QI 10: Focus Session: Exploring Quantum Entanglement with Superconducting Qubits and Resonators (joint session QI/TT)

Harnessing quantum entanglement is crucial for advancing quantum technologies, and superconducting qubits and resonators have shown great promise in this regard. Impressive progress is contemporarily made in generating access to intermediate-scale quantum circuits, for the exploration of applications. These advancements highlight the progress and potential of superconducting qubits in harnessing quantum entanglement, paving the way for further progress in quantum communication, computation, and sensing. Organized by Oded Zilberberg.

Time: Tuesday 9:30–13:30 Location: HFT-FT 131

Invited Talk QI 10.1 Tue 9:30 HFT-FT 131

Loophole-free Bell Inequality Violation with Superconducting Circuits — •Andreas Wallraff — Department of Physics, ETH Zurich, Switzerland

Superposition, entanglement, and non-locality constitute fundamental features of quantum physics. Remarkably, the fact that quantum physics does not follow the principle of locality can be experimentally demonstrated in Bell tests performed on pairs of spatially separated, entangled quantum systems. While Bell tests were explored over the past 50 years, only relatively recently experiments free of so-called loopholes succeeded. Here, we demonstrate a loophole-free violation of Bell's inequality with superconducting circuits [1]. To evaluate a CHSH-type Bell inequality, we deterministically entangle a pair of qubits and perform fast, and high-fidelity measurements along randomly chosen bases on the qubits connected through a cryogenic link spanning 30 meters. Evaluating more than one million experimental trials, we find an average S-value of 2.0747 * 0.0033, violating Bell's inequality by more than 22 standard deviations. Our work demonstrates that non-locality is a viable new resource in quantum information technology realized with superconducting circuits with applications in quantum communication, quantum computing and fundamental physics.

[1] S. Storz, J. Schär, A. Kulikov, P. Magnard, P. Kurpiers, J. Lütolf, T. Walter, A. Copetudo, K. Reuer, A. Akin, J-C. Besse, M. Gabureac, G. J. Norris, A. Rosario, F. Martin, J. Martinez, W. Amaya, M. W. Mitchell, C. Abellán, J-D. Bancal, N. Sangouard, B. Royer, A. Blais, and A. Wallraff, Nature 617, 265-270 (2023).

Work done in collaboration with Simon Storz, Josua Schaer, Anatoly Kulikov, Paul Magnard, Philipp Kurpiers, Janis Luetolf, Theo Walter, Adrian Copetudo, Kevin Reuer, Abdulkadir Akin, Jean-Claude Besse, Mihai Gabureac, Graham J. Norris, Andres Rosario, Ferran Martin, Jose Martinez, Waldimar Amaya, Morgan W. Mitchell, Carlos Abellan, Jean-Daniel Bancal, Nicolas Sangouard, Baptiste Royer, Alexandre Blais, and Andreas Wallraff

Invited Talk QI 10.2 Tue 10:00 HFT-FT 131

Microwave quantum networks — •Kirill G. Fedorov — Walther-Meißner-Institut, 85748 Garching, Germany — School of Natural Sciences, Technische Universität München, 85748 Garching, Germany — Munich Center for Quantum Science and Technology (MCQST), 80799 München, Germany

Distributing quantum entanglement between distant nodes of a large-scale network is a fundamentally important milestone for many applications in the field of quantum information processing. Here, entanglement in the form of two-mode squeezed light can be employed as a resource for various nonclassical communication protocols, such as quantum teleportation or remote qubit entanglement. Motivated by the recent breakthroughs in quantum computation & simulation with superconducting circuits operated at microwave frequencies, we demonstrate distribution of two-mode squeezed states at carrier frequencies around 5.5 GHz across a local area cryogenic quantum network. We present the experimental evidence for robustness of the microwave entanglement distribution against noise and losses in superconducting channels. Furthermore, we utilize this entanglement resource to perform a coherent state teleportation between distant cryostats with fidelities exceeding the no-cloning limit. Finally, by relying on the same technology and frequency range, we discuss remote entanglement of superconducting qubits with two-mode squeezed microwave light. Our results highlight feasibility of microwave quantum communication and pave the road towards distributed quantum computing with superconducting circuits.

