TT 35: Superconducting Electronics: SQUIDs, Circuit QED

Time: Wednesday 9:30–13:15 Location: H 2053

TT 35.1 Wed 9:30 H 2053

Spin Hamiltonian of 3d/4f single molecule magnets revealed by micro-SQUID-EPR — •Sagar Paul[1], Mario Ruben[2], Shouvik Chattopadhyay[3], Eufemio Moreno-Pineda[4], and Wolfgang Wernsdorfer[1] — [1]Physikalisches Institut, Karlsruhe Institute of Technology (KIT), Germany. — [2]Institute of Nanotechnology, Karlsruhe Institute of Technology, Germany. — [3]Jadavpur University, Kolkata - 700032, India. — [4]Universidad de Panamá, 0824, Panamá.

The single molecule magnets (SMM) exhibit magnetic anisotropy at molecular level, slow relaxation and resonant quantum tunneling of magnetization (QTM) leading to numerous applications in molecular spintronics and quantum information processing. The hyperfine levels observed in micro-SQUID M(H) measurements open possibilities of utilizing nuclear spin in quantum computation. Further, recent observations of large decoherence times of electronic spin states in diluted single crystals of Gd SMMs [1], has re-encouraged the research on such SMMs. A combined micro-SQUID-EPR [2] stands as a unique experimental technique to precisely study the magnetism, in situ while exciting a single crystal with microwave pulse. With this technique, the M(H) loops of 3d/4f monomer/dimer SMMs studied in 30 mK - 5 K range, and for different frequencies of microwave excitation, exhibit absorption peaks associated to specific spin transitions. The peak positions plotted with RF frequency (1-40 GHz) and field angles reveal the entire spin Hamiltonian of the system [2].

[1] G. Handzlik et al., J. Phys. Chem. Lett. 11 (2020) 1508
[2] G. Taran et al., Nat. Commun. 14 (2023) 3361

TT 35.2 Wed 9:45 H 2053

Nb constriction-Josephson-junction nanoSQUIDs on cantilevers patterned by He and Ne focused ion beams — •Jan Ullmann[1], Timur Griener[1], Simon Koch[1], Simon Pfander[1], Chloé Bureau-Oxton[2], Daniel Jetter[3], Andriani Vervelaki[3], Kousik Bagani[3], Ute Drechsler[2], Oliver Kieler[4], Reinhold Kleiner[1], Martino Poggio[3], Armin Knoll[2], and Dieter Koelle[1] — [1]Physikalisches Institut, Center for Quantum Science (CQ) and LISA$^+$, Universität Tübingen, Germany — [2]IBM Research Europe, Zürich, Rüschlikon, Switzerland — [3]Department of Physics and Swiss Nanoscience Institute, University of Basel, Switzerland — [4]Department Quantum Electronics, Physikalisch-Technische Bundesanstalt, Braunschweig, Germany

Nanopatterning of superconducting thin film structures with focused He or Ne ion beams (He/Ne-FIB) offers a flexible tool for creating constriction-type Josephson junctions (cJJs) which can be integrated into strongly miniaturized Superconducting Quantum Interference Devices (nanoSQUIDs). We present our attempts to use He/Ne-FIB for fabricating Nb nanoSQUIDs which shall provide ultra-low noise and high spatial resolution for their application in scanning SQUID microscopy (SSM). The nanoSQUIDs are designed as sensors for magnetic flux and dissipation. We address the possibility to implement multi-terminal, multi-cJJ SQUIDs on custom-made Si cantilevers, which will provide the possibility of simultaneous conventional topographic imaging by atomic force microscopy (AFM). We will discuss the status and challenges of this project to combine SSM and AFM on the nanoscale.

TT 35.3 Wed 10:00 H 2053

Development of ultrasensitive dc SQUIDs with sub-micrometer circuit elements — •Mauro Esattore[1], Michael Paulsen[2], Jörn Beyer[2], Mark Bieler[1], Oliver Kieler[1], Patryk Krzysteczko[2], and Rainer Körber[2] — [1]Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany — [2]Physikalisch-Technische Bundesanstalt, Abbestraße 2-10, 10587 Berlin, Germany

