Superconducting
Quantum
Technologies

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The Proceedings contains report materials of the International Scientific Conference Superconducting Quantum Technologies held July 30 – August 3, 2018 in Moscow. The goal of the meeting is to bring together world leading scientists representing different groups through over the world and to exchange ideas about the field of superconducting quantum circuits, its recent success story and the future of this area of research. The conference was organized under the support of the Moscow Institute of Physics and Technology (MIPT), National University of Science and Technology (MISIS) and the Russian quantum center (RQC).

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Contents

Speakers abstracts:

Posters abstracts:

Indistinguishability of quantum states and rotation counting

D. Averin

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A quantum system is proposed [1] in which the winding number of rotations of a particle around a ring can be monitored and emerges as a physical observable. We explicitly analyze the situation when, as a result of the monitoring of the winding number, the period of the orbital motion of the particle is extended to $n > 1$ full rotations, which leads to changes in the energy spectrum and in all observable properties. In particular, we show that in this case, the usual magnetic flux period $\Phi_0 = h/q$ of the Aharonov-Bohm effect for a particle of charge q is reduced to Φ_0/n. The proposed system consists of two coupled rings with each ring supporting a Wigner molecule. It can be realized in several experimental contexts, including the arrays of mesoscopic Josephson junctions in the regime of individual Cooper pair transport.

[1] Dmitri V. Averin and Christoph Bruder, arXiv:1711.01495.

Quality control of IBM superconducting quantum processor

B. Bantysh

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Superconducting quantum circuits are some of the most perspective physical platforms for implementation of quantum computations. Many large IT-companies are involved in developing quantum processors based on superconducting effects. In 2017 IBM company started to provide an open access to some of its

superconducting quantum processors that allowed us to run arbitrary 5-qubit quantum circuits using 1-qubit rotation gates, Control-NOT (CNOT) gate and measurements in standard basis.

Since the quality of these processors is still far from perfect the determination of its element base quality is of particular interest. The precise characterization of quantum states and quantum gates is required for detecting bottlenecks of quantum computation technologies. To achieve this aim one should use the quantum tomography procedure.

One of the significant problems of quantum tomography is the measurement errors. In the present work we have developed methods of bypassing this problem using the preliminary tomography of measurement imperfections. Using the results of this tomography, we managed to improve the reconstruction procedure by means of fuzzy measurement techniques developed in our previous works. These results have been used for the analyzing of quantum teleportation algorithm quality by separate tomography of its components: the generation of the input and Bell states and Hadamar and CNOT gates. Despite the low quality of two-qubit CNOT gate and Bell state generation the proposed algorithm has shown good performance as measured by the fidelity between its input and output quantum states.

Quantum Regime of a Two-Dimensional Phonon Cavity

A. N. Bolgar, J. I. Zotova, D. D. Kirichenko, I. S. Besedin,
A. V. Semenov, R. S. Shaikhaidarov, O. V. Astafiev

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We realize the quantum regime of a surface acoustic wave (SAW) resonator by demonstrating vacuum Rabi mode splitting due to interaction with a superconducting artificial atom. Reaching the quantum regime is physically difficult and technologically challenging since SAW devices consist of large arrays of narrow metal strips. This work paves the way for realizing analogues of quantum optical phenomena with phonons and can be useful in on-chip quantum electronics.

High fidelity qubit readout using a V-shaped transmon in a 3D cavity

R. Dassonneville, L. Planat, J. Puertas, S. Leger, K. Bharadwaj, F. Foroughi, C. Naud, W. Guichard, N. Roch, O. Buisson[1,2]

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Using the transverse dispersive coupling between a qubit and a microwave cavity is the most common read-out technique in circuit-QED. However, despite important progresses, implementing a fast high fidelity readout remains a major challenge. Indeed, inferring the qubit state is limited by the trade-off between speed and accuracy due to Purcell effect and unwanted transitions induced by readout photons in the cavity. To overcome this, we introduce a circuit with a V-shaped energy spectrum coupled to a 3D-cavity [1,2]. This circuit presents one transmon qubit with a large intrinsic longitudinal coupling to an anharmonic mode, called ancilla mode. This ancilla mode results from the hybridization between the microwave cavity and the V-shape circuit. Longitudinal coupling is a key point to our readout scheme since such a coupling is immune to Purcell effect. We will present qubit readout performance using this 3D V-shaped transmon inserted in a cavity with fidelity as high as 97%. We will also discuss the quantum non-demolition properties of this novel readout as function of the readout photons number.

R. Dassonneville is supported by the CFM recherche foundation. This work is supported by the French Agence Nationale de la Recherche (ANR-CE24-REQUIEM).

[1] É. Dumur, et al, Phys. Rev. B 92, 020515(R) (2015).
[2] É. Dumur, et al, IEEE Trans. On Appl. Supercond. 26, 1700304 (2016).

Teaching this puppy new tricks, or, games people play with 2000-qubit quantum processors

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Having access to a number of actual hardware implementations of a 2000-qubit annealing-based quantum computer allowed us at D-Wave, our customers, and collaborators to start experimenting with protocols going beyond archetypal QA/AQC, such as:
Anneal Offsets: give user per-qubit control over transverse field;
Anneal Pause: specify start and duration of global pause in anneal;
Anneal Quench: specify when to abruptly quench transverse field;
Reverse Anneal: a new quantum algorithm.

These new features have enabled some exciting results in the field of material simulations, such as quantum simulation of a transverse field 8x8x8 cubic Ising lattice, and observation of a Kosterlitz-Thouless topological phase transition.

We are also moving from our standard Chimera topology to much more complex Pegasus topology, which dramatically increases both individual qubit connectivity and complexity of underlying graph, while keeping qubit energy scales the same. In parallel, we are seeing lower qubit noise due to a new fabrication stack.

In my talk I will give an overview of these exciting developments at D-Wave.

Effects of wave mixing on a single artificial atom

A. Yu. Dmitriev, T. Hönigl-Decrinis, R. Shaikhaidarov, V. N. Antonov, O.V. Astafiev

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A well-known effect of four and higher order wave mixing exhibits novel features when two microwave tones are scattered on a single superconducting two-level artificial atom in the strong coupling regime. We study the effect by measuring the intensities of narrow sideband spectral components appeared from multi-photon elastic wave scattering. We derive an analytical expression for the amplitudes and show that the ratio of consequent components does not depend on the scattering order determined by the number of interacting photons per each act of scattering. We attribute this specific feature to the coherent states of input waves and suggest to use wave mixing as a tool for distinguishing non-coherent states of propagating light. Another novel feature we demonstrate is Autler-Townes-like splitting of side peaks, the magnitude of which depends on the scattering order. We also show the results of scattering of short microwave pulses, which lead to Bessel oscillations of side spactral components and to the mixing of classical and quantum states of light.