QI 10.3 Tue 10:30 HFT-FT 131

Investigation of hybrid CV-DV entanglement in the microwave regime — •Simon Gandorfer[1,2], Yuki Nojiri[1,2], Fabian Kronowetter[1,2], Kedar E. Honasoge[1,2], Maria-Teresa Handschuh[1,2], Joan Agustí[1,2], Peter Rabl[1,2,3], Rudolf Gross[1,2,3], and Kirill G. Fedorov[1,2,3] — [1]Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, 85748 Garching, Germany — [2]School of Natural Sciences, Technische Universität München, 85748 Garching, Germany — [3]Munich Center for Quantum Science and Technology (MCQST), 80799 Munich, Germany

Distributing entanglement between spatially separated nodes of a large-scale quantum network is a fundamentally important milestone for many applications. It also provides the quantum resource for various quantum protocols, such as quantum teleportation or remote qubit gate operations. In our experiment, we employ a superconducting transmon qubit in a superconducting 3D aluminium cavity illuminated by one mode of a microwave two-mode squeezed (TMS) state. Here, the TMS state acts as a quantum-correlated reservoir. By choosing an appropriate set of observables, we identify a joint measurement between the qubit and the second mode of the TMS state that allows us to observe a hybrid, discrete-continuous variable, entanglement. We experimentally investigate the entanglement conversion process in this novel hybrid regime and discuss its possible extensions and applications for distributed quantum computing.

QI 10.4 Tue 10:45 HFT-FT 131

Parametric coupler architecture for on-demand reset, readout and leakage recovery of superconducting qubits — •Gerhard Huber[1,2], Federico Roy[2,3], Joao Romeiro[1,2], Leon Koch[1,2], Niklas Bruckmoser[1,2], Niklas Glaser[1,2], Ivan Tsitsilin[1,2], Max Werninghaus[1,2], and Stefan Filipp[1,2] — [1]Technical University of Munich, Physics Department, 85748 Garching, Germany — [2]Walther-Meißner-Institut, 85748 Garching, Germany — [3]Theoretical Physics, Saarland University, 66123 Saarbrücken, Germany

When using superconducting qubits thermal excitations of the initial state, leakage into non-computational states during gate operations and unwanted decoherence due to coupling to a readout mode are, however, major sources of errors. Here, we present a superconducting qubit architecture with tunable qubit-resonator coupling. This architecture allows for the efficient preparation of the qubit ground state, the recovery of leakage from higher states and for on-demand qubit readout activated by a single parametric coupler. We experimentally demonstrate a reset operation that unconditionally prepares the qubit ground state with a fidelity of 99.8 ± 0.02 % and a leakage recovery operation with a 98.5 ± 0.3 % success probability. Furthermore, we implement a coupler-driven readout with a single-shot assignment fidelity of 88 ± 0.4 %. Completing this set of elementary operations with qubit-qubit gates using the same coupling element, reduces the system complexity and facilitates the implementation of scalable quantum processors.

QI 10.5 Tue 11:00 HFT-FT 131

Novel 3D circuit QED architecture for quantum information processing — •Desislava Atanasova[1,2], Ian Yang[1,2], Teresa Hönigl-Decrinis[1,2], Daria Gusenkova[3], Ioan Pop[3], and Gerhard Kirchmair[1,2] — [1]Institute for Quantum Optics and Quantum Information, A-6020 Innsbruck, Austria — [2]Institute for Experimental Physics, University of Innsbruck, A-6020 Innsbruck, Austria — [3]Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany

Superconducting circuits based on 3D architectures offer a way for hardware-efficient quantum information processing. Combined with nonlinearity, a single bosonic mode can replace a multi-qubit register, thus significantly reducing the required control electronics. Compared to their purely planar counterpart, 3D circuits possess longer lifetimes and a straightforward design that eases engineering the interactions in composite systems.

In this work, a superconducting coaxial cavity is coupled to a fluxonium qubit via a readout resonator. The tunability of the qubit, provided by a magnetic flux hose, is used to adjust the cavity-qubit interaction in situ. Combined with an element for two-photon dissipation, this setup could be utilized as an improved building block for a fully protected logical qubit.