Since its first iteration in the early 1960s, the direct current Superconducting QUantum Interference Device (dc SQUID) has been one of the most sought-after applications of superconductor technology. Its sensitivity to even the smallest magnetic fields allows for numerous applications, be it as a magnetometer in the fields of biomagnetism, magnetic flux sensor of cryogenic detectors, or for electrical metrology. In this presentation, we discuss the use of superconductive, sub-micrometer fine-pitch coils to be used in Nb/AlOx/Nb SQUID designs. The aim is to minimize the inductive losses of the signal-to-SQUID coupling, without compromising the overall device layout. It is also possible to achieve outstanding coupled energy resolution - while using the dc SQUID as a current sensor- by adapting the input coil inductances to the impedance of the signal source. Finally, the sub-micrometer input coils allow for a much lower noise energy per bandwidth ϵ ($\epsilon \approx 16k_BT\sqrt{LC}$ under optimum conditions) as well as a wider range on input inductances for existing sensor types. We provide an overview of the fabrication process of the sub-micrometer fine-pitch coils, and some preliminary characterization results.

TT 35.4 Wed 10:15 H 2053

Tunable Superconductor Insulator Transition in a Quantum Phase Slip Interference Device — •Jan Nicolas Voss[1], Micha Wildermuth[1], Max Kristen[1,2], Hannes Rotzinger[1,2], and Alexey V. Ustinov[1,2] — [1]Physikalisches Institut, Karlsruher Institut für Technologie, Karlsruhe, Germany — [2]Institut für Quantenmaterialien und Technologien (IQMT), Karlrsruher Institut für Technologie, Karlsruhe, German

The duality between quantum phase slip nanowires and Josephson junctions has triggered a variety of theoretical and experimental works. However, many aspects of these fluctuations are still not fully understood, especially when interference effects are considered.

We present a realization of a quantum phase slip interferometer based on two strongly coupled granular aluminum nanowires connected in series. In the experiment, the interference is controlled by a gate voltage and manifests as a periodic modulation of the critical Coulomb blockade voltage. Our data show that the modulation amplitude depends on the homogeneity of the wires. To improve the wire homogeneity, we employ the intrinsic electromigration technique ([1]) which allows to adjust the resistances and thus the Coulomb blockade of the individual wires. We observe a strong destructive interference of quantum phase slips, displaying a transition from the insulating to a superconducting state. The circuit is analyzed in detail and future applications are proposed.

[1] J. N. Voss, Y. Schön, M. Wildermuth, D. Dorer, J. H. Cole, H. Rotzinger and A. V. Ustinov, ACS Nano (2021) Mar 23;15(3):4108

TT 35.5 Wed 10:30 H 2053

Design considerations for the optimization of λ-SQUIDs — •Constantin Schuster[1] and Sebastian Kempf[1,2] — [1]Institute of Micro- and Nanoelectronic Systems, Karlsruhe Institute of Technology, Germany — [2]Institute for Data Processing and Electronics, Karlsruhe Institute of Technology, Germany

Cryogenic microcalorimeters such as metallic magnetic calorimeters (MMC) or superconducting transition-edge sensors (TES) have become a mature technology and are presently used in various applications requiring an excellent energy resolution. While development on these established technologies continues to progress, we have recently introduced an alternative microcalorimeter concept, called λ-SQUID. It is based on the strong temperature dependence of the magnetic penetration depth of a superconducting material, affecting the current distribution within a superconducting wire and hence its kinetic and geometric inductance. We use this effect to build a detector in which the mutual inductance between a SQUID and an input coil carrying a constant current becomes temperature sensitive. In this contribution, we present theoretical considerations regarding the design of the sensing element in a λ-SQUID to yield an optimal sensitivity and energy resolution. We show that the noise contribution form the λ-SQUID can be minimised if the specific heat of the sensing element exactly equals the particle absorber. Additionally, we consider the influence of sensing- and input coil stripline width, thickness, and separation on the detector sensitivity using a modified geometric mean distance method adapted to superconductors.

