O 79: Focus Session: Spins on Surfaces I (joint session O/MA)

Organizer: Andreas Heinrich (Center for Quantum Nanoscience, IBS, Seoul, South Korea)

Time: Thursday 10:30–13:00 Location: H15

Invited Talk O 79.1 Thu 10:30 H15

Enhancing quantum coherence of magnetic atoms on a surface — •Yujeong Bae[1,2,3], Kai Yang[2], Philip Willke[1,3], Taeyoung Choi[1,3], Andreas J. Heinrich[1,3], and Christopher P. Lutz[2] — [1]Center for Quantum Nanoscience, Institute for Basic Science, Seoul 03760, Republic of Korea — [2]650 Harry Rd — [3]Department of Physics, Ewha Womans University, Seoul 03760, Republic of Korea

Coherent control of spin states is of central importance in spin-based information processing and spintronic devices. However, the spin coherence of individual atoms on a surface is easily disrupted by interaction with environment such as electric or magnetic field noise as well as unwanted coupling with neighboring spins. Here we demonstrate that a singlet-triplet transition in a pair of antiferromagnetically coupled spin-1/2 atoms yields enhanced spin coherence compared to individual atoms. We used scanning tunneling microscope to assemble two hydrogenated titanuim atoms on MgO(001). At a precisely selected spacing that gives a large interaction energy between two atoms, we obtain spin states having a high degree of protection from disrupting fields, and also provides thermal initialization into the singlet state. We show that a two level system composed of these singlet and triplet states is insensitive to global and local magnetic field variation, resulting in longer spin coherence times compared to individual atoms.

O 79.2 Thu 11:00 H15

Quantum Nanoscience: Atoms on Surfaces as Quantum Spins — •Andreas Heinrich — IBS Center for Quantum Nanoscience at Ewha Womans University, Seoul, Korea

Quantum Nanoscience is a discipline that combines quantum science with nanoscience. It aims to utilize quantum coherence in solid-state and molecular systems. Among the many basic science questions in this field are open versus closed quantum systems and the controlled interaction of the quantum systems with the host materials. Getting control of those methods and concepts will enable engineered quantum systems with controllable quantum coherence. Possible applications range from quantum sensing to quantum computation. Scanning Tunneling Microscopy is a unique tool in that it allows to image surface with atomic resolution, build structures one atom at a time and measure the structures with high energy and spin resolution - all in one machine. We will outline relevant experiments that enable the STM to become a potent tool of quantum nanoscience.

O 79.3 Thu 11:15 H15

Sensing the spin of a spectroscopically dark Ce adatom with an STM — •Markus Ternes[1,2], Chris Lutz[3], Andreas Heinrich[4,5], and Wolf-Dieter Schneider[6,7] — [1]RWTH Aachen University, Germany — [2]Peter Grünberg Institute PGI-3, Forschungszentrum Jülich, Germany — [3]IBM Almaden Research Center, San Jose, CA, USA — [4]Center for Quantum Nanoscience, Institute for Basic Science, Seoul, Republic of Korea — [5]Ewha Womans University, Seoul, Republic of Korea — [6]Fritz- Haber-Institut, Berlin, Germany — [7]École Polytechnique Fédérale de Lausanne, Switzerland

The magnetic moment of rare earth elements originates from the electrons of the partially filled $4f$ orbitals. Accessing this moment electrically as in a scanning tunneling spectroscopy experiment is difficult due to the effective shielding by electrons in the further outward lying $5d$ and $6s$ orbitals. However, recently the influence of $4f$ spins on the EPR signal of neighboring $3d$ spins has been used for its detection [1]. Here we use a different approach to detect the magnetic moment of a single Ce adatom on a Cu_2N ultrathin film on Cu(100). We functionalize the tip apex with a second, Kondo screened spin which we can deliberately couple to other moments on the surface via the tunneling junction [2]. We calibrate this sensor against a well understood Fe atom and subsequently use the splitting of the Kondo resonance when approaching a spectroscopically dark Ce atom to determine its magnetic moment to $\approx 1\mu_B$. [1] F. D. Natterer, *et al.*, *Nature* **543**, 226 (2017). [2] M. Muenks, *et al.*, *Nature Comm.* **8**, 14119 (2017).