15 min. break

Invited Talk QI 10.6 Tue 11:30 HFT-FT 131

Quantum sensing of axionic dark matter with a phase resolved haloscope — •Audrey Cottet — LPEM, ESPCI Paris — LPENS, Ecole Normale Supérieure de Paris

There is a general consensus that a large part of the matter and energy in the Universe is unknown. Well established candidates for dark matter are axions or axion-like particles. Their interaction with particles of the standard model is expected to be very weak. Hence, their detection requires ultimate amplification and measurement techniques. Quantum sensing is appealing in that context. We propose a new type of detector based on a non-linear quantum cavity coupled to a tunable magnetic mode. In order to circumvent the standard quantum limit of detection, we propose to exploit the phase-number variables of the electromagnetic field. The sensitivity of the detector can be pushed further by exploiting interference fringes in a cavity Schrödinger cat state. We expect a figure of merit exceeding by several orders of magnitude that of current detectors. This opens the way to real-time detection of possible axion signals. I will present how these ideas are being implemented experimentally using a hybrid cavity/magnon/superconducting circuit platform.

Invited Talk QI 10.7 Tue 12:00 HFT-FT 131

Demonstration of Quantum Advantage in Microwave Quantum Radar — Réouven Assouly, Rémy Dassonneville, Théau Péronnin, •Audrey Bienfait, and Benjamin Huard — Laboratoire de Physique à l'ENS Lyon, Lyon, France

The quantum radar promises to improve the speed of detection of a target placed in a noisy background by a factor of up to 4 in the low power regime compared to best possible classical radar. Observing this quantum advantage requires exploiting the quantum correlations through a joint measurement of the initially entangled probe and the idler which has never been performed in the previous microwave quantum radar attempts. Following a proposal by Guha and Erkmen [1], we demonstrate a quantum advantage of up to 1.2+/-0.1 in a proof-of-principle quantum radar operating at microwave frequencies.

Using a dual-purpose quantum emitter/receiver based on a Josephson ring modulator, we are able to generate two-mode squeezed states as well as perform the required joint measurement between the idler and the noisy reflected signal. After generation, the idler is stored in a memory mode while the signal half is emitted into a transmission line, goes through a tunable target after which it comes back to the quantum transceiver where it can be jointly measured with the idler using a two-mode squeezing operation followed by a photon-counting measurement via an auxiliary transmon qubit.

[1] Guha, S., Erkmen, B.I., Phys. Rev. A 80, 052310 (2009)

QI 10.8 Tue 12:30 HFT-FT 131

Hot Schrodinger Cat States in a High Coherence Niobium Cavity Coupled to a Superconducting Qubit — •Ian Yang[1,2], Thomas Agrenius[2,3], Vasilisa Usova[1,2], Oriol Romero-Isart[2,3], and Gerhard Kirchmair[1,2] — [1]Institute for Experimental Physics, University of Innsbruck, 6020 Innsbruck, Austria — [2]Institute for Quantum Optics and Quantum Information, Austrian Academy of Sciences, 6020 Innsbruck, Austria — [3]Institute for Theoretical Physics, University of Innsbruck, Innsbruck 6020, Austria

The observation of quantum phenomena often necessitates sufficiently pure states. The standard paradigm for creating pure states has been to cool the system of interest to the ground state or decouple it sufficiently from any hot thermal bath. This requirement can be challenging to achieve.

In this study, we prepare a non-classical state originating from a mixed state, utilising dynamics that preserve the initial purity of the state. We generate a Schrodinger cat state within a high-coherence microwave cavity, operating at a mode temperature of up to two Kelvin, which is one hundred times hotter than its environment.

Our experimental findings have implications in generating nonclassical states for other bosonic degrees of freedom such as in the motion of a massive particle. Furthermore, they reduce the purity requirements of the initial state.