TT 35.6 Wed 10:45 H 2053

Microwave measurements of a Josephson junction based on a 2D HgTe quantum well — •Wei Liu[1,2], Stanislau Piatrusha[1,2], Lena Fürst[1,2], Lukas Lunzer[1,2], Martin P. Stehno[1,2], and Laurens W. Molenkamp[1,2] — [1]Experimentelle Physik III, Physikalisches Institut, Universität Würzburg, Am Hubland, 97074 Würzburg, Germany. — [2]Institute for Topological Insulators, Universität Würzburg, Am Hubland, 97074 Würzburg, Germany

We measured the microwave response of a rf SQUID based on a 2D

HgTe Josephson junction, by inductively coupling it to a superconducting resonator. We extract both the current-phase relation and the phase dependent dynamic dissipation between the Andreev bound states. We focus on non-topological ABSs and study their response to temperature, magnetic field and strong microwave drive. The dynamic dissipation shows a temperature-driven crossover from 2π-periodic oscillations to a π-quasiperiodic pattern with different peak heights at even and odd values of phase π. We show how the magnetic field modulates the current phase relation and the dynamic dissipation peak, leading to effects such as the half flux periodicity, the Josephson diode effect and the splitting and combining of the dissipative peaks. Under a strong microwave irradiation, both the supercurrent and the dynamic dissipation deviate from the adiabatic Josephson effect. We attribute this to the nonequilibrium occupation of Andreev bound states due to photon induced transitions across the energy gap, which enables us to map out the phase dependent effective Andreev gap.

TT 35.7 Wed 11:00 H 2053

Anisotropic magnetic field dependence in hybrid superconductor/semiconductor microwave resonator as a signature of unconventional induced superconductivity — •Simon Feyrer[1], Ignacio Lobato[1], Michael Prager[1], Dominique Bougeard[1], Carlos Balseiro[2], Marco Aprili[3], Christoph Strunk[1], and Leandro Tosi[1,2] — [1]Institute of Experimental and Applied Physics, University of Regensburg, Germany — [2]Centro Atomico Bariloche, Comision Nacional de Energia Atomica, Argentina — [3]Laboratoire de Physique des Solides, Université Paris-Saclay, France

We present measurements of the frequency response of a lumped element microwave resonator made out of hybrid Al/InAs superconductor/semiconductor 2D heterostructures. In our device, the inductor is a narrow wire taylored in the material, dominating the kinetic inductance contribution. The resonance frequency depends on temperature, on power and strongly on in-plane magnetic field. We have observed an anisotropic magnetic field dependence, stronger when the in-plane field is orientated perpendicular to the wire. This anisotropy can be explained by considering the contribution of the kinetic inductance of the InAs 2DEG, where the induced superconductivity is affected by the spin-orbit coupling [1].

[1] D. Phan et al., Phys. Rev. Lett. 128 (2022) 107701

15 min. break

TT 35.8 Wed 11:30 H 2053

Phase locking squeezed states of microwave light — Lukas Danner[1,2], Florian Höhe[2], Ciprian Padurariu[2], Joachim Ankerhold[2], and •Björn Kubala[1,2] — [1]Institute of Quantum Technologies, German Aerospace Center (DLR), Ulm, Germany — [2]ICQ and IQST, Ulm University, Ulm, Germany

Squeezed states of light constitute an important resource for various quantum technological applications, such as using the reduced fluctuations for metrology or the entanglement of a two-mode squeezed state for teleportation or quantum illumination. For all these applications stabilization of the phase is crucial. Josephson photonics devices, where microwave radiation is created by inelastic Cooper pair tunneling across a *dc-biased* Josephson junction in-series with a microwave resonator, are particularly vulnerable as they lack the reference phase provided by an ac-drive. This hampers, for instance, the direct measurement of entanglement [1]. We recently developed a full quantum mechanical theory [2] describing, first, how the intrinsic shot noise of the Josephson-photonics device inevitably diffuses the oscillators phase and how, second, the phase and frequency of the emission can be locked to a weak ac-input. Based on this theory, we show here, how locking mechanism and features change, if Josephson-photonics devices are operated at a resonance, where pairs of photons and thus squeezed radiation are created.

[1] A.Peugeot et al., Phys. Rev. X **11** (2021) 031008
[2] F. Höhe et al., arXiv:2306.15292.

