Visualizing strongly-correlated electrons with a novel scanning tunneling microscope

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Conclusions and outlook

This thesis is dedicated to the study of strongly-correlated electron systems using spectroscopic-imaging scanning tunneling microscopy (SI-STM), with a focus on the physics of lightly doped Mott insulators.

We are convinced that the improvement of scientific apparatus is the foundation of new experimental discoveries. Thus, we designed and built a SI-STM (named *Dome*) that proofs to be the stiffest reported to date (chapter 3), which has direct consequences on the data quality in terms of signal-to-noise ratio. This makes the instrument particularly suited for sensitive quasiparticle interference measurements, as we show in chapter 6 on the correlated metal Sr_2RhO_4.

In parallel to the construction of this microscope, we studied the electron-doped iridate $(Sr_{1\text{-}x}La_x)_2IrO_4$ using a different, commercial STM. Our results, described in chapter 4 and 5, add important contributions to the understanding of the physics of lightly doped Mott insulators. In particular, we show that a pseudogap phase with inhomogeneous electronic order appears upon doping, similar to what it is observed in cuprates. It is the first time that these phenomena are observed in a material different that cuprates, and it shows that they are not unique to the copper oxide planes, but belong to a wider class of quasi two-dimensional Mott insulators. Based on this advanced comparison between iridates and cuprates, we support the claim that iridates should also show unconventional superconductivity at higher doping [87, 88].

Quasiparticle interference (QPI) lead to many insights into the understanding of both the pseudogap and the superconducting phase of cuprates [35, 151]. During our investigation of the iridates, we tried to get momentum space information, with the goal to observe q-space signatures of the inhomogeneous charge order and, eventually, QPI. We were not successful, but we could identify two possible reasons: either the pseudogap puddles are too small, or the commercial STM that we used to measure the iridates cannot resolve those features since it is not very suited for QPI measurements. After having developed and tested a dedicated instrument such as Dome, it seems natural to bring the investigation on the iridates further by trying to detect QPI signatures on the iridates with Dome. The much higher signal-to-noise ratio could, in fact, reveal information that we were previously not able to resolve.

This is just one example of which type of measurements could be performed in the near future with Dome. To conclude this thesis, we give in the following other three more specific examples of experiments that could exploit the microscope's potential. The ideas we present are based on the two qualities that make the microscope 'special': first, the extreme stability that allows high-quality quasiparticle-interference measurements (as shown in chapter 3 and chapter 6), and, second, the high-frequency compatibility of the STM head (discussed in Sec. 3.2.1).

Investigation of the strange metal phase in cuprates

The strange metal phase in cuprates is still largely not understood, and much theoretical and experimental effort has been dedicated to its study in the recent years. In particular, theoretical work predicts STM QPI patterns in the strange metal phase both in the framework of Fermi-liquid and marginal-Fermi-liquid theory[1] in the presence of disorder [141].

SI-STM experiments as suggested in Ref. [141] are a good way to understand whether these descriptions are valid or not. In the case one observed the predicted pattern due to QPI, very precise measurements would be needed in order to distinguish the subtle effects that differentiate the proposed theoretical interpretations. On the other hand, observation of a completely different QPI pattern (or of no pattern at all), would indicate that this phase of matter is beyond the marginal Fermi-liquid description. This would point towards other theoretical interpretations, possibly involving quantum criticality and the absence of quasiparticle-like excitations. In recent years, a completely different approach based on holographic methods[2] was used to describe the properties of the strange metal phase [153, 154]. In general, however, more experimental data is needed to support any of the theoretical scenarios.

We believe that with our microscope we could contribute to a better understanding of the strange metal phase, given the high quality QPI measurements that we can achieve. In order to access the strange metal phase, one needs both to have sam-

[1] The phenomenological marginal Fermi liquid theory was first introduced by Varma et al. [152] and it successfully describes many of the unusual properties seen in the normal state of cuprates.