Manipulating fixed-frequency superconducting qubit states using all microwave drives

D. J. Egger, M. Ganzhorn, G. Salis, P. Barkoutsos, A Fuhrer, P. Muller, I. Tavernelli and S. Filipp

IBM Research - Zurich, Switzerland

Fixed-frequency superconducting qubits and resonators are promising candidates to build a scalable quantum computing architecture because of their stability and long coherence times. However, the lack of energy tunability reduces controllability which may introduce an operational overhead. Additionally, two-qubit gates using microwave drives only may impose conditions on the qubit frequencies. Our experimental results make use of a microwave drive applied to the transition between the second excited state of the qubit and the first excited state of a resonator. This allows us to reset the qubits when the resonator is a readout resonator. Furthermore, we can entangle two qubits by simultaneously driving the two transitions between the second excited state of each qubit and the first excited state of a common coupling resonator. This creates an effective lambda system in

which we create a non-Abelian geometric holonomy to entangle the qubits. The geometric holonomies we investigate are competitive in speed with current all microwave two-qubit gates. Various two-qubit states can be created by changing the amplitudes and phases of the two drives. The SWAP like nature of this geometric operation makes it well suited for variational quantum algorithms that compute molecular energies by exploring the part of Hilbert space with a fixed number of electrons. As explicit example, we present the computation of the hydrogen molecule ground state on a two-qubit device.

Machine learning with noisy intermediate-scale quantum devices

A. Fedorov

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Machine learning techniques are useful for finding atypical patterns in data. It is known quantum computers perform exponentially faster than their classical counterparts for various computational tasks, in particular, for machine learning. We discuss potential applications of near-term noisy intermediate-scale quantum (NISQ) devices for applications in machine learning tasks with special attention to superconducting processors. We realize machine-learning-based tomographic techniques for quantum systems and test them using currently available experimental facilities.

Collective quantum coherent states in large networks of strongly interacting qubits

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Russia

I will present a review of experimental and theoretical study of a coherent collective quantum response in various disordered networks of interacting superconducting qubits. Arrays of superconducting flux qubits and transmons embedded in the transmission line will be addressed. I will discuss different types of interaction between qubits, i.e. the inductive nearest- neighbors interaction, long-range interaction induced by exchange of virtual photons, and capacitance to the ground, and various on- and off-diagonal types of disorder. I will show that the resonances in the frequency dependent transmission coefficient, D(ω), are directly determined by the time- dependent quantum-mechanical correlation function C*i*(t) of qubits. Spatial and temporal oscillations of the correlation function C*i*(t) are the fingerprints of equilibrium and non-equilibrium collective states. These collective coherent states will be mapped to the Anderson localization of spinon-type excitations, and for the non-equilibrium case, to the Floquet time-crystalline order in interacting qubits networks.

Direct Evidence of Proximity Induced Abrikosov Vortex Core in a Nonsuperconducting Metal

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We report on the experimental observation and theoretical study of proximity induced Abrikosov vortices on the surface of a 50 nm-thick layer of Cu in the hybrid structure Cu/Nb with ultra-low temperature Scanning Tunneling Spectroscopy (STS) [1]. It was shown that in the studied samples the non-superconducting Cu-layer acquires superconducting correlations due to the proximity effect with 100 nm-thick superconducting Nb. The presence of the proximity effect at the surface of Cu is evidenced by observation of a proximity gap in the tunneling conductance spectra dI(V)/dV in clear relation to the value of the superconducting gap of bulk Nb. The evolution of the proximity spectra with temperature was also studied in the range (0.3-4.2) K. Upon application of an external magnetic field, spatial variations of the tunneling conductance spectra were observed in the detailed STS maps as round nm-size spots, in the centers of which the proximity gap vanishes. The density of spots rises continuously with magnetic field; it corresponds perfectly to the expected density of Abrikosov vortices in Nb. We identify the observed spots as proximity induced vortices in Cu. Using the quasiclassical Usadel formalism, theoretical approach was developed to calculate selfconsistently the quasiparticle spectra in the vortex core in three dimensions in a superconductor-normal metal bilayer. The results of numerical calculations are in excellent agreement with experimental data and make it possible to determine the size and the shape of the proximity vortex cores, and to evaluate the coherence length in Cu.

[1] V. S. Stolyarov, T. Cren, C. Brun, I. A. Golovchanskiy, O. V. Skryabina, D. I. Kasatonov, M. M. Khapaev, M. Yu. Kupriyanov, A. A. Golubov, and D. Roditchev, Nature Communications 9, 2277 (2018).

Duality and the Charge Quantum Interference Device

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R. Shaikhaidarov[3,4], H. Rotzinger[2],
S. Linzen[5], M. Ziegler[5], V. Antonov[3,4], U. Hubner[5], H-G. Meyer[5],
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The duality between phase and charge in superconducting devices holds the promise of new electronic devices and of the realisation of a robust quantum current standard, capable of disseminating the new definition of the ampere, based on effects exactly dual to those that enable the Josephson voltage standard [1]. We present the experimental realisation of a Charge Quantum Interference Device (CQUID, right figure) [2], a quantum sensor dual to the Superconducting Quantum Interference Device (SQUID, left figure). The CQUID is made out of 3.3 nm thin atomic layer deposited (ALD) highly disordered superconducting niobium nitride film close to the superconductor-insulator transition. Two narrow constrictions in a wire made from this film are connected in series via a small superconducting island and act as barriers for flux tunnelling across the superconductor, carried by coherent quantum phase slips (CQPS) of the superconducting order parameter [3]. The CQUID becomes a charge sensitive quantum interferometer based on the Aharonov-Casher effect: We demonstrate control of flux tunnelling (phase slip) interference across multiple CQPS junctions in a continuous superconductor by an induced charge on the island.

This is the exact duality to the SQUID, which is a specific realisation of the Aharonov-Bohm effect, where the high sensitivity to magnetic flux stems from the interference of Cooper-pair tunnelling across a continuous insulator in the Josephson junction. We also discuss recent DC measurements of disordered superconducting wires.

[1] J. E. Mooij and Y. V. Nazarov, Superconducting nanowires as quantum-phase slip junctions, Nature Physics 2, 169 (2006).
[2] S. E. de Graaf et al. Charge quantum interference device, Nature Physics 14, 590 (2018).
[3] O. V. Astafiev et al., Coherent quantum phase slip, Nature 484, 355 (2012).

Quantum Microwave Communication with Superconducting Quantum Circuits*

S. Pogorzalek[1,2], K. Fedorov[1,2], P. Eder[1,2], M. Fischer[1,2], E. Xie[1,2], F. Deppe[1,2], A. Marx[1], R. Gross[1,2,3]

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Superconducting quantum circuits represent a highly successful platform to study fundamental quantum effects and develop components for applications in quantum technology. A prospering subfield is quantum microwave communication & sensing, which aims at developing novel components, experimental techniques, and theory models building on the quantum properties of continuous-variable propagating microwaves. It provides the foundations for distributed quantum computing & communication via microwave quantum local area networks or sensing applications based on the illumination of an object with quantum microwaves (quantum radar).

Here, we report on the generation of two-mode squeezed (TMS) microwave states by flux-driven Josephson parametric amplifiers (JPAs) and their use for the demonstration of a fundamental quantum communication protocols [1-3]. In particular, we use the TMS states for the implementation of remote state preparation (RSP). In this protocol, the sender has knowledge of the quantum state, which has to be transmitted. More specifically, we investigate continuous variable RSP with an analog feed-forward scheme and experimentally demonstrate feasibility of the RSP protocol in the microwave domain by remotely preparing squeezed states with squeezing levels below the vacuum limit.

*Supported by the German Research Foundation through FE 1564/1-1, the graduate school ExQM of the Elite Network of Bavaria, and the IMPRS ‘’Quantum Science and Technology’’.