O 79.4 Thu 11:30 H15

Scanning tunneling spectroscopy of Co atoms at long Cu chains — Neda Noei[1], •Alexander Weismann[1], Roberto Mozara[2], Oleg Kristanovski[2], Alexander I. Lichtenstein[2], and Richard Berndt[1] — [1]Institut für Experimentelle und Angewandte Physik, Christian-Albrechts-Universität zu Kiel, D-24098 Kiel, Germany — [2]Institut für Theoretische Physik, Universität Hamburg, D-20355 Hamburg, Germany

The interaction of an impurity atom carrying a localized spin with a host metal often leads to the many-body Kondo effect. We prepared atomic chains with lengths of hundreds of Cu atoms on a Cu(111) surface, and spectroscopically probed the Kondo resonance of Co adatoms on pristine terraces, at such chains, and at the end of chains. Distinctly different amplitudes, widths and spectroscopic line shapes are observed for the three cases and they are qualtatively reproduced by multi-orbital many body calculations that combine DFT with continuous-time quantum Monte Carlo.

O 79.5 Thu 11:45 H15

Spin selective tunneling processes between Yu-Shiba-Rusinov states — •Haonan Huang[1], Jacob Senkpiel[1], Robert Drost[1], Ciprian Padurariu[2], Simon Dambach[2], Björn Kubala[2], Juan Carlos Cuevas[3], Alfredo Levy Yeyati[3], Joachim Ankerhold[2], Christian R. Ast[1], and Klaus Kern[1,4] — [1]MPI für Festkörperforschung, Stuttgart, Germany — [2]Institut für komplexe Quantensysteme, Universität Ulm, Ulm, Germany — [3]Departamento de Física Teórica de la Materia Condensada, Universidad Autónoma de Madrid, Madrid, Spain — [4]EPFL, Switzerland

A Yu-Shiba-Rusinov (YSR) state is a pair of in-gap states resulting from the interaction of magnetic atoms with a superconductor. We are experimentally able to introduce any YSR state of desired energy position and peak heights to the apex of a superconducting vanadium STM tip, and then use this novel tip to characterize sample YSR defects to study spin selective tunneling. YSR-YSR tunneling happens resonantly when the bias voltage is at the sum of tip and sample YSR energies. If the temperature is finite, there is thermal occupation of the originally empty YSR state, which results in thermally assisted YSR-YSR tunneling that happens at the difference of tip and sample YSR energies. The relative spin orientation will change the intensity of both processes, and Green's function theory can readily explain the spin selection rules. We use a mK-STM to study the YSR-YSR tunneling processes from 15mK to 1K, and the temperature dependence of thermal and normal YSR-YSR processes gives insight of their spin dynamics.

O 79.6 Thu 12:00 H15

Integrating Yu-Shiba-Rusinov states into a tunnel junction — •Christian R. Ast[1], Haonan Huang[1], Jacob Senkpiel[1], Robert Drost[1], Simon Dambach[2], Ciprian Padurariu[2], Björn Kubala[2], Juan Carlos Cuevas[3], Alfredo Levy Yeyati[3], Joachim Ankerhold[2], and Klaus Kern[1,4] — [1]MPI für Festkörperforschung, Stuttgart — [2]Institut für komplexe Quantensysteme, Universität Ulm, Ulm — [3]Universidad Autónoma de Madrid, Madrid, Spain — [4]EPFL, Lausanne, Switzerland

Magnetic impurities in a superconductor give rise to subgap features called Yu-Shiba-Rusinov (YSR) states. On or near surfaces, these impurities can be well studied locally by scanning tunneling microscopy (STM). We have observed a non-trivial energy dependence of the YSR state as a function of tip-sample distance, similar to findings that have been reported before. The occurrence of this phenomenon deep in the tunneling regime suggests a non-negligible influence of the tip on the YSR impurity. Therefore, in order to interpret this energy dependence, a more holistic model of the tunnel junction including the YSR state is necessary. To this end, we discuss a model that extends the existing Green's function description of YSR states and also bridges a gap to related models.

