O 15: Spins on surfaces at the atomic scale I

Time: Monday 15:00–18:00 Location: WILL/A317

Invited Talk O 15.1 Mon 15:00 WILL/A317

Tuning Spin-1/2 Interactions in Graphene: From Long-Range Coupling to Altermagnetic Order — •Beatriz Viña-Bausá[1], Manuel A. García-Blázquez[1], Antonio T. Costa[2], Joao C. G. Henriques[2], Roberto Carrasco[1], Eva Cortés-del Río[1], Diego Expósito[1], Pierre Mallet[3], Jean-Yves Veuillen[3], Joaquín Fernandez-Rossier[2], Juan J. Palacios[1], and Iván Brihuega[1] — [1]Dept. Física de la Materia Condensada, Universidad Autónoma de Madrid, Spain — [2]International Iberian Nanotechnology Laboratory, Portugal — [3]Université Grenoble Alpes, France

Here, we demonstrate that graphene, functionalized with H atoms, serves as a versatile platform for engineering and investigating long-range magnetic interactions. Through scanning tunneling microscopy, we manipulate spin-1/2 moments induced by single H atoms on graphene and quantify their coupling via spin excitations using inelastic electron tunneling spectroscopy[1]. Our measurements reveal robust ferromagnetic and antiferromagnetic exchange interactions in H pairs, extending over nanometer-scale distances. Additionally, guided by symmetry selection, we realize unconventional magnetic phases in our system, namely altermagnets and Lieb ferrimagnets[2]. Our results, supported by mean-field Hubbard and density functional theory calculations put forward hydrogenated graphene as a promising material for simulating exotic spin systems.

[1] B. Viña-Bausá, et al., arXiv:2511.06887 (2025)
[2] B. Viña-Bausá, et al., Nano Letters 25,11554-11561 (2025)

O 15.2 Mon 15:30 WILL/A317

versatile building blocks for molecular qubits on surfaces — •Saba Taherpour[1,2], Corina Urdaniz[1,3], Jisoo Yu[1,3], Jose Reina-Galvez[1,3,4], Kevin Lizárraga[1,3], and Christoph Wolf[1,3] — [1]Center for Quantum Nanoscience, Institute for Basic Science (IBS), Seoul 03760, Korea — [2]Department of Physics, Ewha Womans University, Seoul 03760, Korea — [3]Ewha Womans University, Seoul 03760, Korea — [4]University of Konstanz, 78457 Konstanz, Germany

Electron spins are natural quantum objects. Molecules that host an electron spin S=1/2 can therefore be considered qubit candidates provided they have reasonable coherence times. In this work, I will show based on first-principles calculations how the charge transfer across an Ag/MgO interface can be utilized to change the charge and spin state of 3d transition-metal phthalocyanine molecules. Iron(II) phthalocyanine (FePc) emerges as a promising qubit candidate. We present density functional theory calculations and nonequilibrium quantum transport simulations based on recent developments of all electrical electron spin resonance in atomic scale magnetic transport junctions. Our results indicate that FePc on the Ag/MgO substrate can be used as molecular building block of on-surface qubit architectures.

O 15.3 Mon 15:45 WILL/A317

Creating multi-well energy landscapes from coupled orbital memory states — •Kira Junghans, Niek M. M. Aarts, Hermann Osterhage, Julián D. Rojas-Castillo, and Alexander A. Khajetoorians — Institute for Molecules and Materials, Radboud University, Nijmegen, The Netherlands

The interaction between atomic spins on surfaces is usually dictated by the exchange interaction. Its short-range nature strongly favors spin orientations that are either ferro- or antiferromagnetic. Recently, it was shown that memory can be created from an atomic spin using its valency [1]. Unlike the exchange interaction, it was shown that the interactions between orbital memory elements are long-range. This can lead to complex stochastic dynamics often needed in computational schemes based on theoretical neuroscience [2]. Exploiting this new functionality requires a deeper understanding of the nature of the interaction as well as the uniqueness of this material system.

