TT 1: Focus Session: Disordered and Granular Superconductors: Fundamentals and Applications in Quantum Technology I

Superconducting qubits and quantum circuits are traditionally fabricated from simple superconductors such as aluminum or niobium. Recently, strongly disordered and granular superconductors have become a promising alternative for quantum devices that seek a combination of large impedance and low losses: here, the high kinetic inductance of disordered and granular superconductors is a key asset. While these particular materials are in the focus of fundamental superconductivity materials research already for a long time, their application in quantum technologies now motivates a tight interaction of these two research fields.

Organizers: Marc Scheffler (University of Stuttgart), Joachim Ankerhold (Ulm University)

Time: Monday 10:00–12:45 Location: H6

TT 1.1 Mon 10:00 H6

Fate of the superfluid density near the SIT in amorphous superconductors — •Benjamin Sacepe — Néel Institute, CNRS Grenoble, France

Superconducting films of amorphous Indium Oxide (a:InO) thin films undergo a transition to insulation upon increasing disorder, driven by the localization of preformed Cooper pairs. The continuous decrease of the critical temperature as the critical disorder approaches indicates a similarly continuous suppression of the superfluid density. In this talk I discuss the fate of the superfluid density in the vicinity of this transition to insulation. We have accurately measured the superfluid density by a systematic study of the plasmon dispersion spectrum of microwave resonators made of a:InO, combined with DC resistivity measurements, as a function of disorder. We observed that the superfluid stiffness defines the superconducting critical temperature over a wide range of disorder, highlighting the dominant role of phase fluctuations. Furthermore, we found that the superfluid density remains surprisingly finite at the critical disorder, indicating an unexpected first-order nature of the disorder-driven quantum phase transition to insulator.

TT 1.2 Mon 10:30 H6

Superconducting silicon: material and devices — •Francesca Chiodi[1], Pierre Bonnet[1], Daniel Flanigan[2], Raphaelle Delagrange[1], Dominique Débarre[1], and Hélène le Sueur[2] — [1]C2N, Université Paris-Saclay, CNRS, Palaiseau, France — [2]SPEC, Université Paris-Saclay, CEA, CNRS, Gif-sur-Yvette, France

Silicon is one of the most well-known materials, and the main actor in today electronics. Despite this, silicon superconductivity was only discovered in 2006 in laser doped Si:B samples. Laser annealing is instrumental to cross the superconductivity threshold, as the required doping is above the solubility limit, and cannot be reached using conventional micro-electronic techniques. Laser doping allows the realisation of epitaxial, homogeneous, thin silicon layers (5-300 nm) with extreme active doping as high as 11 at. %, and without the formation of B aggregates.

Silicon is a disordered superconductor, with a lower carrier density (1e20 to 5e21 cm-3) than metallic superconductors, a critical temperature modulable with doping from 0 to 0.8 K, and a relatively high resistivity that allows to easily match the devices to the void impedance.

We have realised microwave silicon resonators, working in the 1-12 GHz range and with quality factors about 4000. We have shown a strong non-linear response with power, observing a Kerr coefficient of the order of 300 Hz/photon where less than 1 Hz/photon was expected. To better understand the losses and recombination mechanisms, we have measured the relaxation dynamics of the resonators following a light or a microwave pulse.

TT 1.3 Mon 10:45 H6

Nanocrystalline boron-doped diamond as a model granular superconductor — •Georgina Klemencic[1], David Perkins[2], Jon Fellows[3], Soumen Mandal[1], Chris Muirhead[2], Robert Smith[2], Sean Giblin[1], and Oliver Williams[1] — [1]Cardiff University, UK — [2]University of Birmingham, UK — [3]University of Bristol, UK

We present results of an experimental investigation into Boron-doped Nanocrystalline Diamond (BNCD), which we argue to be an exemplary model for granularity in a low-temperature superconducting system.

Through measurement of the fluctuation conductivity [1], we have indirectly measured the inter- and intragrain diffusion lengths, in an experimental application of the theoretically proposed 'fluctuation spectroscopy' technique. The fluctuation conductivity is well predicted by theories of granular superconductors and the magnetoresistance exhibits the same glassy behaviour as high-T_c samples [2]. In this respect, we find that BNCD is a good system for distinguishing high-T_c behaviours from granular superconductor behaviours.

