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Pairing insights in iron-based superconductors from scanning tunneling microscopy

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ABSTRACT

Scanning tunneling microscopy (STM) has made tremendous progress in the study and understanding of both classical and unconventional superconductors. This has motivated a rapidly growing effort to apply the same techniques to the iron-based high-T_c superconductors since their discovery in 2008. Five years have brought exciting advances in imaging and spectroscopic investigation of this new class of materials. In this review, we focus on several recent STM contributions to the identification of the gap symmetry and pairing glue. We highlight the unique capabilities and challenges still ahead for STM studies of iron-based superconductors.

1. Introduction

Magnetism has long been thought to be antagonistic to superconductivity. Therefore, the 2008 discovery of superconductivity in iron-containing $LaO_{1-x}F_xFeAs$ [1], with transition temperature T_c rapidly climbing to 55 K upon replacement of La by magnetic rare earth elements [2], was unexpected and provoked worldwide excitement. As in the case of cuprates, the superconductivity emerges from the antiferromagnetic parent compounds, suggesting a link between spin fluctuations and electron pairing in both materials [3]. This finding opens a new avenue to address the two ultimate goals in the field of superconductivity: to seek the microscopic origin of the high T_c and then design new materials with higher T_c. Despite extensive experimental and theoretical explorations, iron-based superconductors (Fe-SCs) still face fierce debates on a number of issues including gap symmetry, a prerequisite for understanding the secret of high-T_c superconductivity. An excellent review by Johnston has thoroughly discussed the puzzle in Fe-SCs through 2010 [4]. Another comprehensive review by Stewart covers the rapidly-moving field through 2011 [5].

Scanning tunneling microscopy (STM) provides unique capabilities to image the atomic and electronic structure of a surface with a sub-unit-cell spatial resolution. STM has been applied with great success to the study of conventional and cuprate superconductors [6]. The local density of states directly measured by STM spectroscopy provides indispensable information about the superconducting gap structure, its spatial inhomogeneity and behaviors near impurity as well as vortex core states. Furthermore, via quasiparticle interference (QPI) imaging, STM can provide momentum-resolved information about pairing symmetry, collective excitations, and competing phases. All these accomplishments motivate the growing use of STM to study Fe-SCs in the quest to understand the intricate electron pairing in these materials.

Following an early review of STM studies of Fe-SCs by Yin et al. [7], STM has made considerable new progress and greatly contributed to the study of some of the most unusual and remarkable properties of these materials. A more thorough review by Hoffman recently discussed the cleaved surface configurations, superconducting and other spectral gaps, and vortex states [8]. Our new review here will begin with a brief introduction to the STM technique in Section 2, then concentrate on the experimental highlights in the pairing symmetry of Fe-SCs obtained over the past year by STM, such as tunneling spectroscopy in Section 3, QPI in Section 4, and vortex state in Section 5. In Section 6, we conclude by mentioning a few very recent hints of higher T_c in iron-based materials, as well as suggestions for future STM experiments that should shed additional light on these materials.

2. Scanning tunneling microscopy and spectroscopy

STM is based on the quantum tunneling of electrons between two electrodes separated by a thin potential barrier. A sharp metallic tip, which acts as a local probe, is brought within a short distance (typically several Å) of an electrically conducting sample surface. The tip can be positioned with sub-Å precision in both the *xy* plane and the *z* direction using a three-dimensional piezoelectric scanner, as schematically illustrated in Fig. 1a. Applying a bias voltage between the metallic tip and conducting sample leads to a measurable tunneling current; the polarity of the bias voltage determines the direction of the net electron flow. For instance, a negative bias voltage applied to the sample will allow electrons

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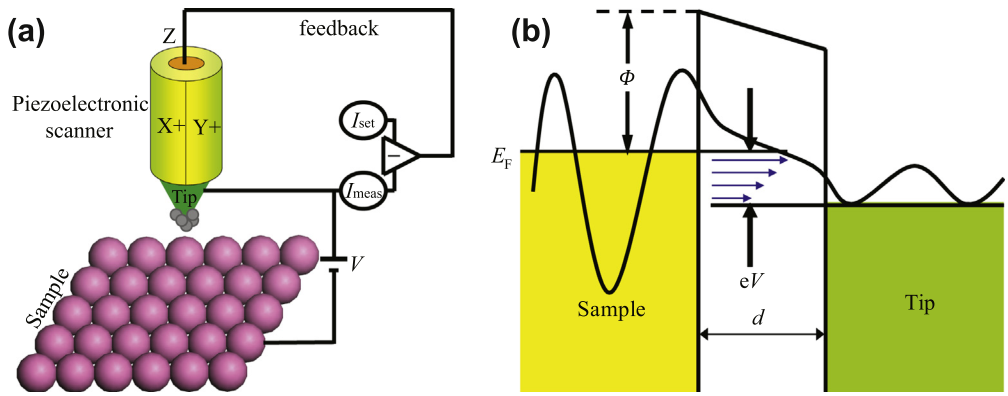

