment-fluctuating regime called the spin freezing crossover. The spin freezing crossover regime shows the anomalous frequency dependence of the self-energy ($\Sigma(\omega) \sim \omega^{1/2}$) and slow relaxation of the spin correlation ($\langle S_z(\tau) S_z(0) \rangle \sim \tau^{-1}$).

Recently, it has been pointed out that such a spin freezing crossover state has a striking similarity to the Sachdev-Ye-Kitaev (SYK) model [1], which shows a maximally chaotic behavior as probed by out-of-time-ordered correlators (OTOCs), and is expected to be a holographic dual to black holes. Motivated by this observation, we study OTOCs for the Hubbard model with a new technique using an imaginary-time four-point function with unusual time ordering [2]. The results show that in the spin freezing crossover regime a spin-related OTOC rapidly decays without oscillations in a short time, and relaxes more slowly as a power law in a long time. This is in a good agreement with the behavior of OTOCs in the SYK model, providing a firm evidence that the spin freezing crossover regime in the multiorbital Hubbard model effectively realizes the SYK strange metal state.

[1] P. Werner, A. Kim, and S. Hoshino, Europhys. Lett. **124**, 57002 (2018).

[2] N. Tsuji and P. Werner, Phys. Rev. B **99**, 115132 (2019).

Control of the DC and AC Josephson effects on the ballistic InAs nanowires

Sadashige Matsuo[1, 2]

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The semiconductor technology provides the high electrical controllability and long mean free path in the nanostructures. Recently the transparent interfaces of the superconductors and semiconductors have been realized, resulting in the recent research development of the exotic superconducting phenomena using the superconducting proximity effect on the semiconductors as represented by the Majorana Fermions realized in the superconductor-semiconductor nanowire junctions [1].

Here we show the experimental results of the Josephson effect in single and double InAs ballistic nanowires. First, we report on the Shapiro steps measured in the Josephson junctions of the single InAs nanowires. We found that steps appear at the fractional values of the quantized voltage in addition to the integer steps. These fractional Shapiro steps are attributed to skewness of current-phase relation anticipated in the ballistic Josephson junctions [2]. These results provide important information to establish the phase dynamics in the ballistic Josephson junctions [3].

Second, we report on the DC Josephson effect in the ballistic double nanowire. In the experiment, we measured the supercurrent in the gate-tunable double nanowire. From the results, we evaluated the supercurrent carried by Cooper pair splitting (CPS), which only appears when both the nanowires have finite conduction channels. CPS is one of the necessary ingredients to engineer the MFs with no magnetic field in the double nanowires [4]. Therefore, our results will provide the way to realize the robust MFs with no magnetic field in the ballistic nanowires [5].

[1] R. M. Lutchyn, *et al*. Nature Reviews Materials **3**, 52 (2018).
[2] A. A. Golubov, *et al*. Rev. Mod. Phys. **76**, 411 (2004).
[3] K. Ueda, S. Matsuo, *et al*., accepted in Phys. Rev. Research (2020).
[4] J. Klinovaja, *et al*. Phys. Rev. B **90**, 045118 (2014).
[5] K. Ueda, S. Matsuo, *et al*. Sci. Adv. **5**, 2194 (2019).

Single-molecule investigation of charge and energy dynamics by photon-STM

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Transfer of charge and energy in matters is an important dynamic process in various energy-converting phenomena. Since those dynamic processes are governed by wave functions that vary on the atomic scale, it has been difficult to directly investigate the essential physics by conventional optical methods. Recently, we have been conducting a series of atomic-scale investigation of charge and energy transfer in molecular systems using a scanning tunneling microscope (STM) combined with optical techniques (photon-STM) [1-4]. In the seminar, I will describe how an electron goes through the molecular orbitals to form spin singlet and triplet excitons in the single-molecule and how the energy is dissipated by luminescence or energy transfer to the other molecule (Figure).

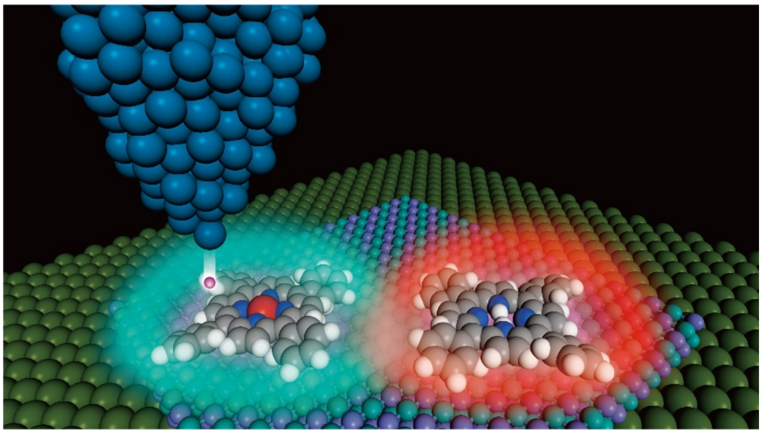

Figure: Schematic illustration of a coupled molecule system investigated with scanning tunneling microscopy.

[1] H. Imada, K. Miwa, M. Imai-Imada, S. Kawahara, K. Kimura, Y. Kim, Nature, **538**, 364 (2016).

[2] H. Imada, K. Miwa, M. Imai-Imada, S. Kawahara, K. Kimura, Y. Kim, Phys. Rev. Lett., **119**, 013901 (2017).

[3] K. Miwa, H. Imada, M. Imai-Imada, K. Kimura, M. Galperin, Y. Kim, Nano Lett., **19**, 2803 (2019).

[4] K. Kimura, K. Miwa, H. Imada, M. Imai-Imada, S. Kawahara, J. Takeya, M. Kawai, M. Galperin, Y. Kim, Nature, **570**, 210 (2019).

Atomic-scale magnetic resonance of quantum spins on a surface

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Recently, the ability to drive electron spin resonance (ESR) of individual atoms using a scanning tunneling microscope (STM) provided a major step forward in sensing and manipulating magnetism at the atomic scale. In the first part, I will describe the implementation of continuous-wave ESR in STM [1]. The ultrahigh energy resolution of ESR has allowed the measurement of the magnetic interaction between two atoms [2], the detection of nuclear spins [3], as well as the exploration of quantum fluctuations in designed spin arrays. Next, I will talk about coherent spin control using all-electric pulsed ESR [4]. By modulating the atomically-confined magnetic interaction between the STM tip and surface atoms, we drive quantum Rabi oscillations of single spins in as little as ~20 nanoseconds. Ramsey fringes and spin echo signals allow us to improve quantum coherence. I will also show the coherent operations on engineered atomic dimers. Coherent control of spins arranged with atomic precision thus provides a solid-state platform for quantum simulation of many-body systems.

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[3] P. Willke, Y. Bae, K. Yang, J. Lado, A. Ferrón, T. Choi, A. Ardavan, J. Fernández-Rossier, A. J. Heinrich and C. P. Lutz, Science **362**, 336 (2018)
[4] K. Yang, W. Paul, S.-H. Phark, P. Willke, Y. Bae, T. Choi, T, Esat, A. Ardavan, A. J. Heinrich and C. Lutz, Science **366**, 509 (2019)