A special feature of BNCD is its morphology, in which grains extend vertically through the film, making the bulk material structurally akin to a naturally occurring Josephson junction array. In recent work, we have found evidence of metastable phase slip-like excitations in the current-voltage characteristics of macroscopic bridges fabricated from BNCD, which we attribute to this morphology [3].

[1] G. M. Klemencic et al., Phys. Rev. Mater. 1.4 (2017): 044801
[2] G. M. Klemencic et al., Sci. Rep. 9.1 (2019): 1-6
[3] G. M. Klemencic et al., Carbon 175 (2021): 43-49

TT 1.4 Mon 11:00 H6

Distribution of the order parameter in strongly disordered superconductors: analytic theory — •Anton V. Khvalyuk[1,2] and Mikhail V. Feigel'man[2,3] — [1]Skolkovo Institute of Science and Technology, 143026 Skolkovo, Russia — [2]L. D. Landau Institute for Theoretical Physics, 119334 Moscow, Russia — [3]Moscow Institute of Physics and Technology, 117303 Dolgoprudny, Russia

We present an analytic theory of inhomogeneous superconducting pairing in strongly disordered materials, which are moderately close to Superconducting-Insulator Transition. Within our model, single-electron eigenstates are assumed to be Anderson-localized, with a large localization volume. Superconductivity then develops due to coherent delocalization of originally localized preformed Cooper pairs. The key assumption of the theory is that each such pair is coupled to a large number $Z \gg 1$ of similar neighboring pairs. We derived integral equations for the probability distribution $P(\Delta)$ of local superconducting order parameter $\Delta(\boldsymbol{r})$ and analyzed their solutions in the limit of small dimensionless Cooper coupling constant $\lambda \ll 1$. The shape of the order-parameter distribution is found to depend crucially upon the effective number of "nearest neighbors" $Z_{\mathrm{eff}} = 2\nu_0 \Delta Z$. The solution we provide is valid both at large and small Z_{eff}; the latter case is nontrivial as the function $P(\Delta)$ is heavily non-Gaussian. One of our key findings is the discovery of a broad range of parameters where the distribution function $P(\Delta)$ is non-Gaussian but also free of "fat tails" and other features of criticality. The analytic results are supplemented by numerical data, and good agreement between them is observed.

15. min. break

TT 1.5 Mon 11:30 H6

Spectroscopy of a single Josephson impurity in a high kinetic inductance array — •Serge Florens[1], Sébastien Léger[1], Théo Sépulcre[1], Denis Basko[2], Izak Snyman[3], and Nicolas Roch[1] — [1]Néel Institute, CNRS, Grenoble, France — [2]LPMMC, UGA, Grenoble, France — [3]Wits University, Johannesburg, South Africa

Superconducting arrays constitute a promising platform to explore a large class of physical phenomena, from quantum phase transitions to non-linear quantum optics in the microwave domain. We design a fully-tunable model system where a long chain of several thousands linear Josephson elements, acting as a high inductance transmission line, is terminated by a small Josephson junction endowed with a strong non-linearity, acting as a single impurity. From microwave spectroscopic measurements, we extract the phase shift and the inelastic losses induced by the impurity onto the linear modes of the array. In agreement with a microscopic modeling of the circuit, we put into evidence a huge renormalization of the Josephson tunnel energy at the impurity site, and show that the associated enhancement of phase fluctuations provides the dominant dissipation mechanism in the array.

TT 1.6 Mon 12:00 H6

Low energy electrodynamics of strongly disordered superconductors — •Götz Seibold[1], Lara Benfatto[2], and Claudio Castellani[2] — [1]BTU Cottbus-Senftenberg, Cottbus, Germany — [2]University of Rome 'La Sapienza', Rome, Italy

In this contribution we will discuss the static and dynamical response of strongly disordered superconductors based on investigations of the attractive Hubbard model with strong on-site disorder and by including fluctuations beyond the Bogoljubov-de Gennes approach. It turns out that paramagnetic processes mediate the response of all collective modes, with a substantial contribution of charge/phase fluctuations [1,2,3]. In particular, we show that for strongly disordered superconductors phase modes acquire a dipole moment and appear as a subgap spectral feature in the optical conductivity which even survives long-range Coulomb interactions. The same processes turn out to dominate also the third-order current at strong disorder [5]. In this regard we show that disorder strongly influences the polarization dependence of the non-linear response, with a marked difference between the homogenous and the disordered case. Our results are particularly relevant for recent experiments in cuprates, whose band structure is in a first approximation reproduced by our lattice model.

