TT 21: Focus Session: Strongly Disordered Superconductors

The very nature of the disorder-induced superconductor-insulator transition has remained enigmatic in the past two decades. Very recently, a new generation of experiments has been performed that addresses not only DC-properties, but also the fate of the superfluid stiffness very close to the superconductor-insulator transition. These experiments reveal the superfluid dynamics at the transition in unprecedented clarity and were enabled by the advent of high-resolution microwave techniques. This provides a natural link to quantum circuits, where the ultra-high kinetic inductance is exploited in these materials is exploited for new types of high-fidelity quantum bits.
Organizers: Christoph Strunk (University of Regensburg), Ferdinand Evers (University of Regensburg)

Time: Tuesday 9:30–12:45 Location: H 0104

Invited Talk TT 21.1 Tue 9:30 H 0104
The fate of the superfluid density near the superconductor-insulator transition — •Benjamin Sacepe — Neel Institute, CNRS Grenoble, France

Superconducting films of amorphous Indium Oxide (a:InO) undergo a transition to insulation with increasing disorder, which is due to the localization of pre-formed Cooper pairs. The continuous decrease in critical temperature as critical disorder is approached suggests an equally continuous suppression of superfluid density. In this talk I will discuss a systematic study of the superfluid density measured via plasmon dispersion spectroscopy 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.

Invited Talk TT 21.2 Tue 10:00 H 0104
Vortices in dirty superconducting films — •Elio König — Max-Planck Institute for Solid State Research, 70569 Stuttgart, Germany

In this talk about the long standing question of superconductivity in dirty two-dimensional samples I will first review exemplary experiments and summarize theories put forward within the two main paradigms dubbed "bosonic" and "fermionic" approach, respectively.

Next, I will present a theory for the finite temperature vortex-unbinding transition in homogeneously disordered superconducting films. This theory incorporates the effects of quantum, mesoscopic, and thermal fluctuations stemming from length scales ranging from the superconducting coherence length down to the Fermi wavelength and allows to determine the dependence of essential observables on microscopic characteristics.

Finally, the last part of the talk is dedicated to the voltage generation in 2D superconducting films of finite width (strips) at zero temperature and subjected to a finite current bias. We show by means of a variational Ansatz that the voltage is generated by multi-vortex configurations (instead of single or double vortex configurations considered previously). At the border of its applicability, our theory also evidences the superconductor-insulator quantum phase transition.

Invited Talk TT 21.3 Tue 10:30 H 0104
Superfluid stiffness of a strongly disordered superconductor close to the superconductor-insulator transition — •Alexander Weitzel[1], Lea Pfaffinger[1], Ilaria Maccari[2], Klaus Kronfeldner[1], Thomas Huber[1], Lorenz Fuchs[1], Simon Reinhardt[1], James Mallord[1], Sven Linzen[3], Evgeni Il'ichev[3], Nicola Paradiso[1], and Christoph Strunk[1] — [1]Institute for Experimental and Applied Physics, University of Regensburg, D-93040 Regensburg, Germany — [2]Department of Physics, Stockholm University, Stockholm SE-10691, Sweden — [3]Leibniz Institute of Photonic Technology, D-07745 Jena, Germany

In superconducting thin films, the superconductor-insulator transition (SIT) is a paradigmatic example of a quantum phase transition: With increasing disorder the critical temperature of the superconductor is suppressed towards zero until an insulating ground state that is expected at a critical level of disorder with normal state resistance $R_N \simeq h/4e^2$. Notably, in many materials the mechanism of the SIT is not entirely clear, with competing explanations based on suppression of the order parameter modulus or proliferation of phase fluctuations. Using a tank circuit compatible with dc transport measurements, we investigate ultra-thin atomic layer deposited NbN films and trace the evolution of the superfluid stiffness as a function of disorder close to the SIT. We observe a sharp Berezinskii-Kosterlitz-Thouless transition in dc transport and in superfluid stiffness that persists even up to $R_N \simeq h/e^2$. In the vicinity of the SIT, phase fluctuations suppress the superfluid stiffness, consistent with a bosonic mechanism of SIT.

15 min. break

Invited Talk TT 21.4 Tue 11:15 H 0104
Thermally enhanced superconductivity and photonic dissipation in Josephson junction arrays — •Andrew P. Higginbotham — James Franck Institute and Department of Physics, 929 E 57th St, Chicago, IL 60637, USA — IST Austria, Am Campus 1, 3400 Klosterneuburg, AT

I will present two studies exploring the limits of superconductivity in long Josephson junction arrays. The first study shows that apparent superconductivity persists for vastly weaker chains than expected within a zero-temperature theory. This behavior is consistent with thermal effects, which effectively melt the insulator and restore superconducting behavior [1]. The second study finds dissipation arising from photon-photon interactions. I will discuss the possible relevance of this dissipation as a source of photonic friction in equilibrium, and as a source of many-body stabilization in nonequilibrium.
[1] S. Mukhopadhyay et al., Nat. Phys. **19** (2023) 1630.