Here, we study the stochastic dynamics of Co and Fe atoms on black phosphorus with scanning tunneling microscopy and spectroscopy. We quantify how the state favorability and lifetimes are influenced in dimers at different distances and by the neighboring atoms' state. We find that heterogenous dimers can also lead to complex stochastic noise, analogous to multi-well behavior. Furthermore, we investigate the dynamics of multiple coupled atoms and show that the state favorabilities can be tuned by the states of all surrounding atoms.

[1] B. Kiraly et al., Nat. Comm. 9, 3904 (2018).
[2] B. Kiraly et al., Nat. Nanotechn. 16, 414 (2021).

O 15.4 Mon 16:00 WILL/A317

Single spin control of atomic defects in monolayer MoS_2 — •Kwan Ho Au-Yeung[1,3], Wantong Huang[1,3], Johanna Matusche[1,3], Paul Greule[1,3], Jonas Arnold[1,3], Lovis Hardeweg[1,3], Máté Stark[1,3], Luise Renz[1,3], Affan Safeer[2], Daniel Jansen[2], Jeison Fischer[2], Thomas Michely[2], Wolfgang Wernsdorfer[1,3], Christoph Sürgers[1,3], Johannes Schwenk[1,3], Wouter Jolie[2], and Philip Willke[1,3] — [1]Physikalisches Institut, Karlsruhe Institute of Technology, Karlsruhe — [2]II. Physikalisches Institut, Universität zu Köln, Köln — [3]Center for Integrated Quantum Science and Technology, Karlsruhe Institute of Technology, Karlsruhe

Point defects in two-dimensional (2D) semiconductors host localized quantum states that can function as sensors, single-photon emitters, and qubits, but their controlled realization and individual addressability in atomically thin hosts remain challenging. Here we combine scanning tunneling microscopy with electron spin resonance (ESR-STM) to achieve single-spin control of atomic defect in a monolayer transition-metal dichalcogenide. Using STM manipulation, we create individual point defects, including sulfur vacancies and substitutional impurities in monolayer MoS_2 on graphene/Ir(111). Scanning tunneling spectroscopy and ESR measurements reveal their electronic structures and magnetic properties respectively, while pulsed ESR schemes enable quantum control of their spin states at the atomic scale. Our results demonstrate that monolayer MoS_2 provides a solid-state quantum platform that directly links 2D materials engineering with atomic-scale spin initialization, control, and readout.

O 15.5 Mon 16:15 WILL/A317

Imaging 2D ferromagnetic order with a single nickelocene molecule — •Leonard Edens[1], Trisha Sai[1], Divya Jyoti[1], Stefano Trivini[1], Fabian Schulz[1], and Nacho Pascual[1,2] — [1]CIC nanoGUNE BRTA, 20018 Donostia - San Sebastián, Spain — [2]Ikerbasque, Basque Foundation for Science, 48013 Bilbao, Spain

Lanthanide intermetallic compounds formed on coinage metal (111) surfaces exhibit ferromagnetic ground states with moments robustly aligned towards a polarization axis, even in the single monolayer limit. Characteristic of these 2D magnetic systems is the intricate dependence of the easy axis on 4f occupancy, and the formation of a moiré-induced superstructure with the support, which causes an inhomogeneous local magnetization [1]. Here, we study two representative alloys of this family of materials, $GdAu_2$ and $TbAu_2$, which respectively magnetize in- and out-of-plane. To sense their magnetic state, we employ a single nickelocene molecule adsorbed on the tip of a scanning tunnelling microscope. By quantifying the directional exchange field atom-by-atom, we characterize incommensurate order and local perturbations to the moiré-congruent magnetic texture. Further insight into the nature of the exchange field is gained by studying its dependence on vertical separation and externally applied magnetic fields.

[1] Edens et al. Advanced Materials (2025).
https://doi.org/10.1002/adma.202510753

O 15.6 Mon 16:30 WILL/A317

Two-photon transition in an Er-Ti atomic spin pair — •Dasom Choi[1,2], Yaowu Liu[1,2], Stefano Reale[2,3], Jeongmin Oh[1,2], Lei Fang[1,2], We-hyo Seo[1,2], Andreas Heinrich[1,2], Fabio Donati[1,2], and Soo-hyon Phark[1,2] — [1]Department of Physics, Ewha Womans University, Seoul, Republic of Korea — [2]Center for Quantum Nanoscience (QNS), Institute for Basic Science (IBS), Seoul, Republic of Korea — [3]QuTech and Kavli Institute of Nanoscience, Delft University of Technology, Delft, The Netherlands