QI 10.9 Tue 12:45 HFT-FT 131

Material losses characterization in superconducting resonators based on α and β Tantalum — •Ritika Dhundhwal[1], Haoran Duan[2], Lucas Brauch[1], Soroush Arabi[1], Qili Li[3], Sudip Pal[6], Jose Palomo[5], Dirk Fuchs[1], Alexander Welle[4], Mark Scheffler[6], Zaki Leghtas[5], Jasmin Aghassi-Hagmann[2], Christian Kübel[2], Wulf Wulfhekel[1], Ioan M. Pop[1,3,6], and Thomas Reisinger[1] — [1]IQMT, KIT — [2]INT, KIT — [3]PHI, KIT — [4]IFG, KIT — [5]ENS, Paris — [6]Uni Stuttgart

Implementation of tantalum as a new material platform in transmon qubit has shown promising results with coherence time exceeding 0.3 ms[1]. To understand the underlying cause for record breaking coherence times, the main focus has been on use of alpha phase tantalum to achieve high quality qubits and resonators whereas the beta phase remains largely unexplored. In this work, we compare internal quality factor in lumped element resonators as a function of photon number and temperature. We use various material characterization tools to investigate surface and bulk properties of tantalum. Further, we vary the energy participation ratio in tantalum metal-substrate and metal-air interfaces to estimate the loss tangent and get insight into dominant loss mechanism. [1] Place, A.P.M., Rodgers, L.V.H., Mundada, P. et al. Nat Commun 12, 1779 (2021).

QI 10.10 Tue 13:00 HFT-FT 131

Quantum phases in frustrated arrays of Josephson junctions: Effective XY spin models — •Benedikt Pernack, Mikhail V. Fistul, and Ilya M. Eremin — Theoretische Physik III, Ruhr-Universität Bochum, Bochum, Germany

Motivated by experiments on superconducting qubit networks [1,2], we present here a detailed analysis of collective quantum phases occurring in *frustrated* quasi-$1D$ saw-tooth arrays of small (quantum) Josephson junctions (f-JJAs). Frustration is introduced through the periodic arrangement of 0- and π-Josephson junctions with the Josephson coupling energies of different signs. In the frustrated regime the classical ground state is highly degenerate and formed by various patterns of vortex/antivortex penetrating each basic cell of an f-JJA.

In the quantum frustrated regime using the variational approach we derive an effective XY spin Hamiltonian. Depending on the length L of an f-JJA we obtain two very different regimes: a) $L \ll L_{cr} = \sqrt{C/C_0}$, where C and C_0 are a 0-Josephson junction and superconducting island capacitances, accordingly, the quantum superposition of vortex and antivortex in a single cell dominates; b) $L \gg L_{cr} = \sqrt{C/C_0}$, the quantum superposition of vortex and antivortex is strongly suppressed, and a long (short) exchange interaction is established. In latter case using mean-field analysis and numerical diagonalization of the effective XY spin model, we characterize quantum phases in various f-JJAs.

QI 10.11 Tue 13:15 HFT-FT 131

Frustrated $2D$-Josephson junction arrays with topological constraints — •Oliver Neyenhuys, Mikhail V. Fistul, and Ilya M. Eremin — Theoretische Physik III, Ruhr-Universität Bochum, Bochum 44801, Germany

Geometrical frustration in correlated systems can give rise to a plethora of ordered states and intriguing phases. We theoretically analyze a subset of vertex-sharing frustrated lattices, built up by corner sharing superconducting triangles interrupted by 0-Josephson junctions on two edges and a π-Josephson junction on the third edge. Such lattices have multiple degenerate free energy minima composed of different patterns of vortices/antivortices (V/AV) penetrating each triangle. Exemplary for the Kagome lattices with periodically arranged 0- and π-Josephson junctions, we identify various classical and quantum phases. We derive an effective Ising-type spin Hamiltonian, describing the interaction between V/AVs. Strongly anisotropic long-range interactions between well separated V/AVs emerge from the constraints due to flux quantization in any hexagon loop. In the classically frustrated regime, we calculate the temperature-dependent spatially averaged spin polarization $m(T)$ characterizing the crossover between the ordered and disordered V/AV states. In the coherent quantum regime, we analyze the lifting of the degeneracy of the ground state and the appearance of the highly entangled states[1].

[1] O. Neyenhuys, M. Fistul and I. Eremin, Long-range Ising spins

models emerging from frustrated Josephson junctions arrays with topological constraints, PhysRevB.108.165413 (2023)