Fig. 1. (a) Schematic of an STM. A voltage V is applied between a sharp metallic tip and a conducting sample surface, leading to a measurable tunneling current I_{meas} which decays exponentially with tip-sample separation *d*. In standard constant-current topographic imaging, the difference (or the error signal) between I_{meas} and the setpoint current I_{set} is fed back to the *z* piezo to control the tip height. (b) Tunneling process of electrons between the tip and sample across a vacuum barrier of width *d* and height ϕ. The electron wave functions of both the sample and tip decay exponentially into vacuum with a small overlap, allowing electrons to tunnel between them. With a negative bias voltage *V* applied to the sample, electrons tunnel from the occupied states of the sample to the empty states of the tip.

to tunnel from the occupied states of the sample through the vacuum barrier into the empty states of the tip (Fig. 1b). Upon reversing the bias polarity, the electrons will tunnel in the opposite direction, from occupied states of the tip into empty states of the sample. Based on the Tersoff-Hamann theory [9], the tunneling current *I* can be well approximated by

$$I \propto e^{-2\kappa d}, \quad \kappa = \frac{\sqrt{2m\phi}}{\hbar} \approx 0.5\sqrt{\phi}\ \text{Å}^{-1} \tag{1}$$

where ϕ is a mixture of the work functions of the tip and sample measured in eV and *d* is the tip-sample separation measured in Å. For typical metals, $\phi \sim 5$ eV, so *I* will increase by about one order of magnitude for every Å decrease in *d*.

In topographic mode, the surface is mapped based on the decay of tunneling current *I* with increasing tip-sample separation *d*. With the bias voltage *V* fixed, the error signal between the measured current I_{meas} and the setpoint current I_{set} is fed back to the *z* piezo to control *d* as the tip is rastered across the sample surface (Fig. 1a). The *z* trajectory of the tip therefore maps a contour of constant integrated electron density of states (DOS). This technique is referred as constant-current mode. In the case of homogeneous DOS, the contour corresponds to the geometric topography of the surface. However, if the DOS varies spatially, the resulting image contains a mixture of DOS and geometric information. By setting the tunneling voltage V_{set} far from the energy range of spatially inhomogeneous states, the contribution of the inhomogeneous DOS can be significantly reduced, so that geometry will dominate the topographic image as desired.

In addition to revealing the geometry of a sample surface, STM can also probe the evolution of sample DOS with energy, up to several eV from the Fermi level (E_F) in both occupied and unoccupied states. The DOS can be accessed by switching off the feedback circuit to fix *d*, sweeping the bias voltage *V*, and recording the tunneling current *I*(*V*). The conductance *dI*/*dV* can be obtained either by numerical differentiation of *I*(*V*) or by a lock-in amplifier technique. In the latter case, a small modulation is added to the bias voltage *V*, and the tunneling current *I* is demodulated to yield *dI*/*dV*. Although the interpretation of *dI*/*dV* spectra can be quite complex, in ideal conditions *dI*/*dV* is a good measure of the sample DOS. If these *dI*/*dV* spectra are recorded on a dense array of locations in real space with well-chosen V_{set}, the spatial variation of the sample DOS can be extracted. This DOS mapping technique has been applied to measure local gap variations and magnetic vortices [6–8].

3. Tunneling spectroscopy

Like cuprates, all Fe-SCs are layered compounds. Most can be mechanically cleaved to expose an atomically flat and clean *ab*-surface, suitable for characterization by surface-sensitive probes. To date, STM spectroscopy techniques have revealed a wide distribution of reduced gap values $2\Delta/k_BT_c$ across materials [8], varying degrees of gap inhomogeneity within materials (inhomogeneous doped AFe_2As_2 [10–12] *vs.* homogeneous LiFeAs and FeSe [13,14]), multiple superconducting gaps within a single material due to the multi-band electronic structure [12], non-universal pairing gap symmetry [14,15], and symmetry breaking in both superconducting and parent phases [14,16,17]. Here, we extend the discussion of pairing and normal state symmetry based on recent results from higher energy conductance features, atomic impurity imaging, and normal state spectroscopy.

3.1. Electron-boson coupling

Collective modes, which couple strongly to electrons and may serve as "glue" for Cooper pairing, often appear as additional conductance features at energies beyond the superconducting gap. This higher energy structure was first observed and quantitatively analyzed in conventional superconductor Pb-insulator-Pb tunnel junctions, where minimum in dI^2/dV^2 at positive energy $\Omega + 2\Delta$ was found to correspond to phonon mode energy [18]. However, the exact shape of the dI^2/dV^2 spectrum should be computed from a *k*-space integral involving the pairing gap, electron density of states, and density of states of the phonon (or other collective mode). In unconventional cuprates and Fe-SCs, the asymmetric electron pairing, complex Fermi surface and multi-band coupling complicate the calculation and preclude any universal relationship between the mode energy Ω and a regular feature of dI^2/dV^2. Therefore, in different materials, Ω has been inconsistently extracted from several features in *dI*/*dV* or dI^2/dV^2.

Tunneling experiments on cuprates showed a similar dip-hump structure in *dI*/*dV* at energies above the gap, and several studies [6,19–22] specifically matched the spectral features to the energy of a spin resonance mode Ω_r near (π, π) observed by neutron scattering [23,24]. This supports the importance of spin fluctuations in the pairing mechanism of high-T_c cuprates [3].

Soon after the discovery of Fe-SCs, the importance of spin fluctuations was suggested in these materials as well, with the proposal that the high-T_c superconductivity arises through spin flip quasiparticle excitations between the Γ-centered hole pockets