Invited Talk TT 21.5 Tue 11:45 H 0104
Spectral Gap and Order Parameter Statistics in Disordered Superconducting Films — •Matthias Stosiek — Department of Applied Physics, Aalto University, Finland

The interplay of disorder and superconductivity leads to a rich variety of phenomena like the development of superconducting islands at superconductor-insulator transitions or an enhancement of the superconducting critical temperature.

These phenomena are enabled by the local fluctuations of superconducting observables. In particular, two observables are of outstanding interest: the superconducting order parameter and the spectral gap of the local density of states. While identical in absolute value in BCS theory, these observables can differ dramatically in dirty superconductors. In many previous studies, this difference was assumed to be negligible in the weakly disordered regime.

In the here presented work, we aim to elucidate this assumption. For this, we conducted a computational study of disordered thin-film superconductors within fully self-consistent mean-field theory. To produce our results, we employed a self-written, highly optimized self-consistency solver [1] that we made publicly available [2]. Our results include: (i) demonstration of only small correlations between the two observables even in the weakly disordered regime; (ii) indications of a non-local relation between order parameter and spectral gap.
[1] M. Stosiek, B. Lang, F. Evers, Phys. Rev. B 101 (2020) 144503
[2] https://github.com/ccmt-regensburg/self_ consistency_ solver

TT 21.6 Tue 12:15 H 0104
Temperature-Dependent Vortex Dynamics and Current Limitations in a $[(SnSe)_{(1+\delta)}]_3[NbSe_2]_1$ Ferecrystal — •Linus P. Grote[1], Wieland G. Stoffel[1], Mahni Müller[1], Theodor U. Griffin[1], Olivio Chiatti[1], Danielle Hamann[2], David C. Johnson[2], and Saskia F. Fischer[1,3] — [1]Novel Materials Group, Humboldt-Universität zu Berlin, 10099 Berlin, Germany — [2]Department of Chemistry and Materials Science Institute, University of Oregon, Eugene OR 97403, USA — [3]Center for the Science of Materials Berlin, 12489 Berlin, Germany

The evidence of two-dimensional superconductivity in van der Waals superlattices has recently received a lot of attention [1]. Our study investigates the temperature, magnetic field, and current-dependent superconducting properties of a ferecrystal - a layered van der Waals heterostructure with $NbSe_2$ monolayers separated by SnSe spacers [2]. Current-voltage characteristics indicate a Berezinskii-Kosterlitz-Thouless phase transition and suggest two-dimensional superconductivity, while an intermediate temperature range exhibits phase slip lines and reduced critical currents. Magnetic field measurements reveal the nature of phase slip lines and determine the in-plane and out-of-plane Ginsburg-Landau coherence lenghts. Our findings contribute insights into the complex interplay of vortex behavior and superconducting properties in superconducting heterostructures, enhancing understanding of superconductor current limitations.

[1] A. Devarakonda et al., Science **370** (2020) 231
[2] O. Chiatti et al., J. Phys.: Condens. Matter **35** (2023) 215701

TT 21.7 Tue 12:30 H 0104

Finite-size scaling in the vicinity of the BKT transition — •Lea Pfaffinger[1], Alexander Weitzel[1], Sven Linzen[2], Evgenii Il'ichev[2], Nicola Paradiso[1], and Christoph Strunk[1] — [1]Experimental and Applied Physics, University Regensburg, Germany — [2]Leibniz Institute of Photonic Technology, Jena, Germany

In 2D superconducting thin films the unbinding of thermal vortex-antivortex pairs should lead to a finite resistance above the Berezinskii-Kosterlitz-Thouless (BKT) temperature [1]. However, experimental results often showed a broadened transition by correlated disorder in the samples. Very recently, this was avoided in homogeneously disordered 3nm NbN films grown by atomic layer deposition [2]. Finite size effects were expected to affect the transition for sizes smaller than $\Lambda_p = 2\lambda^2/d$, but surprisingly, the transition in our films agrees with theory down to a width of 10μm $\simeq \Lambda_p \ll$ 2mm. When further reducing the width to $w \lesssim 1\mu$m, we observe a finite resistance even for $T < T_{BKT}$. We study the evolution of this broadened transition regime vs. width and additionally compare the power law exponent in IV characteristics with theoretical predictions.

[1] J. Kosterlitz, D. Thouless, J. Phys. C: Solid State Phys., **6** (1973) 1181
[2] A. Weitzel et al., Phys. Rev. Lett. **131** (2023) 186002
[3] A. Anderson, J. Lidmar, Phys. Rev. B, **87** (2013) 224506