O 79.7 Thu 12:15 H15

Interplay between Yu-Shiba-Rusinov states and spin-flip excitations on magnetic impurities on superconducting $NbSe_2$ substrate — •Shawulienu Kezilebieke[1], Rok Žitko[2], Marc Dvorak[1], Teemu Ojanen[3], and Peter Liljeroth[1] — [1]Department

of Applied Physics, Aalto University School of Science, 00076 Aalto, Finland — [2]Jožef Stefan Institute, Jamova 39, SI-1001 Ljubljana, Slovenia — [3]Laboratory of Physics, Tampere University of Technology, Tampere FI-33101, Finland

Exchange coupling between a magnetic impurity and a superconducting substrate results in the formation of Yu-Shiba-Rusinov (YSR) bound states, which have been recently used in artificial designer structures to realize exotic quasiparticles known as Majorana fermions. At strong coupling, the energies of YSR states are deep in the superconducting gap. At weak coupling, the YSR states migrate towards the superconducting gap edge. Additional spectral features can appear in the presence of magnetic anisotropy with spin $S \geqslant 1$, in particular spin-flip excitations outside the superconducting gap. Despite extensive experiments on magnetic impurities that exhibit separately either spin-flip excitations or YSR states, these phenomena have not been observed simultaneously. Here, we investigate the spectral evolution in different metal phthalocyanine molecules on $NbSe_2$ surface as a function of the coupling with the substrate. Using scanning tunneling microscopy (STM), we tune the exchange coupling strength and for manganese phthalocyanine (MnPc) we demonstrate a smooth spectral crossover from the YSR states to intrinsic quantum spin states.

O 79.8 Thu 12:30 H15

Fractional charge tunneling between Shiba states in STM devices — •Ciprian Padurariu[1], Haonan Huang[2], Björn Kubala[1], Simon Dambach[1], Christian R. Ast[2], and Joachim Ankerhold[1] — [1]Institute for Complex Quantum Systems and IQST, Ulm University, 89069 Ulm, Germany — [2]Max-Planck-Institut für Festkörperforschung, 70569 Stuttgart, Germany

We present the theory and experimental realization of tunneling between tip and substrate Shiba states in superconducting STM devices operating at 15 mK. The simple analytical results are in good agreement with conductance measurements exhibiting peaks in the tunnel current at a number of sub-gap bias voltages. [1] The voltages are identified as resonances of sub-gap discrete magnetic states, so called Shiba states, that form inside a volume around the magnetic impurity of coherence length size. [2]

When a Shiba state formed around an impurity in the STM tip is brought into proximity with a Shiba state formed around an impurity in the substrate, new resonances arise at characteristic values of the voltage. The tunnel current at the new resonances is a result of the interplay between coherent transport processes and incoherent relaxation. The elementary transport process carries a fractional charge proportional to the electron-hole asymmetry in the device.

[1] M. Ruby, F. Pientka, Y. Peng, F. von Oppen, B. W. Heinrich, and K. J. Franke, Phys. Rev. Lett. **115**, 087001 (2015).

[2] M. I. Salkola, A. V. Balatsky, and J. R. Schrieffer, Phys. Rev. B **55**, 12648 (1997).

O 79.9 Thu 12:45 H15

Renormalization of single-ion magnetic anisotropy by charge fluctuations — •David Jacob — Dpto. de Física de Materiales, Universidad del País Vasco UPV/EHU, San Sebastián, Spain — IKERBASQUE, Basque Foundation for Science, Bilbao, Spain

Inelastic spin-flip excitations associated with single-ion magnetic anisotropy of quantum spins can be strongly renormalized by Kondo exchange coupling to the conduction electrons in the substrate, as shown recently for the case of Co adatoms on CuN_2 islands [1]. In this case, differential conductance spectra show zero-bias anomalies due to a Kondo effect of the doubly degenerate ground state, and finite-bias step features due to spin-flip excitations. Here I consider spin-1 quantum magnets with positive uniaxial anisotropy, where the ground state is nondegenerate and hence the Kondo effect does not take place [2]. Nevertheless, despite the absence of Kondo effect the magnetic anisotropy can still be strongly renormalized, both by exchange coupling to the conduction electrons and also by charge fluctuations. Interestingly, in contrast to the renormalization by Kondo exchange, charge fluctuations lead to asymmetric spectra, which, for strong charge fluctuations, mimic Fano-Kondo lineshapes, even though the origin is completely different.

References: [1] J. C. Oberg *et al.*, Nature Nanotechnol. **9**, 64 (2014); [2] D. Jacob, Phys. Rev. B **97**, 075428 (2018)