[1] Kirill G. Fedorov et al., Scientific Reports 8, 6416 (2018).
[2] Kirill G. Fedorov, et al., Phys. Rev. Lett. 117, 020502 (2016).
[3] Stefan Pogorzalek et al., Phys. Rev. Applied 8, 024012 (2017).

Josephson effect in suspended single-walled carbon nanotubes

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We study suspended, 300-nm-long single-walled carbon nanotubes (SWCNT) contacted using MoRe leads. Good contact transparency of the superconductor-nanotube interface allows for the observation of proximity-induced superconductivity in our SWCNT devices. The magnitude of the switching supercurrent ranges up to 20 nA and can be tuned periodically by gate-induced charge. The gate charge modulates the retrapping current even more strongly, and its magnitude becomes vanishingly small far away from the charge degeneracy point.

Under rf irradiation, our SWCNT devices display clear Shapiro steps, the shape of which depend on the rf frequency and power. Under certain conditions the observed steps become hysteretic, indicating small dissipation on the Josephson phase dynamics at the rf frequency.

In these SWCNT devices we find mechanical resonances around a frequency of 1.5 GHz, while the Q factors amount up to 15000 near the charge degeneracy point. Mechanical modes can be observed also in the superconducting regime by inducing Shapiro steps resonantly with the mechanical mode. The shape of the resonant response reflects the interplay between the Josephson dynamics and the mechanical degrees of freedom. Our results can be analysed in terms of the Josephson force acting on the mechanical motion.

[1] C. Padurariu, C. J. H. Keijzers, and Yu. V. Nazarov, Phys. Rev. B 86, 155448 (2012).

Technological aspects for fabrication of solid-state qubit-devices

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The cleanroom at the Leibniz IPHT in Jena (Germany) offers a variety of fabrication methods in the field of micro- and nanotechnology. Standard applications range from nanoscale metal pattern on wafer scale as ultrasensitive sensors for surface-enhanced molecular spectroscopy over multilayer circuits for SQUID systems and MEMS-based thermoelectric sensors for space applications to microfluidic chips with sub-millimeter features for lab-on-a-chip devices.

Recently, new quantum technologies attract the interest of both, scientific communities and industry, and their superconducting quantum circuits are one promising direction. More than 20 years of experience in the field of superconducting devices and circuits on thin-film basis, especially in the realization of solid state qubits are present at the Leibniz IPHT. Our work is underway to establish a reproducible fabrication of artificial atoms that will serve as the foundation of basic research in the field of quantum metamaterials [1] and could be extended to applications in quantum computation. The buildings blocks of our devices are submicron $Al/Al_2O_3/Al$-Josephson junctions [2], which are produced by the shadow evaporation technique.

Recent progress in the field of ultra-thin NbN films produced by atomic layer deposition (ALD) has been gained. Due to their high kinetic inductance, these thin NbN layers not only form the basis of single photon detectors but also open new ways of exploring novel physics [3].

[1] P. Macha, G. Oelsner, J.-M. Reiner, M. Marthaler, S. André, G. Schön, U. Hübner, H.-G. Meyer, E. Il’ichev,and A. V. Ustinov, Implementation of a quantum metamaterial using superconducting qubits, Nature communications 5, 5146 (2014).
[2] G. Oelsner, U. Hübner, S. Anders,and E. Il'ichev, Application and fabrication aspects of sub-micrometer-sized Josephson junctions, Low Temp. Phys.43, 779 (2017).
[3] S. Linzen, M. Ziegler, O.V. Astafiev, M. Schmelz, U. Hübner, M. Diegel, E. Il’ichev, and G.-G. Meyer. Structural and electrical properties of ultrathin niobium nitride films grown by atomic layer deposition, Supercond. Sci. Technol.30, 035010 (2017).

Superinductors based on strongly disordered superconductors and their use for the protected qubits and fault tolerant operations

L. Ioffe

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I review the theoretical models of the Josephson arrays that form logical qubits protected from local noises, discuss experimental constraints on their designs and the challenges of their implementation. I will discuss optimal geometries that provide best compromise between the level of protection and complexity of their design. I argue that the best solution is provided by the qubit that relies on the hybrid fabrication of conventional submicron Al-AlOx junctions and high kinetic inductivity nanowires based on strongly disordered superconductors. This hybrid structure allows realization of a composite Josephson element that displays robust π-periodicity of the Josephson energy. Even small arrays of such elements are expected to provide exponential suppression of the sensitivity to local noises. Moreover, two orthogonal controls that couple to the charge and phase degrees of freedom permit arbitrary Clifford rotations in the protected subspace.

Experimental realization of a quantum heat valve: Towards a superconducting Otto refrigerator

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Superconducting circuit QED (Quantum Electro-Dynamics) presents a prominent platform for quantum thermodynamics. Here, we consider a superconducting qubit coupled between two nominally identical coplanar waveguide (CPW) resonators, each terminated by a normal-metal mesoscopic resistor as a heat bath. We observe tunable photonic heat transport through the resonator-qubit-resonator assembly when the temperatures of the two heat baths are unequal. Using a theoretical model here developed, we are able to reproduce experimental data. Importantly, the reservoir-to-reservoir heat flux depends on the interplay between the qubit-resonator and the resonator-reservoir couplings, yielding qualitatively dissimilar results in different coupling regimes. Our Quantum Heat Valve is a technological prerequisite for the realization of quantum heat engines and refrigerators that can be obtained, e. g., by exploiting the time-domain dynamics and coherence of driven superconducting qubits.

[1] Alberto Ronzani, Bayan Karimi, Jorden Senior, Yu-Cheng Chang, Joonas Peltonen, ChiiDong Cheng, and Jukka P. Pekola, Realization of a quantum heat valve, arXiv:1801.09312, Nature Physics (2018), to be published.
[2] B. Karimi and J. P. Pekola, Otto refrigerator based on a superconducting qubit: Classical and quantum performance, Phys. Rev. B 94, 184503 (2016).

Large-scale superconducting quantum annealing machine based on 2.5D packaging technology and application specific architecture

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Quantum annealing is a promising technique which leverages quantum mechanics to solve hard combinatorial optimization problems [1]. D-Wave Systems Inc. [2] is the first company to commercialize superconducting quantum annealing machine in 2011 and ship a new machine with 2000 qubits in 2017. However, integration of larger number of qubits as well as improvement of qubit coherence are required for practical applications. In this talk we will overview our technological integration scheme for large-scale superconducting quantum annealing machine in AIST [3]. The scalability is achieved by QUIP (QUbit, Interposer and Package substrate) structure, which is based on our multi-layer fabrication and multi-chip 2.5D packaging technology such as

Through Silicon Via (TSV) and flip-chip bonding. We have also developed an Application Specific Annealing Computing (ASAC) architecture in order to increase the available hardware budget and reduces the cost and time for R&D. In addition, we will explain how to design quantum annealing machine for factoring.

This presentation is based on results obtained from a project commissioned by the New Energy and Industrial Technology Development Organization (NEDO).

[1] T. Kadowaki & H. Nishimori, Phys. Rev. E 58 (1998) 5355.
[2] D-Wave Systems, https://www.dwavesys.com/.
[3] M. Maezawa, K. Imafuku, M. Hidaka, H. Koike, S. Kawabata, arXiv:1712.05561.