[1] G. Seibold et al., Phys. Rev. B 92, 064512 (2015)
[2] T. Cea et al., Phys. Rev. B 89, 174506 (2014)
[3] G. Seibold et al., Phys. Rev. Lett. 108, 207004 (2012)
[4] G. Seibold et al., Phys. Rev. B 103, 014512 (2021)

TT 1.7 Mon 12:15 H6

Decoupling of the Quasiparticle Number and Lifetime in a Disordered Superconductor Probed by Quasiparticle Fluctuation Measurements — •Steven A. H. de Rooij[1,2], Kevin Kouwenhoven[1,2], Jochem J. A. Baselmans[1,2], Vignesh Murugesan[2], David J. Thoen[1,3], and Pieter J. de Visser[2] — [1]SRON - Netherlands Institute for Space Research, Leiden, The Netherlands — [2]Department of Microelectronics, Delft University of Technology, The Netherlands — [3]Kavli Institute of NanoScience, Delft University of Technology, Delft, The Netherlands

In a superconductor, the number of quasiparticles (N_{qp}) decreases exponentially when lowering the temperature, while the quasiparticle lifetime increases, i.e. $\tau_{qp} \sim 1/N_{qp}$. Measuring quasiparticle fluctuations, induced by thermal fluctuations, give access to both τ_{qp} and N_{qp}. In disordered superconductors, these fundamental quasiparticle properties have hardly been studied, although these materials are widely applied in high kinetic inductance quantum circuits and kinetic inductance detectors. We measured quasiparticle fluctuations in the disordered superconductor β-Ta, embedded in a NbTiN microwave resonator, probing both the dissipation (i.e. quasiparticles) and kinetic inductance (i.e. Cooper-pairs). We observe a non-conventional temperature dependence of τ_{qp}, i.e. $\tau_{qp} \nsim 1/N_{qp}$, which results in a strong reduction of the quasiparticle fluctuations with decreasing temperature. This behavior is similar to that of the conventional superconductor Al, where we relate it to quasiparticle trapping [arXiv:2103.04777], which may also play a role in disordered superconductors.

TT 1.8 Mon 12:30 H6

Current-enhanced superfluid stiffness near the Berezinskii-Kosterlitz-Thouless transition in strongly disordered NbN-films — •Alexander Weitzel[1], Lea Pfaffinger[1], Klaus Kronfeldner[1], Thomas Huber[1], Lorenz Fuchs[1], Sven Linzen[2], Evgenii Il'ichev[2], Nicola Paradiso[1], and Christoph Strunk[1] — [1]Experimental and Applied Physics, Uni Regensburg, Germany — [2]Leibniz Institute of Photonic Technology, Jena, Germany

We investigate resistivity and kinetic inductance in long and ultrathin NbN strips near the superconductor-insulator transition. Resistive transition is dominated by superconducting fluctuations of both amplitude and phase of the order parameter. Near the foot of the transition, the resistivity displays a square-root cusp divergence of the conductance expected for the Berezinski-Kosterlitz-Thouless (BKT) transition. The superfluid stiffness of the very same strip (measured using an RLC-resonator technique) displays a sharp drop close to the universal value of $2T_{\mathrm{BKT}}/\pi$. Current voltage (IV) characteristics become non-linear below T_c, with a complex back-bending shape that signals a heating instability. At lower temperatures, IV-characteristics feature a peculiar negative curvature in a log-log representation. This indicates a reduction of dissipation with respect to the standard power-law behavior of the IV-characteristics and is corroborated by the observation of an unexpected increase of kinetic inductance near the critical current.