TT 35.9 Wed 11:45 H 2053

Magnetic bound-states embedded in tantalum superconducting thin films — •Soroush Arabi[1], Qili Li[2], Ritika Dhundhwal[1], Lucas Brauch[1], Pal Sudip[3], Dirk Fuchs[1], Jose Palomo[4], Marc Scheffler[3], Zaki Leghtas[4], Christian Kübel[5,6,7], Thomas Reisinger[1], Ioan Pop[1,2,3], and Wulf Wulfhekel[1,2] — [1]IQMT, Karlsruhe Inst. of Technology, Karlsruhe, Germany — [2]PHI, Karlsruhe Inst. of Technology, Karlsruhe, Germany — [3]PHI, Universität Stuttgart, Stuttgart, Germany — [4]ENS, Paris, France — [5]INT, Karlsruhe Inst. of Technology, Karlsruhe, Germany — [6]Joint Research Laboratory Nanomaterials, Technical University of Darmstadt, Darmstadt, Germany — [7]KNMF, Karlsruhe Inst. of Technology, Karlsruhe, Germany

Tantalum has been established as a new material platform for superconducting quantum devices with record coherence times. This has sparked intensive efforts to quantify the sources for the high performance and to find ways to further improve it. In this work, we study different phases of tantalum thin films, grown on sapphire (Al_2O_3) and magnesium oxide (MgO) substrates using different deposition methods such as direct current magnetron sputtering and also electron beam evaporation techniques. By employing a millikelvin MBE-STM system, we characterize these thin films at nanoscale. In sputtered films that have been exposed to air we observe magnetic bound-states poisoning the superconducting gap. Moreover, we show that epitaxial films grown under ultra-high vacuum condition do not suffer from the presence of those magnetic bound states.

TT 35.10 Wed 12:00 H 2053

Engineering the speedup of quantum tunneling in Josephson systems via dissipation — Johannes Hauff[1], Joachim Ankerhold[1], Gianluca Rastelli[2], Wolfgang Belzig[3], Sabine Andergassen[4], and •Dominik Maile[1] — [1]Institute for Complex Quantum Systems, Ulm University — [2]INO-CNR BEC Center and Dipartimento di Fisica, Università di Trento — [3]Fachbereich Physik, Universität Konstanz — [4]Informatics, TU Wien

We theoretically investigate the escape rate occurring via quantum tunneling in a system affected by tailored dissipation. Specifically, we study the environmental assisted quantum tunneling of the superconducting phase in a current-biased Josephson junction. We consider Ohmic resistors inducing dissipation both in the phase and in the charge of the quantum circuit. We find that the charge dissipation leads to an enhancement of the quantum escape rate. This effect appears already in the low Ohmic regime and also occurs in the presence of phase dissipation that favors localization [1]. We further discuss the influence of temperature on the observed effect and possible technological applications.

[1] D. Maile, J.Ankerhold, S. Andergassen, W. Belzig, G. Rastelli Phys. Rev. B 106 (2022) 045408

TT 35.11 Wed 12:15 H 2053

Hybrid high-T$_c$ two dimensional superconductor into quntum circuit — •Haolin Jin[1], Giuseppe Serpico[1], Christian N. Saggau[2], Tommaso Confalone[2], Yejin Lee[2], Poya Yang[1], Edourad Lense[1], Nicola Poccia[2], and Uri Vool[1] — [1]Max Planck institute for chemical physics of solids, Dresden, Germany — [2]Leibniz Institute for Solide state and Materials Research, Dresden, Germany

In the realm of superconducting quantum devices, van der Waals (vdW) materials are promising due to their high flexibility, relatively small volume, and tunable electronic properties. However, integrating the vdW material into the quantum circuit with high coherence is still an outstanding problem. In this study, we incorporate thin vdW flake of $Bi_2Sr_2CaCu_2O_8$ (BSCCO) into a Nb resonator circuit. The integration of BSCCO at the current antinode transforms the resonant mode, while maintaining a high quality factor (Q 10^4). Through temperature and power sweeping measurements, we demonstrate that the dissipation attributed to BSCCO in the circuit is predominantly due to interface dielectric losses and its behavior can be modeled by a bath of Two-Level Systems (TLS). By understanding the loss mechanisms in vdW based quantum circuits, we can optimize circuit coherence and pave the way to future hybrid circuits for quantum technology applications.