Superconducting Qubits for Analog Quantum Simulation

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In this talk I want to present the research activities of the Superconducting Quantum Circuits group at the Institute for Quantum Optics and Quantum Information in Innsbruck.

I will give an introduction to circuit quantum electrodynamics and our 3D circuit QED architecture. I will show how we want to use this architecture to realize a platform for quantum many body simulations of dipolar XY models on 2D lattices using state of the art circuit QED technology. The central idea is to exploit the naturally occurring dipolar interactions between 3D superconducting qubits to simulate models of interacting quantum spins. The ability to arrange the qubits on essentially arbitrary geometries allows us to design spin models with more than nearest-neighbor interaction in various geometries.

Combining these ideas with our waveguide architecture, will allow us to study open system dynamics with interacting spin systems. The platform will allow us to investigate the interplay between short range direct interactions, long range photon mediated interaction via the waveguide and the dissipative coupling to an open system.

The effect of microwaves on the properties of superconductors

T.M.Klapwijk

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Conventional superconductors are moving into increasingly more challenging tasks for quantum computation, amplifiers, optical single photon detectors and astronomical instruments. In all cases the interaction with electromagnetic radiation is a crucial ingredient, of which a lot of knowledge had been generated about 5 decades ago. Most of this knowledge addresses cases close to the critical temperature, whereas current experiments and technological developments are routinely carried out at millikelvin temperatures. In my talk, I will present recent developments on microwave kinetic inductance detectors, single photon detectors, and amplifiers in the context of 'old' and 'newly' developed knowledge, also taking into account the differences between superconducting materials.

Sources of Decoherence In Superconducting Quantum devices

S. de Graaf[1], A.k Adamyan[2], T. Lindström[1], D. Erts[3],
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Despite the promises of superconducting qubits, their performance is presently limited by short coherence times due to defects intrinsic to materials. As a result, future quantum computers would require massive error correction circuits, which seem to be very challenging to build. Another more promising path would be to improve this coherence time, which would relax the constraints on the quantum error correction circuits and would thus make a quantum computer more feasible. This task is considered one of the main challenges in the field. Our recent results [1] gave vital clues to the long-standing problem of noise and decoherence in superconducting devices: a technique for on-chip Electron Spin Resonance (ESR) [2], allowed to identify, for the first time, the chemical species responsible for the flux noise in superconducting circuits [3]. Furthermore, the most recent noise measurements in superconducting resonators point to the link between charge and flux noise in superconducting circuits [3]: a mild sample treatment has lead to tenfold reduction of the surface spins, responsible for the flux noise, as evidenced by ESR, and this treatment has also lead to tenfold reduction of the low frequency noise in superconducting resonator, usually associated with the charge noise. The chemical identification of the possible remaining sources of noise in superconducting devices allows for an active chemical intervention, aiming at silencing the defects and, therefore, improving the coherence in superconducting quantum devices.

[1] Phys. Rev. Lett. 118, 057703, (2017).
[2] Journ. of Appl. Phys. 112, 123905, (2012).
[3] Phys. Rev. Lett. 118, 057702, (2017).
[4] Nature Comm. 9, 1143, (2018).

Coaxial multilayer superconducting circuits for quantum computing

P. Leek

University of Oxford Department of Physics, UK

Superconducting circuits are well established as a leading platform for the development of universal quantum computers. In order to advance to a practically useful level, architectures are needed which combine arrays of many qubits with selective qubit control and readout, without compromising on coherence. The strong coupling of superconducting qubits to microwave resonators, realising circuit quantum electrodynamics (QED), has been demonstrated to be a powerful architecture for controlling qubit coherence and implementing coupling and readout of qubits, however the circuit layout required to scale to many qubits rapidly becomes complex. In this talk I will present our work on a coaxial multilayer version of circuit QED [1] in which qubit and resonator are fabricated on opposing sides of a single chip, and control and readout wiring are provided by coaxial wiring running perpendicular to the chip plane, providing a potentially simple route to scaling to grids of many qubits.

[1] Rahamim et al., Applied Physics Letters 110, 222602 (2017).

Electromagnetically induced transparency in superconducting quantum circuits From classical to quantum

Y. Liu

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In this report, I will mainly discuss how to realize electromagnetically induced transparency (EIT) and Aulter-Townes splitting (ATS) in superconducting quantum circuits. I will introduce several new research results when the classical control field is changed to the quantum control field. In particular, I will show how to discern EIT and ATS spectra when the mean photon number of the quantum control field is changed from zero to the finite number.

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Majorana qubit operations in Josephson-qubit chains

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We analyze possibilities to implement Majorana degrees of freedom in a chain of superconducting quantum bits. The analysis is based on modified Jordan-Wigner-type transformations. Qubits, formed by Majorana zero modes, may be manipulated via local control of superconducting quantum bits. We demonstrate how single-qubit and two-qubit quantum logic gates can be achieved by braiding the effective Majorana modes. We comment on generalizations of this approach to larger circuits, using extra spin-coupler degrees of freedom, and on the experimental realization of this scheme.

Parity effect does not mean a superconductor free of quasiparticles

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We experimentally demonstrate that it is possible to observe a clear parity effect on a superconducting aluminum island even when there is, on average, a single quasiparticle excitation left on the island. The island is coupled to normal metal leads with tunnel junctions, and we monitor its charge state in real time with a capacitively coupled charge detector. At low temperatures, the most probable charge state is even, as expected, but also the odd states have significant occupation probabilities due to the quasiparticles present. The occupation probabilities and tunneling rates between the charge states are quantitatively explained by Cooper pairs breaking on the island. We further demonstrate that the pair breaking is caused by the backaction of the single-electron transistor used as a charge detector. With sufficiently low probing currents, our superconducting island is free of quasiparticles 97% of the time.

Next generation superconducting qubits

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We will describe superconducting fluxonium qubits which reliably reach the condition $T_2 > 100$ μsec. A combination of high coherence, extreme anharmonicity, and strong coupling in fluxoniums opens up interesting applications for quantum information science. These include novel schemes for fast two-qubit gates, improved diabatic quantum optimization algorithms, and analog quantum simulations of many-body physics. We will also present a novel qubit, entitled Blochniun, derived from fluxonium by increasing its shunting inductance ten fold. The non-linearity of Blochnium is based on the formation of Bloch bands by a single Josephson junction. The low-energy spectrum of Blochnium is flux-insensitive due to quantum fluctuations of the Josephson phase and this can be a good starting point for engineering topologically-protected superconducting qubits.

Possible extensions of the toolbox for quantum-optics on superconducting systems

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In spite of the completely different range of transitions frequencies between the quantized levels, superconducting quantum circuits working at low temperatures behave quite similar as systems built up from atoms, spins, or other real quantum objects. In this talk, we report on experimental investigation concerning the adaption of quantum-optics techniques to superconducting systems.

In a first part, we discuss the tuning of a flux qubit's energy levels by a microwave tone via a dynamical Zeeman shift which is equivalent in exploiting the light shift in real atoms. This method has the advantage of no additional introduced low-frequency noise compared to the tuning by additional DC-fields. We demonstrate the usability of such an approach by spectroscopic measurements of the shifted energy levels. A theory including the relevant microwave fields allows a very good description of the experimental data and indicates the influence of the driving fields to the dissipative rates of the qubit, that for strong driving can be additionally exploited [1].

