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

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Summary

Among the different phenomena occurring in condensed matter, superconductivity is one of the most fascinating ones. Remarkably, the electrical resistivity of a superconductor vanishes bellow a characteristic temperature. Superconductivity develops in certain materials due to the formation of electron pairs, so called Cooper pairs. Below the superconducting critical temperature, Cooper pairs condense into a coherent macroscopic quantum state that is described as a charged superfluid. The notion of Cooper pairing is essential towards the understanding of superconducting correlations among the different classes of conventional, unconventional and disordered superconductors. Therefore, probing the superfluid in order to measure the properties of its constituents is extremely important for shedding more light on superconducting correlations.

In this thesis we use Josephson and noise scanning tunneling microscopy for the study of conventional, unconventional (iron-based) and disordered superconductors in the atomic scale. On the one hand, Josephson scanning tunneling microscopy (JSTM) allows us to directly visualize the superfluid density with high spatial resolution. On the other hand, noise scanning tunneling microscopy (NSTM) is employed for measuring the shot noise which detects the charge of the carriers forming a superconducting condensate.

These novel scanning tunneling microscopy (STM) techniques are introduced in Chapter 2. For JSTM, the important theoretical considerations of the Josephson effect are analysed. In addition, we review the relevant models for describing such JSTM junctions together with the methods for extracting the superfluid density via tunneling spectroscopy measurements. From an experimental perspective, we discuss how to form a JSTM junction by decorating our STM tip apex with lead, a conventional superconductor, and note the importance of electronic filtering for reducing unwanted noise. Later in Chapter 2, the basic principles of NSTM are presented with emphasis on the bandwidth limitations of conventional STM circuitry that prohibit shot noise measurements. We then explore how to overcome this fundamental limitation with the use of a high-frequency amplifier. Last but not least, we summarize the methods that we use in order to quantitatively determine the shot noise from NSTM measurements.

In Chapter 3, the JSTM technique is performed on the unconventional iron-based superconductor Fe(Se,Te). By directly probing the condensate in the atomic scale we find its superfluid density to be spatially inhomogeneous. Intrigued by this behaviour of the superfluid we investigate possible reasons that cause such strong density variations. We exclude crystal disorder, superconducting gap variations and scattering as the origin of the observations. However, we find that the superfluid density follows the spatial irregularities of the coherence of the quasiparticles. We uncover that this correlation holds for distances associated with the length scale of superconductivity in Fe(Se,Te). Our findings suggest that the superfluid is intrinsically inhomogeneous resembling cuprate superconductors where a similar correlation between the superfluid density and the coherence of quasiparticles has been found to hold in the macroscopic scale. We finally give an outlook of how JSTM can be used in other topical superconductors for gaining insight into their superfluid density.

Our next scientific adventure, presented in Chapter 4, is again on Fe(Se,Te) where we discover peculiar impurity state resonances. The use of a superconducting STM tip allows us to perform spectroscopy with unprecedented energy resolution. We find impurity resonances inside the superconducting gap of Fe(Se,Te) which we argue that stem from the local interaction between the superfluid and magnetic impurity defects. Surprisingly, we discover that in Fe(Se,Te) the energy of the so called Yu-Shiba-Rusinov states, disperses spatially and it can be tuned by adjusting the tip-sample distance. Towards explaining this unusual behaviour we realize that the low and inhomogeneous superluid density in Fe(Se,Te) allows for partial electric field penetration in its interior. This way the electric field of our tip-probe interacts with the impurity state, effectively gating it. Our hypothesis is tested via theoretical simulations by using the single-impurity Anderson model. It is found that this simple treatment of our system reproduces well the experimental findings. Finally we compare our results with recent reports of Majorana fermions on Fe(Se,Te).

NSTM on a conventional superconductor, lead, is the subject of Chapter 5. In this work we essentially measure the charge of the carriers transported in a STM junction formed by a lead tip and surface. We verify using NSTM that for a specific voltage bias range Andreev reflection processes occur effectively, transferring charge of twice the electron charge across the junction. Further, we perform shot noise mapping in the atomic scale around argon nanocavities, to demonstrate that Cooper pairs are not affected by disruptions on a length scale smaller than the superconducting coherence length.

Finally, in Chapter 6 we deal with a different class of superconductivity. The disordered superconductor TiN is examined above its critical temperature via NSTM with the use of a metallic tip. We find that there exist carriers with charge that is twice the electronic one, while the material is in a non-superconducting state that resembles a metal in terms of conductance spectroscopy. This remarkable observation hints towards the existence of pre-formed Cooper pairs in TiN, a concept that has been discussed theoretically and explored via conventional STM spectroscopy in the context of disordered superconductivity. Our study further corroborates these ideas by directly probing the charge of the carriers in the metallic state of TiN.