Multi-photon process becomes a key ingredient in quantum information science, offering a promising route to nonlinear quantum transitions and entanglement generation. Extending this to atomic spin qubits on surfaces is of great interest, yet has not been demonstrated. In this work, we investigate a spin-pair of Er and Ti atoms adsorbed on a MgO/Ag(100) surface using a scanning tunneling microscope (STM). By applying pulsed electron spin resonance in the STM, we realize two-photon resonant transitions corresponding to an angular momentum change of $\Delta m = \pm 2$ of the spin-pair, a phenomenon beyond the conventional single-photon processes as shown at the single atom

level. Our work demonstrates the ability to coherently control higher-order quantum transitions at the single spin level, which provides a novel pathway towards implementing multi-quantum gate operations in atomic spin qubits, highlighting the potential of single atomic lanthanides on a surface for quantum information processing.

O 15.7 Mon 16:45 WILL/A317

Landau-Zener transitions of multilevel atomic spins — •Lukas Veldman[1,2], Henrik Lichtl[1,2], Nicolaj Betz[1,2], Johannes Schust[1], Laëtitia Farinacci[1,3], Fernando Delgado[4], Susanne Baumann[1,2], and Sebastian Loth[1,2] — [1]University of Stuttgart, Institute for Functional Matter and Quantum Technologies — [2]Center for Integrated Quantum Science and Technology (IQST), University of Stuttgart — [3]Carl Zeiss Stiftung Center for Quantum Photonics — [4]Instituto de Estudios Avanzados IUDEA, Departamento de Física, Universidad de La Laguna, Tenerife, Spain

The ability to perform Landau-Zener (LZ) transitions is a powerful and relatively unexplored tool to study and control spins on the nanoscale. LZ transitions provide spectroscopic information about energy level crossings, state populations and can even be used as a driving mechanism for coherent control over quantum spin states. In an idealized picture of a two level system (TLS), these qualities can be relatively easily understood via the LZ model. Here, we show LZ transitions on antiferromagnetic Fe chains on Cu2N/Cu(100) induced by ramping the magnetic field emanating from the tip of a scanning tunneling microscope (STM). Using real time measurement of the spin state we distinguish between classical and quantum tunneling transition processes. We find that avoided level crossings in higher excited states play a significant role in the dynamics between the ground states, showcasing the necessity to go beyond the TLS approximation used in the standard LZ model.

O 15.8 Mon 17:00 WILL/A317

Robustness of zero-energy edge states to disorder in bottom-up designed Fe chains on a superconducting Rashba alloy — •Harim Jang[1], Daniel Crawford[2], Jens Wiebe[1], Stephan Rachel[3], and Roland Wiesendanger[1] — [1]Department of Physics, University of Hamburg, Hamburg, Germany — [2]Department of Physics and Nanoscience Center, University of Jyväskylä, Finland — [3]School of Physics, University of Melbourne, Parkville, Australia

In this talk, we report on the role of disorder for the observation of Majorana zero modes (MMs) and a topological gap in a tailored 1D magnet-superconductor hybrid (MSH) system, showing the robustness of MMs to disorder, even in cases for which the topological gap is fully suppressed. We constructed 1D spin chains from Fe atoms on the Rashba surface alloy BiAg2/Ag(111) with proximity-induced superconductivity from a Nb(110) substrate. While the Fe chains have perfect crystalline order by design, the BiAg2/Ag(111) film exhibits nanoscale potential disorder, observed by scanning tunneling microscopy. However, this doesn't prevent the emergence of zero-energy states at the Fe chain's ends, in agreement with tight-binding calculations which show that they only appear in the topologically non-trivial regime [1]. This may not only explain earlier observations of MMs in disordered MSH systems, but also provides novel perspectives for the realization of robust Majorana qubits. [1] H. Jang et al., arXiv:2506.17414 (2025)