A second important tool for quantum optics experiments on chip would be the realization of single microwave photon detection. In our work we suggested to use a single underdamped Josephson junction [2]. The system we are considering consists of a microwave cavity shunted to ground by a single Josephson junction. The coupling between the two systems results in certain specific features [3]. As we will show they are mainly resulting from the non-linearity of the Josephson junction.

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Circuit QTD with superconducting qubits

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I discuss implementations of circuit quantum thermodynamics, cQTD, using a superconducting qubit coupled to mesoscopic resistors as heat baths. I demonstrate the operation of a quantum heat valve and present ways to realize quantum thermal machines and progress in realizing a wideband continuous calorimetric detector for single microwave photons emitted by a qubit and for electrons tunneling through a tunnel barrier.

Work done in collaboration with Bayan Karimi, Libin Wang, Alberto Ronzani, Jorden Senior, Yu-Cheng Chang, Joonas Peltonen, ChiiDong Cheng, Olli-Pentti Saira, Dmitry Golubev, Michele Campisi, Rosario Fazio, Fredrik Brange, and Peter Samuelsson

Resonance Fluorescence from an artificial atom strongly coupled to a cavity

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We experimentally study the resonance fluorescence from an atom strongly coupled to a cavity in two regimes and the observed Mollow triplets are drastically different from the atom coupled to an open space. In regime 1, a single superconducting artificial atom is strongly coupled to a cavity. In regime 2, one of sidebands of the driven artificial atom is strongly coupled to a cavity. The unusual resonance fluorescence is directly revealed by measuring the emission spectrum from the strongly driven artificial atom which is simultaneously strongly coupled a cavity and an open space. We clearly observed the main features of resonance fluorescence determined not by relaxation rate of the atom but by the coupling strength between the atom and the cavity.

Quantum algorithms implementation on IBM quantum computers: from digital modeling of spin dynamics to quantum machine learning

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We report on implementation of a set of quantum algorithms on 5- and 16-qubit superconducting quantum processors of IBM Quantum Experience. In the first part of this work, we point out that superconducting quantum computers are prospective for the simulation of far-from-equilibrium dynamics of many-body systems, including nonadiabatic phenomena and quenches, and perform proof-of-principle digital simulations of two spin models with real quantum hardware. In the second part of the work, we implement several quantum cryptography protocols, including a famous BB84 quantum key distribution scheme as well as a superdense coding. We concentrate on the analysis of quantities, which directly characterize a quality of information transfer between different parts of the chips and can therefore be used to quantify imperfections of real quantum devices. In the third part of the work, we realize an algorithm, which solves a classification problem for maximally entangled states in low-dimensional Hilbert spaces. We discuss methods which can be used to extract valuable information from imperfect experimental data and develop algorithm-dependent tricks aimed to suppress errors of the physical devices. The algorithms we implement can serve as fine and deep benchmarks of capabilities of real quantum processors from the perspective of quantum information science and quantum modeling.

Full counting statistics of quantum phase slips

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One of the prominent manifestations of quantum phase slip (QPS) in quasi-1d superconductors is the nonvanishing voltage drop generated across such systems under external current bias. Another QPS-related effect in superconducting nanowires is shot noise of the voltage. In our talk we discuss the full counting statistics of voltage fluctuations generated by the QPS in superconducting bridges and nanowires. With the aid of the Keldysh technique combined with duality arguments we derive the generating function fully describing voltage fluctuations and explicitly evaluate this function in some limits. For example, at zero frequency or in the long-time limit voltage fluctuations are described by Poisson statistics, just as it could be expected intuitively. We also evaluate all voltage cumulants at nonzero frequencies and under external current bias.

Basic elements of adiabatic superconducting artificial neural network

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Superconducting quantum interferometers provide an opportunity to build the tunable magnetic flux transformers which are widely used as couplers in quantum circuits. Nonlinearity of Josephson junction current-phase relation allows making the transfer function of these transformers linear or vice versa highly nonlinear on demand. In this work we consider a possibility to design the flux transformers playing the role of artificial neuron and synapse of a superconducting adiabatic artificial neural network of perceptron type. Our neuron is capable of providing one-shot calculation of sigmoid and hyperbolic tangent activation functions, while synapse is featured by both positive and negative signal transfer coefficients. The proposed adiabatic artificial neural network seems to be the most energy-efficient implementation of the neuromorphic circuit of the considered type capable of operation with quantum circuits in a single cryogenic package.

Nonlinear dynamics in SQUID metamaterials: Breathers, chimeras, flat bands and machine learning predictions

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Metamaterials made of SQUIDS form very interesting nonlinear laboratories where geometry and nonlinearity conspire in producing a wealth of localized and extended modes. While in the weakly coupled limit we may obtain discrete breathers, close to the geometric SQUID resonance formation of beautiful chimera states appears. The latter involves a counter-intuitive spatiotemporal pattern that engages the whole metamaterial and where coherence and incoherence coexist. In this presentation we summarize work on coupled SQUID units that explores the rich nonlinear dynamics of the metamaterial [1] and focus in particular on recent results that explore the role that nonlinearity plays even at the single SQUID level [2]. Furthermore, we show that novel geometrical SQUID arrangements, as in a Lieb lattice form, lead to the formation of flat bands that improve the functionality of the metamaterial [3]. Finally, we explore the possibility of using machine learning in order to predict spatiotemporal events in these lattices and show that specific types of neural networks perform the prediction task with high efficiency [4].

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Traveling-wave Josephson parametric amplifiers with three-wave mixing

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Recently, the Josephson parametric amplifiers (JPAs) found a wide application in quantum information technologies. In comparison with conventional cavity-based JPAs the amplifiers based on the traveling waves allow non-reciprocal performance in combination with larger dynamic range and substantially larger bandwidth. The serious challenge in designing these amplifiers is realization of the spatial phase matching of the pump, the signal, and the idler waves. We show that in the JPAs with three-wave mixing, i.e. when the sum of the signal and the idler frequencies is equal to the pump frequency, a nearly perfect phase matching (i.e. the similar relation for the corresponding wave vectors) can be realized in sufficiently wide bandwidth without sophisticated dispersion engineering. We developed the concept of such traveling-wave JPAs with three-wave mixing exploiting either the non-centrosymmetric Josephson nonlinearity or the drive by the flux traveling wave. The quantum regime of operation of these amplifiers allowing production of entangled microwave photon pairs will also be discussed. The experimental data obtained at PTB with Nb trilayer circuits will be presented.