[2] These methods, indeed, do not involve quasiparticles.

ples in the right doping range and to raise the temperature above T_c. Since STM energy resolution gets worse at higher temperatures (see Sec. 2.5), and, in general, measurements become more challenging, we propose to study $Bi_2Sr_2Cu_2O_{6+\delta}$, the single layer compound of the BSCCO family. This material has a lower T_c at optimal doping ($T_c \approx 20\,K$) than other members of the BSCCO family, which would make the strange metal phase accessible more easily. Our sample stage includes a resistive heater that we have already tested. We could measure 24h-long spectroscopic maps at 30 K without the observation of significant drift. This makes the exploration of the strange metal phase in $Bi_2Sr_2Cu_2O_{6+\delta}$, in principle, experimentally possible.

Other insights into the strange metal phase could come from the analysis of the self energies extracted from STM QPI data [155]. This method has been theoretically proposed [149], but has not been applied to data yet. We plan to first develop and apply the proposed data analysis methods onto the simpler system of Sr_2RhO_4 (described in chapter 6), and, if successful, proceed with STM self-energy analysis in cuprates, at low temperature and, eventually, in the strange metal phase.

Scanning noise spectroscopy

The other experiments we want to propose is based on the technique of *scanning noise spectroscopy*. This technique has recently been developed in our group, and, when first applied on cuprate high-T_c superconductors, it lead to interesting insights on the insulating nature of the material along the perpendicular 'c-axis' direction [59]. The technique is based on the development and construction of a new, low-temperature, high-frequency amplifier that allows us to measure the tunneling current in the MHz regime, simultaneously to conventional DC STM measurements [58]. This gives access to information about the current fluctuations (i.e., the noise) that are typically hidden in the 'averaged' DC current signal. Most prominently, it allows us to measure shot noise, which gives an indication of the nature of the charge carriers.

The amplifier has been developed in our group, and, to date, it has been optimized and used on a commercial STM from Unisoku [58]. We are currently at the last stages of construction and testing of a second generation amplifier that will be installed in Dome. One of the hindering factors for the quality of the high-frequency signal is the tip-to-ground capacitance. This number, on the order of 30 pF for the Unisoku system, can be reduced with a smart design of the tip holder (in fact, its origin mostly lies in the geometry of the latter). When designing the STM head for Dome, we worked towards achieving a very low tip-to-ground capacitance, as described in Sec. 3.2.1. This, combined with the superior stability of the microscope, should increase the signal-to-noise ratio of high-frequency measurements for Dome by a factor of three with respect to the Unisoku commercial system. This would enable noise spectroscopy measurements at much lower tunneling current ($\approx 50\,pA$) than it is now possible, making these experiments applicable to many more quasi two-dimensional layered materials.

In addition to further exploring cuprate high-T_c superconductors with scanning noise spectroscopy, we propose to apply this technique to the iridates described in chapter 4. Here, shot noise measurements could additionally reveal different behaviors in the Mott and pseudogap phases, bringing further insights on the nature of the carriers in both phases. In particular, in the Mott regime, an enhancement of the shot noise at the dopant locations could indicate charge trapping, confirming our proposed scenario of frozen electrons.

Shaking the condensate

The last experiment we want to propose regards the exploration of non-equilibrium superconductivity in cuprates. In other words, how is the superconducting state affected when the condensate is moving?

Our idea is based on a proposal by Semenov et al. [156], where they theoretically investigate the effect of applying a microwave field to BCS superconductors. At very low temperatures and with a microwave energy lower than the energy gap (to avoid direct Cooper pair breaking from microwaves), they find that the microwave field would lead to coherent, excited Cooper pairs with an oscillating center of mass motion. This would create a substantial modification of the single-particle density of states, that could be detected by tunneling spectroscopy experiments. We are excited by the possibility to investigate a similar scenario in cuprates.

Dome is provided with semirigid coaxial cables that allow for high-frequency measurements (up to a few GHz). Therefore it is technically possible and relatively simple to apply a microwave excitation to the sample while performing standard spectroscopic STM measurements. We investigated this possibility, and simulations predict that, with minor changes to the experimental setup, we would be able to induce the desired oscillating current densities in the sample. A closer look at the numbers reveals that we would need temperatures much lower than 4 K to observe the effect predicted by Ref. [156]. However, at 4 K, there could still be some detectable effect of microwaves on the coherence peaks of the superconducting gap. If we are able to detect this signature, it would be extremely interesting to see how its magnitude changes locally, given the electronically inhomogeneous landscape of cuprates. A different effect of microwaves on different areas would give insights on how the condensate is moving inside the material.