O 15.9 Mon 17:15 WILL/A317

Coherent control of a single 4f electron spin — •Yaowu Liu[1,2], Dasom Choi[1,2,3], Stefano Reale[1,2], Jeongmin Oh[1,2,3], Lei Fang[1,2], We-hyon Soe[1,2], Andreas Heinrich[1,2,3], Soo-hyon Phark[1,2], and Fabio Donati[1,2,3] — [1]IBS Center for Quantum Nanoscience (QNS) — [2]Ewha Womans University, Seoul 03760, Korea — [3]Department of Physics, Ewha Womans University, Seoul 03760, Republic of Korea

Electron spins on surface provide an atomic scale qubit platform for quantum information science using scanning tunneling microscopy (STM). Lanthanide atoms, with their strongly localized 4f electrons, can be potential candidates for single atom qubits with a long quantum coherence. However, STM tunneling current can strongly reduce the coherence time of surface atoms if they are probed directly. To circumvent this issue, it is possible to use an alternative scheme where a Ti (S = 1/2) atom located in a position within a 1 nm distance from a single Er atom on MgO surface can sense the quantum spin states of its 4f electron shells. In this work, we performed pulsed electron spin resonance (ESR) on the Er atom and demonstrated coherent control of 4f-electron spin of a single Er atom. Moreover, we observed a tenfold enhancement of Rabi rate compared to the direct drive of Ti atom from the tip, which is ascribed to the anisotropy of exchange interaction between the two spins.

O 15.10 Mon 17:30 WILL/A317

Kondo physics of composite molecular spins made from coupled nanographenes — •David Jacob — Department of Physics, University of Alicante, Spain

Open-shell nanographenes can now be fabricated by on-surface synthesis (OSS) and stabilized on metallic substrates, enabling access to their intrinsic (multi)radical character. Scanning-tunneling spectroscopy (STS) reveals clear Kondo signatures, demonstrating that these nanographenes host quantum spins whose magnitude reflects their degree of radicality [1]. By covalently linking such magnetic nanographenes, coupled spin systems can be engineered in controlled geometries–including dimers [2], hexagons [3], chains [4], and other topologies–allowing quantum magnetism to be probed at the atomic scale. Here we investigate coupled nanographenes whose constituent units have different spin magnitudes. We show that the composite nature of the resulting effective molecular spin leads to a rich spectrum of spin excitations and to unconventional Kondo behavior.

References:

[1] *JACS Au* **3**, 1358 (2023); *Phys. Rev. Res.* **6**, L022061 (2024).
[2] *Phys. Rev. B* **106**, 205405 (2022); *Nano Lett.* **23**, 9353 (2023).
[3] *Angew. Chem. Int. Ed.* **60**, 25224 (2021).
[4] *Nature* 588, **287** (2022).

O 15.11 Mon 17:45 WILL/A317

Site-Specific magnetism of Ho atoms on MgO — •Andrés Pinar Solé[1,2], Merve Ercelik[1,2], Jungseok Chae[1,2], Fabio Donati[3], Dmitriy Borodin[1,2], and Andreas Heinrich[3] — [1]Center for Quantum Nanoscience (QNS), Institute for Basic Science (IBS) — [2]Ewha Womans University — [3]Department of Physics, Ewha Womans University

Holmium (Ho) atoms on ultrathin MgO films are model systems for single-atom magnetism, where spin stability and relaxation strongly depend on the local crystal field and adsorption site. Isolated Ho atoms on oxygen sites of Ag(100)/MgO exhibit magnetic bistability but lack clear inelastic spin-excitation features; nevertheless, their magnetic states can be switched and read electrically through spin-polarized tunneling.

By extending to Ho dimers, additional spin-flip excitations become accessible, providing deeper insight into the electronic and magnetic states of Ho on MgO. The magnetic behavior of Ho dimers reflects the intra-atomic exchange coupling between the highly localized 4f moment and the outer valence-shell spins. Certain Ho dimers exhibit pronounced inelastic conductance steps, revealing strong magnetic interactions both between the atoms and with the surrounding MgO crystal field. Using STM-based atom manipulation, we precisely assemble Ho dimers on bridge and oxygen sites and probe their magnetic and electronic properties via Kelvin probe force microscopy (KPFM) and inelastic electron tunneling spectroscopy (IETS) in a combined STM/AFM UHV setup.