Giant noise due to temperature fluctuations at the superconducting transition in TiN nanowires

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At low temperatures, spontaneous fluctuations of current or voltage in a conductor can provide additional insight into thermal transport in superconducting nanostructures. At the onset of superconducting transition, these fluctuations can be caused by different factors: temperature fluctuations, order parameter fluctuations, or resistance fluctuations due to phase slips. Such fluctuations are usually considered as a parasitic factor, but they can be used to direct measurement of the electron kinetics in the system (the electron heat capacity, the thermal conductivity). Here, we present results of our studies of spontaneous current fluctuations in superconducting TiN nanowires. In the vicinity of the superconducting transition we have observed giant noise (10^{-17} V^2/Hz), much larger that Johnson-Nyquist noise. It can be interpreted in terms of thermodynamic temperature fluctuations in TiN films with the following parameters: T_c = 4 K, dT_e ~ 0.1 K, dR/dT~10^5 Ω/K, I_{bias} ~ 1 mkA. We do not know if there is only one noise source considered as temperature fluctuation, however we provide conclusive evidence of the dominance of this source at the onset superconducting transition. The expected value for thermal noise in that sample is about 10^{-18} V^2/Hz. The large signal of thermal noise allows us to determine the heat capacity, the thermal conductivity at a given point of the resistive transition simultaneously. That could be convenient method to investigate thermal transport of superconducting structures.

Superconducting integrated receiver for the purposes of diagnosing a person's mental state.

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According to studies of the structure of human skin structure by optical coherence tomography revealed that the upper part of the duct of the sweat gland (which secretes perspiration from the gland at the pore on the surface of the skin) is a spiral. [1] It was suggested that the ducts of the sweat glands may be imperfect, spiral antennas with a regime of axial radiation. Based on the dimensions of these channels, the resonant frequencies of the antennas lie in the terahertz frequency range (70-600 GHz).

The sweat glands are located on the surface of the human skin and form an active system that works in concert with a set of different stimuli: psychological, mental and emotional. Emotional stress can lead to sweating, unrelated to thermoregulation. By now, the behavior of the body's own radiation in the terahertz frequency range remains unexplored.

We conducted a study of the dependence of the radiation of the skin of 19 volunteers on mental loads. As main radiation detectors, a superconducting integrated receiver (SIR), which measured the brightness temperature of a human body under the influence of psychological stress, and the galvanic skin response sensor (GSR), which is often used to detect stress, were used. At the same time, the detector tracked changes in the sympathetic nervous system of a person undergoing psychological stress. Investigation of the correlations of the obtained data from these two devices showed that the dependence between the signals SIR and GSR varies depending on the mental burden on the person. The overall correlation of signals over the entire period of the experiment may not be very high, but when considering correlations at separate stages of the experiment, the correlation can reach 0.6-0.9.

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Collective and edge states in superconducting transmon chains

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Chains of qubits coupled via nearest-neighbor interaction are expected to form band structure similar to atomic excitations in crystals. To achieve this regime, a two requirements have to be satisfied: the number of structure periods of the qubit lattice should be large enough for the zone formalism to be meaningful and the coupling strength should exceed loss and disorder rates. Carefully engineered, such systems can exhibit interesting properties, such as topological order [1-3].

In the present work we aim at experimentally demonstrating the emergence of band structure in linear chains of a one-dimensional chain of transmon qubits with a two-qubit unit cell with alternating coupling strength that has been suggested recently [4]. We will explore experimentally single- and two-photon nonlocal collective bulk excitations of the chain, which can be identified via two-tone spectroscopy with frequency multiplexing. Similarly, we expect to find a single- and double-photon edge states, which are identified by the single-dimensional topological order parameter, the Zak phase.

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Development and fabrication of Josephson Parametric Amplifier

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Rapid development of quantum technologies has led to a need for devices able to amplify signal with added noise near the quantum limit. Josephson parametric amplifiers satisfy these requirements and have wide range of applications such as single shot measurements [1] and light squeezing [2]. In the present work we develop Josephson parametric amplifier based on two coupled nonlinear resonators made of SQUID chains. The device was fabricated by methods of optical lithography and e-beam evaporation of thin aluminium films. We demonstrate operation of parametric amplifier: the observation of nonlinear response, amplification of a weak probe signal which depends on pump frequency and power, amplifier saturation at high signal amplitudes for different pump levels [3]. We managed to reach amplification of 20 dB which is high enough to exploit advantages of quantum-limited amplifier.

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Z-pulses on transmon qubits

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Z-pulse is a qubit frequency tuning operation that can be used to implement several types of two-qubit gates (e.g. iSWAP, cPhase) or to initialize factorized states in a multiqubit system (this can be subsequently used for analog modeling of spin arrays). [1] [2] In this poster, we overview the frequency tuning by a flux biasing line. [3] Our sample was fabricated on a silicon substrate in a two-layer architechture using photolithography (for the Nb layer) and shadow evaporation (for the Al Josephson junctions) and investigated via standard methods in a dilution fridge. We provide tuning pictures of qubits with different Z-pulse voltages, Ramsey fringes and compare our results with computer simulations. We will as well present some information about the calculation of the filtering of the flux line and its mutual inductance to the qubit.

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Quantum walks and their implementation using superconducting circuits

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Quantum walks, which are quantum analogs of random walks, have been used to develop new tools for quantum information theory. These tools include, e.g., new algorithms for quantum computation and new quantum-enhanced machine learning methods. It is hence important to study fundamental properties of quantum walk dynamics on graphs, also by considering feasible experimental implementations. Here we present two proposals of quantum walk dynamics implementation.

First, we consider a quantum walk dynamics on a cycle graph. Such a graph can be thought of as an array of tunnel-coupled quantum dots that are arranged in a circle. If one puts an electron in this quantum system, then this electron will walk and spread coherently showing one-particle quantum walk dynamics. By injecting the second electron into the system richer dynamics can be expected due to mutual repulsion between two electrons [1]. This quantum walk dynamics of two indistinguishable fermions, in particular, can be used in the preparation of a two-qudit entangled state of two distinguishable subsystems of high dimensions.

Second, we consider a quantum walk dynamics on directed graphs. The essential part of constricting probability unitaries, which are the building blocks of a flexible quantum walk operator, is coherent controlization - a process by which prior unspecified operation on subsystems is coherently conditioned on the state of a control qubit. Here we show a method that allows coherent controlization in a register of superconducting transmon qubits coupled to an auxiliary microwave cavity [2]. The proposed method is based on the conditioning of the one-qubit rotations on the vacuum state of the cavity, and is scalable to a large number of qubits via a nested construction.

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Single-photon response in superconducting strips of width up to 5μm

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Superconducting single-photon detectors (SSPD) [1,2] became a device of choice in many quantum optics applications. For a long time it was a common notion that the detection of a single photon occurs only in a superconducting strip of 50-150 nm wide, comparable to the size of a hot spot. In a recent theoretical paper [3], it was predicted that the efficiency is independent of the width of the detector strip. We have experimentally observed a single-photon response in superconducting strips with a width of up to 5 μm over a wide wavelength range from 405 nm to 1550 nm [4]. We present our further study of the detection mechanism in straight bridges of 10 μm in length and 1-5 μm in width in which we observe the internal quantum efficiency close to 100% at wavelengths of 405 nm and 633 nm.

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Development of microwave single photon detector

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Single-photon (SP) sources and detectors are key elements in quantum information processing, including Boson sampling, quantum simulations, linear optical quantum computing. Contrary to developed optical and infrared single-photon sources and detectors, progress of the devices in microwave frequency range is more complicated due to 4 orders of magnitude smaller photon energy. Recently, substantial progress was achieved in microwave SP source [1], but publications on broad-band (10-100 GHz) Microwave Single-Photon Detectors (MSPD) are still absent.

