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STM of quasiparticle scattering resonances in $Bi_2Sr_2CaCu_2O_{8+\delta}$

E.W. Hudson[a], S.H. Pan[a,1], K.M. Lang[a], A.K. Gupta[b], K.-W. Ng[b], J.C. Davis[a,*]

[a]*Department of Physics, University of California, Berkeley, CA 94720-7300, USA*
[b]*Department of Physics and Astronomy, University of Kentucky, Lexington, KY 40506-0055, USA*

Abstract

High-resolution, low-temperature scanning tunneling microscopy and spectroscopy on $Bi_2Sr_2CaCu_2O_{8+\delta}$ reveal the existence of large numbers of scattering centers in this material. The spatial and spectroscopic characteristics of these features are consistent with theories of quasiparticle scattering from atomic scale impurities in a d-wave superconductor. These characteristics include breaking of local particle–hole symmetry and an inverse square dependence of their local density-of-states (LDOS) on distance from the scattering center. Furthermore, these observations identify a source for the anomalously high levels of low-energy excitations in $Bi_2Sr_2CaCu_2O_{8+\delta}$ at low-temperatures.

Keywords: Bi-2212; Quasiparticle scattering resonances; STM/STS

Many important effects of impurity atoms on the macroscopic properties of high-T_c superconductors [1] are known. Recently, several proposals for scanning tunneling microscope (STM) study of impurity quasiparticle scattering in these systems [2–6] have been made. Theory indicates that scattering at impurities can reveal information about the symmetry of the order parameter, the momentum dependence of the energy gap, and the microscopic mechanism of superconductivity. Several workers predict that impurity atoms create quasiparticle scattering resonances (QPSRs) that have characteristic signatures both in the spatial shape of the quasiparticle cloud near the scattering center and in their tunneling spectrum.

Here we report preliminary observations of atomic scale quasiparticle scattering in single crystal $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO). We use a high-resolution STM and BSCCO single crystals, the details of which are discussed elsewhere [7–9]. Atomic resolution imaging of a large area (a subset of which is shown in Fig. 1), is followed by a map of the differential conductance at zero bias on the same area. Such a map is a measure of the LDOS of low-energy quasiparticles and a typical example is shown in the inset of Fig. 1. This map reveals a large number of localized bright features which have a relatively high LDOS near the Fermi energy E_f. These features are of similar size and shape, with a diameter $d = 3.1 \pm 0.2$ nm, and appear to be randomly distributed. Approximately 20 of these features are observed in this 50 nm field of view. The same average density of these features was observed in multiple samples. For reasons to be outlined below, we attribute these LDOS features to quasiparticle scattering from atomic scale defects or impurities, and thus refer to them as QPSRs.

We have carried out a series of spectroscopic measurements on a number of QPSRs. In Fig. 2, a typical tunneling spectrum measured at the center of a single QPSR (solid line) is compared with that taken on a 'regular' superconducting area of the crystal (dashed line). The most significant difference between these two curves is a peak in the tunneling conductance spectrum at energies near E_f (zero bias). Investigation of large numbers of QPSRs show that this peak occurs at varying energies ω_0, but always just below E_f, with an average value of $\omega_0 = -1.3 \pm 0.4$ meV, a width (FWHM) of 4 meV, and

[1] Present address: Department of Physics, Boston University, Boston, MA 02215, USA.
* Corresponding author.
E-mail address: jcdavis@socrates.berkeley.edu (J.C. Davis)

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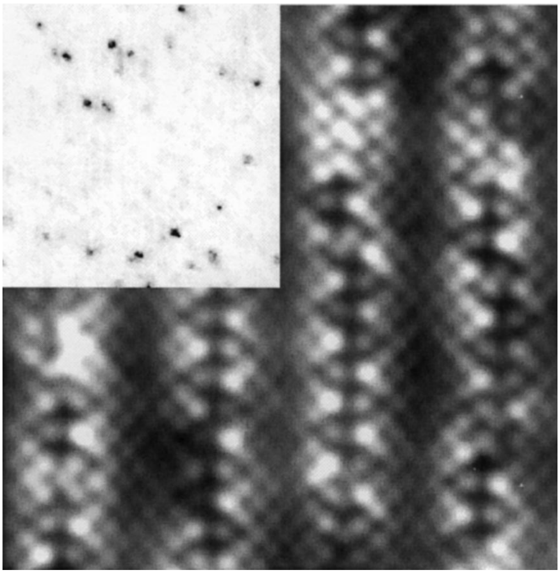

Fig. 1. Typical constant current topograph (10 nm square), showing both atomic resolution and the supermodulation. Inset: A 50 nm square zero-bias conductance map. The QPSRs appear as ~ 3 nm diameter dark regions, owing to their higher zero bias conductance.

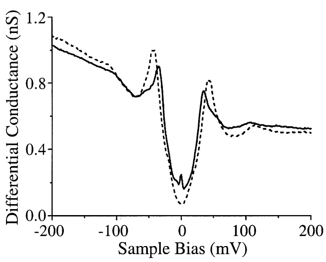

Fig. 2. Tunneling conductance versus sample bias taken at two different locations on the BSCCO crystal. The dashed line is taken on a 'regular' superconducting region, where QPSRs are absent. The solid line is a typical spectrum taken at the center of a QPSR, exhibiting a low-energy resonance peak.

an amplitude of 20–30% of the normal state conductance. This amplitude decays over about two coherence lengths ($\xi_0 \approx 1.5$ nm). Fitting a power law to the fall-off outside of a coherence length gives a dependence of $r^{-1.97 \pm 0.07}$, in excellent agreement with predictions of an inverse square dependence on distance from the scattering center r.

The above data give direct evidence of a strong source of low-energy quasiparticle excitations in BSCCO. The observed QPSR characteristics are consistent with quasiparticle scattering from atomic scale scatterers in a d-wave (but not s-wave) superconductor. Finally, this experiment demonstrates the possibility of using a single atomic scale scatterer as a probe of high-T_c superconductivity. This technique might eventually be used, with specific elemental impurities deliberately doped into different atomic planes.

Note added in proof

After submission of this paper, we have become aware of another STM study of defects in $Bi_2Sr_2CaCu_2O_{8+\delta}$ [10].

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