TT 35.12 Wed 12:30 H 2053

Circuit-QED hardware for simulating features of quantum gravity — •Mohammad Atif Javed, Daniel Kruti, Ahmed Kenawy, Tobias Herrig, Christina Koliofoti, Oleksiy Kashuba, and Roman-Pascal Riwar — Peter Grünberg Institute, Theoretical Nanoelectronics, Forschungszentrum Jülich, D-52425 Jülich, Germany

The symbiosis of ideas between high-energy and condensed-matter physics has a long and fruitful tradition, be it the elusive Majorana fermion, the relativistic effects in graphene and Weyl semimetals, or the BCS theory serving as a blueprint for the Higgs mechanism. Here, we show that superconducting circuits can simulate fundamental and even highly speculative aspects of quantum gravity. We focus on two effects: Hawking radiation and quantum metrics. First, we demonstrate that the cosine behaviour of Josephson junctions allows for creating analogue wormholes with a single transient flux quench, subsequently permitting the system to evolve autonomously (unlike ultracold gases in which the drive is continuous). We propose two ways to detect the presence of these wormholes, first by observing the behavior of a wavepacket as it traverses the system and second by measuring how the correlations evolve in time in their presence. Second, using multistable Josephson junctions, we study how to create superpositions of different spacetime metrics. We can demonstrate the presence of this superposition with a wavepacket moving across the system that will split as it entangles with different metrics.

TT 35.13 Wed 12:45 H 2053

Circuit QED with two $\mathcal{PT}$-symmetric non-Hermitian qubits — •Mikhail Fistul[1], Grigory A. Starkov[2], and Ilya M. Eremin[1] — [1]Institut für Theoretische Physik III, Ruhr-Universität Bochum, Bochum, Germany — [2]Theoretische Physik IV, Universität Würzburg, Würzburg, Germany

Motivated by recent experiments on single non-Hermitian superconducting [1] or spin-qubits [2] we present here a detailed analysis of an exmplary $\mathcal{PT}$-symmetric circuit QED composed of two biased non-Hermitian qubits embedded in a lossless resonator [3]. We consider a resonant quantum circuit as $|\omega_r - \Omega| \ll \omega_r$, where Ω and ω_r are qubits and resonator frequencies, respectively, providing well-defined groups of quasidegenerate resonant states. Non-Hermiticity is introduced via a staggered gain/loss parameter, γ of individual qubits. Using the direct numerical diagonalization and the generalized Schrieffer-Wolff transformation we obtain the dependence of low-lying eigenspectrum on the interaction strength between a single qubit and the resonator, g, identify the $\mathcal{PT}$-symmetry broken and unbroken phases, and exeptional points of second and third order. We also show that in $\mathcal{PT}$-symmetric circuit QED non-Hermiticity mixes the "dark" and the "bright" states.

[1] W. Chen, M. Abbasi, Y. N. Joglekar, K. W. Murch, Phys. Rev. Lett. **127** (2021) 140504
[2] Y. Wu, et. al., Science **364** (2019) 878
[3] G. A. Starkov, M. V. Fistul, I. M. Eremin, arXiv:2309.09829

TT 35.14 Wed 13:00 H 2053

Nonlinear Conductivity in Superconductor MgB_2 Films — •Clemens Schmid[1], Markus Gruber[1], Corentin Pfaff[2], Karine Dumesnil[2], Thomas Hauet[2], Stephane Mangin[2], and Oleksandr Dobrovolskiy[1] — [1]Faculty of Physics and Vienna Doctoral School in Physics, University of Vienna, Vienna, Austria — [2]Université de Lorraine, CNRS, IJL, Nancy, France

Knowing the maximal vortex velocities is essential for assessing the energy relaxation mechanisms in superconductors and their applications in superconducting single-photon detectors (SSPDs) [1]. The dynamics of vortices at a few km/s velocities is furthermore interesting itself, because of the question regarding the ultimate speed limits for magnetic flux transport in superconductors and generation of sound and spin waves in heterostructures [2]. Here, we investigate the current-voltage curves of single crystal MgB_2 20 nm-thick films which have comparably high critical temperatures of 30 K [3] and are interesting as potential materials for SSPDs. In the regime of nonlinear conductivity, we investigate the escape of non-equilibrium electrons from the vortex cores and compare the associated relaxation time of quasiparticles for MgB_2 films of different structural quality and capped with a good-conductor (Au) layer. The deduced parameters are discussed in the context of crossover from global to local instability models and the application of MgB_2 films in SSPDs [4].

[1] D. Vodolazov et al., Phys. Rev. Appl. 7 (2017) 034014
[2] O. Dobrovolskiy et al., Nat. Commun. 11 (2020) 3291
[3] M. Muralidhar et al., J. Phys. D: Appl. Phys. 57 (2023) 053001
[4] I. Charaev et al., arXiv 2308.15228 (2023)