Josephson and noise scanning tunneling microscopy on conventional, unconventional and disordered superconductors

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Conclusions and outlook

This thesis is devoted to the study of pairing correlations in different families of superconductors using the novel Josephson and noise scanning tunneling microscopy techniques. We believe that by measuring the properties of the electron pairs (Cooper pairs) in a superconductor we obtain valuable information about superconducting correlations.

The Josephson scanning tunneling microscopy (JSTM) technique allowed to directly visualize the superfluid density of the unconventional iron-based superconductor Fe(Se,Te) (Chapter 3). We discovered that the superfluid density in this material is strongly inhomogeneous in the atomic scale and correlates with the coherence of the quasiparticles. Therefore, we suggest that superconductivity appears to be needed for coherent quasiparticles locally on the length scale of Cooper pairing.

Later on, we studied how the superfluid in Fe(Se,Te) is perturbed by magnetic impurities (Chapter 4). The energy resolution of the JSTM technique allowed us to resolve the spatial dispersion of Yu-Shiba-Rusinov in-gap bound states in Fe(Se,Te). We further proposed a tip-gating mechanism that is responsible for our observations. That is, the low carrier density in Fe(Se,Te) favours the penetration of the electric field of the tip in its interior. As a result, this tip-induced effect gates the impurity as we simulated using the single-impurity Anderson model.

The noise scanning tunneling microscopy (NSTM) technique was employed for measuring the charge of the transported carriers in junctions consisting of conventional or disordered superconductors (Chapters 5 and 6). In the case of superconductor-insulator-superconductor junctions made of lead, we observed doubling of the transported charge when the voltage-bias of the junction is in a range where Andreev reflection processes happen. In addition, when mapping the shot noise in the atomic scale we observe that charge pairing is not influenced by disruptions in the superfluid smaller than the superconducting coherence length. In the experiment shown in Chapter 6, where the disordered superconductor TiN was investigated, we found evidence of pre-formed Cooper pairs above the critical temperature T_C.

We have the belief that the two novel techniques that we used in this thesis have great potential therefore they should be employed in more experiments.

One instance of potential application of the JSTM technique is in examining the superconducting state of graphene-based superlattices [1]. Inspecting the superfluid with JSTM in such systems would be of great importance, among others, in answering the question: *How does the superfluid density and its spatial distribution evolve as a function of the twist angle?* In addition, JSTM would play an important role in detecting pair density waves in strained graphene as it has been suggested theoretically in Ref. [2]. Similar experiments on cuprate superconductors [3] have been very insightful on detecting spatial periodic modulations of the order parameter hence, we expect JSTM to be enlightening on superconducting strained graphene as well.

Furthermore, we foresee that the JSTM technique would be crucial for depicting the order parameter of disordered superconductors close to the superconductor-insulator transition. In this regime, electronic granularity emerges and the consensus among scientists about the superconducting state often involves a description where superconducting patches are enclosed in a matrix of zero local order parameter [4]. *Since the JSTM technique is ideal for visualizing the order parameter, it would be instructive to employ it for imaging the evolution of the superfluid density in disordered materials close to the superconductor-insulator transition*.

It is important to note that future JSTM experiments would benefit from superconducting tips that exhibit high robustness. According to our experience, scanning on a disordered material with a Pb-coated superconducting tip is a challenge. The topography of disordered superconductors exhibits strong irregularities, hence severe junction instabilities are often observed which ultimately lead to detachment of the Pb coating. For this reason we strongly believe that it is imperative to improve the current methods for making a superconducting tip towards higher yield and robustness. *We propose to focus on automated methods of tip preparation using machine learning algorithms which have been very useful in previous experiments* [5].

Concerning the NSTM technique we are confident that it can provide important information in numerous experiments. As we already hinted in Chapter 5, some examples of potential atomically resolved shot noise measurements concern the fluctuating stripe order [6],the Kondo effects in heavy fermion systems [7] or the signatures of Majorana modes in one-dimensional wires on a superconducting surface [8].

The suggestion to perform NSTM experiments in order to reveal the exotic physics of Majorana fermions is perhaps the one with the broadest scientific interest. This is because Majorana-based devices have immense potential applicability in quantum computing. One promising platform that has been conjectured to host Majorana fermions, is Fe(Se,Te). As we have seen in Chapter 4, in the vortex cores of Fe(Se,Te), robust zero-bias peaks have been detected and interpreted as signatures of Majorana quasiparticles [9, 10]. However, such spectroscopic signatures are not considered as conclusive proofs for the existence of these exotic particles that are their own anti-particles. For this reason, more and more works [11] across different platforms have recently focussed on alternatively methods that would provide compelling evidence of Majorana fermions.

Along these lines, we see great potential for the NSTM technique as alternative technique for probing Majorana quaiparticles. *Specifically for Fe(Se,Te) we see shot noise mapping of its vortex cores as an important future experiment*. As discussed by Bolech and Demler [12] the shot noise would allow to distinguish between Majorana and trivial bound states.

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