Our idea of MSPD is based on threshold photon absorption in a superconducting nanobridge with low critical temperature T_{c1} ~ 0.1 K, which corresponds to threshold photon frequency ~7 GHz. For nanobridge embedded in coplanar line with $T_{c2} >> T_{c1}$, photon absorption results in superconducting pair breaking and kinetic inductance change for relatively small number of pairs in nanobridge, the change being detected by reflection of test signal with frequency $f < 2\Delta(T = 0) = 3.52\ T_{c1}$. As a material of MSPD nanobridge, we tested iridium, gold-molybdenum (Au-Mo) and platinum-titanium (Pt-Ti) bilayers with different layer thicknesses. We present dc electron transport measurements of the nanobridge structures, which show that Pt-Ti bilayers witn T_c~0.15-0.2 K are most suitable for MSPD operation. Preliminary microwave measurements of fabricated Pt-Ti MSPD-structures show proper behavior of reflected test signal amplitude and phase as a function of temperature (near T_{c1}) and microwave power. The Pt-Ti MSPD-structures also show frequency threshold detection of microwave power,P , with different functional reflected signal phase dependence on power (phase~P^2 below 9 GHz and phase~P above 9 GHz).

These results are promising for further development and optimization of MSPDs.

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Sub-micron inorganic masks for high-quality Josephson structures fabrication

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We present a novel technology of Ge/Nb bilayer inorganic masks for fabrication of submicron Josephson junctions (JJs) and devices on their basis. Inorganic masks could significantly improve quality of Josephson structures due to higher purity of the process itself compared to conventional organic resists. Usage of organic resists results in resist residues on substrate and extraction of organic solvents in process of JJ fabrication, which is one of the reasons of parasitic two-level system formation. We fabricated 200×500 nm^2 $Al/Al_2O_3/Al$ single Josephson junctions and SQUID structures, smallest JJ area being limited only by the electron beam lithography resolution. Low temperature (20 mK – 1 K) electron-transport measurements demonstrate good quality of our structures. Inorganic masks technology has high potential for single crystal JJ fabrication and drastic improvement of superconducting qubit coherence time.

Opening the Quantum Box: A Probabilistic Perspective on Quantum Annealers

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We apply an inverse Ising method to perform a detailed characterisation of D-Wave quantum annealer. From raw experimental samples we reconstruct the topology of the Ising model corresponding to the D-Wave quantum processor and compare it to the hardware-implemented Chimera graph. Our results demonstrate existence of spurious inter-qubit couplings not present in the Chimera graph. By the means of a linear regression analysis we find a relationship between the input D-Wave parameters and the reconstructed parameters of the Ising model. We also search for hidden multi-body interactions between qubits that characterise deviation of the observed probability distribution from the Gibbs distribution and show that the multi-body effects are negligible. Our results show that D-Wave annealer is well described as a Gibbs sampler with an effective quasi-uniform temperature.

Control of qubit states by unipolar impulses: theoretical analysis and design issues

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We analyze the control of qubit states by short unipolar magnetic field pulses. In superconducting technologies, such an control with a picosecond timescale can be realized using fluxons in rapid single-flux-quantum logic circuits. We proposed a new approach to the theoretical analysis of such a procedure, based on the Magnus representation for the evolution operator (propagator) of qubits. An expression was obtained for the propagator in the form of a polynomial in powers of the Magnus matrix. This allows us to find a solution to the problem of fast quantum control outside the framework of perturbation theory. As an example, the switching between single qubit states was considered. An analog of the known pi-pulses in the Rabi-technique is found. An analytical consideration was carried out for the general case of two interacting qubits (a four-level system). The conditions for the parameters of the picosecond pulses, suitable for logical operations in such systems, are studied.

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Fabrication of hybrid RF-SQUID

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Various applications of superconducting qubits benefit from building up circuits with small scatter of device parameters, high anharmonicity and small physical size [1]. There is a particular interest in qubits based on Josephson junctions (JJ) embedded in a highly inductive environment. Qubits built in a fluxonium configuration [2, 3] are demonstrated to obtain high decoherence times and strong anharmonicity. The shunting inductance in these qubits is typically implemented with an array of relatively large JJs. Moreover, inductively shunted JJs are also interesting in terms of an investigation of coherent quantum phase slip effect [4]. In our work we provide a method for fabrication of Josephson SIS junctions (Al-AlOx-Al) embedded in a new type of highly inductive environment: kinetic inductance made from NbN disordered thin films. We demonstrate RF-SQUID realized with that method.

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Quantum fluctuations and density of states in low-dimensional superconductors

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We investigate the effect of phase fluctuations on single-particle density of states (DOS) in ultrathin superconducting films and nanowires. Using an effective action approach, we obtain a non-perturbative correction to DOS in such systems and evaluate it both analytically and numerically. Phase fluctuations in quasi-two-dimensional films yield a tail of electron states at subgap energies while in quasi-one-dimensional nanowires fluctuations also smear the gap edge singularity in DOS.

Many-body synchronization of interacting qubits by engineered ac-driving

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Contemporary view of generic properties of quantum ensembles where the interactions and disorder are simultaneously present is that those systems reveal the two states: the ergodic state and many-body localized (MBL) phase. The general statement is that the ergodic, or delocalized, phase of a closed many-body quantum

system is characterized by the eigenstate thermalization hypothesis. It says that the wave function evolution of excitations from a narrow energy domain is nothing but a relaxation of observables to the Gibbs distribution. In contrast, the MBL phase reveals the non-ergodicity with an absence of an eigenstate thermalization. In this work we introduce the many-body synchronization of an interacting qubit ensemble which allows one to switch dynamically from MBL to an ergodic state. We show that applying of pi-pulses with altering phases, one can effectively suppress the MBL phase and, hence, eliminate qubits disorder. The findings are based on the analysis of the Loschmidt echo dynamics which shows a transition from a power-law decay to more rapid one indicating the dynamical MBL-to-ergodic transition. It should be emphasized, that being applied to all the qubits simultaneously, the sequence of pi-pulses disregards a microscopic details of the disorder in qubits frequencies. We expect that this transition offers a technique for an effective suppression of inhomogeneous broadening in the qubit ensembles and quantum metamaterials.

Parametrically driven hybrid qubits-photon systems: dissipation-induced quantum entanglement and photon production from vacuum

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We consider a dissipative evolution of parametrically-driven qubits-cavity system under the periodical modulation of coupling energy between two subsystems, which leads to the amplification of counterrotating wave processes. We reveal a very rich dynamical behavior of this hybrid system. In particular, we find that the energy dissipation in one of the subsystems can enhance quantum effects in another subsystem. For instance, cavity decay assists to stabilize entanglement and quantum correlations between qubits even in the steady state and to compensate finite qubit relaxation. On the contrary, energy dissipation in qubit subsystem results in the enhanced photon production from vacuum for strong modulation, but destroys both quantum concurrence and quantum mutual information between qubits. Our results provide deeper insights to nonstationary cavity quantum electrodynamics in context of quantum information processing and might be of importance for dissipative quantum state engineering.

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Suppression on chaos in frustrated Dicke model

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In study[1] was shown that in a Dicke Hamiltonian quantum chaos emerges. We investigated chaotic properties of a frustrated Dicke Hamiltonian i.e. containing a quadratic in spin-projection term. Quasiclassical and exact numerical calculations for small systems were performed. As a result Poincare sections and phase portraits for quasiclassical model, spin dynamics and energy level distribution for quantum Hamiltonian were obtained. It was shown that this system posses no chaotic behaviour, meaning that frustration suppresses quantum chaos.

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Excess noise and thermoelectric effect in topological SNS junction with chiral Majorana liquids

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The ongoing search of systems with topological *p+ip*-superconducting order is focused on artificial hybrid structures. These are spin-orbital coupled materials where a proximity effect of *s*-wave pairing and exchange Zeeman field are induced. In particular, it is possible to implement quantum interferometers on a surface of a 3D topological insulator, covered with superconducting and magnetic insulator films. Theory predicts that interferometers involving 1D charge-neutral chiral Majorana channels, which are the edge modes of 2D topological *p+ip*-superconducting regions, have unusual transport properties [1-3]. Beside of that they might be utilized as readout devices for topological qubits [2]. In the works [1-3] the normal transport of charged Dirac fermions influenced by their splitting to Majorana ones and the interference of the latter were studied. In contrast, we propose a dual model of topological SNS contact [4,5]. In this device the Josephson current is carried by interfering Andreev pairs in Dirac channels which link chiral Majorana liquids at the edges of *p+ip*-superconductors.

We formulate the scattering matrix approach and effective Keldysh action for this contact which allows one to calculate non-equilibrium current and noise. We analyze current-phase relationships and thermoelectric effect and show that geometric asymmetry of the contact results in a supercurrent without a thermal and phase biases. The pattern of critical current has unconventional period of h/e as a function of Aharonov-Bohm flux. This h/e-periodicity follows from chiral structure of the normal region where Dirac channels are spatially separated and Andreev pairs are non-local. The current-phase relationships can have sawtooth-like shape with spikes at unusual even phases of $2\pi n$. Presence of gapless Majorana channels in the superconducting leads enhances a heat and thermal conductances compared to conventional Josephson junctions. In the regime of a finite thermal bias we show that the interference of Andreev pairs causes non-sinusoidal Aharonov-Bohm oscillations of thermoelectric and heat currents. It is remarkable that depending on the Aharonov-Bohm flux, the direction of thermoelectric current can be both from the hot to cold lead and vice versa. Also, the interference between Andreev pairs and Majorana quasiparticles results in the excess zero-frequency noise at low temperatures which is sensitive to the Aharonov-Bohm phase as well. It follows from the fluctuation-dissipation theorem that the real part of the junction impedance exceeds the single channel conductance e^2/h which can be considered as a consequence of the interactions in the bulk of topological superconductors.

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Superconducting spintronics and re-orientation of the easy axis in the ϕ_0 Josephson junction

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Investigation of Josephson junctions in combination with magnetic systems is one of the intensively developing field of condensed matter physics [1]. Possibility to manipulate the magnetic properties by Josephson current attracts much attention today [2-4].

We study physical phenomena in ϕ_0-junction with direct coupling between magnetic moment and Josephson current. By using a realistic model of Josephson junction including quasiparticle and displacement current, we simulate the IV-characteristics together with magnetic precession. It is demonstrated that a character of precession essentially change in the voltage interval corresponding to the ferromagnetic resonance. The current interval is characterized by a cascade of different states of precession, which might be observed by changing bias current along IV-characteristic. These results give an opportunity to manipulate the magnetic properties by

Josephson current, and also, to manipulate the superconducting properties by magnetic moment precession. We demonstrate the magnetic moment reversal by superconducting current in the framework of ϕ_0-junction model [5]. The observed features might find an application in different field of spintronics.

We study theoretically a dynamics of the ϕ_0 Josephson junction, which shows features reminiscent of a Kapitza pendulum [6]. We find that, starting with the magnetization along the z-axis, the character of the magnetization dynamics changes crucially as a stable position of the magnetic moment is realized between the z- and y-axes, depending on the values of the system parameters. Changes in critical current and spin-orbit interaction lead to different stability regions for the magnetization. Excellent agreement is obtained between analytical and numerical results at low values of the Josephson to magnetic energy ratio.

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Application of kinetic inductance of thin-film niobium nitride in experiments on single electron transport

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We are studying single-electron transport phenomena in tunnel junctions surrounded by meanders of highly inductive thin-film niobium nitride (NbN) [1]. The proposed approach to create high-impedance environment potentially has several advantages over the currently existing techniques – thin-film resistors and arrays of the Josephson junctions [2, 3]. We present the results of numerical simulations of the planned experiment [4]. We also discuss the technology to fabricate Cu/Al/AlOx/Cu tunnel junctions. The current fabrication progress is presented.

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Engineering and investigating a two-qubit system

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Superconducting circuits are promising candidates as to become quantum bits in a potential quantum computer. However, large systems of interacting qubits are needed to perform complex calculations and solve problems that are intractable by conventional computers. To achieve this, first of all, it is necessary to build a system of at least two interacting qubits, and thus we have developed an architecture where two transmons [1] are connected directly through a capacitor. A single coplanar resonator is used to readout the qubit states. We calculated the dependence of the coupling constants on the capacitances for our particular design and simulated these capacitances using various FEM methods. Finally, the experimental data containing testimony of the qubit-qubit coupling are presented.

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Dynamics of mesoscopic qubit ensemble coupled to cavity: role of collective dark states

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We consider dynamics of a disordered ensemble of qubits interacting with single mode photon field, which is described by exactly solvable inhomogeneous Dicke model. In particular, we concentrate on the crossover from few-qubit systems to the system of many qubits and analyze how collective behavior of coupled qubits-cavity system emerges despite of the broadening. We show that quantum interference effects survive in the mesoscopic regime -- dynamics of an entangled Bell state encoded into the qubit subsystem remains highly sensitive to the symmetry of the total wave function. Moreover, relaxation of these states is slowed down due to the formation of collective dark states weakly coupled to light. Dark states also significantly influence dynamics of excitations of photon subsystem by absorbing them into the qubit subsystem and releasing quasiperiodically in time. We argue that predicted phenomena can be useful in quantum technologies based on superconducting qubits. For instance, they provide tools to deeply probe both collective and quantum properties of such artificial macroscopic systems.

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Development of compact superconducting microwave beam splitter for boson sampling experiments

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Superconducting quantum circuit is one of the most robust ways for realization of quantum systems. One of the most interesting effects can be observed due to single photons interactions [1]. To conduct these experiments different devices like single-photon source and an element for entanglement of quantum states are required. The most natural realization for such element is a beam splitter [2]. In microwave range it is convenient to use a hybrid beam splitter [1]. For single photon experiments a commercial beam splitter is not suitable because of dispassion in connectors and wires. Therefore, it is natural to use a beam splitter on-chip.

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Quantum detector tomography of waveguide-integrated SNSPD

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We report on quantum tomography of waveguide-integrated superconducting nanowire single photon detector (WSNSPD). Utilizing close-to-unity internal detection efficiency of our WSNSPDs, we extract single and double photon efficiency from dependencies of the number of counts on the number of photons, and demonstrate how to find hot-spot correlation length without an ambiguity. We identify the main source of systematic error, the bias circuit response, which is unavoidable for any SNSPD, and suggest an explicit procedure how to wash it out. We discuss what our method gives for deeper study of local non-equilibrium states in SNSPDs.

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