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# Dynamic pair breaking in cuprate superconductors via injection of spin-polarized quasiparticles in perovskite F–I–S heterostructures

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**Abstract**

We report experimental evidence of dynamic Cooper pair breaking induced by spin-polarized quasiparticles in cuprate superconductors by studying the critical current density and quasiparticle density of states of ferromagnet–insulator–superconductor (F–I–S) heterostructures. The spin diffusion length and relaxation time are also estimated. © 2000 Elsevier Science B.V. All rights reserved.

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Non-equilibrium superconductivity has been extensively studied since the 1970s [1]. Most of the investigation has focused on the effects of simple quasiparticle (QP) injection and extraction in conventional s-wave superconductors. In contrast, there is insufficient theoretical understanding of spin-polarized QP transport in superconductors, largely due to the complications of combined non-equilibrium (see articles in Ref. [1]) and magnetic pair-breaking effects [2] induced by spin-polarized currents. Recently, the concept of spin injection has been investigated in high-temperature superconductors (HTS) by passing an electrical current through a perovskite ferromagnetic manganite to introduce spin-polarized quasiparticles (QPs) [3,4]. However, the reported suppression of critical currents in the perovskite ferromagnet–insulator–superconductor (F–I–S) appear to be primarily induced by Joule heating. To amend this problem, we adopted a pulsed current technique and in situ thermometry [5], so that the effect of Joule heating is limited to $<10$ mK. In this work, we report macroscopic and microscopic experimental evidence of dynamic pair breaking induced by spin-polarized QP currents in perovskite F–I–S heterostructures. These results are compared with control samples of N–I–S heterostructures (N: non-magnetic metal).

The F–I–S and N–I–S samples are fabricated using the pulsed-laser deposition technique [5]. The chemical formulae and thicknesses of the constituent layers are:

- **F:** $La_{0.7}Ca_{0.3}MnO_3$ (LCMO) and $La_{0.7}Sr_{0.3}MnO_3$ (LSMO), 100 nm.
- **I:** $SrTiO_3$ (STO), 2.0 nm; and yttria-stabilized-zirconia (YSZ), 1.3 nm.
- **N:** $LaNiO_3$ (LNO), 100 nm.
- **S:** $YBa_2Cu_3O_7$ (YBCO), 100 nm.

The effect of spin-polarized current $I_m$ on the critical current density ($J_c$) of YBCO is shown in Fig. 1(a), and the absence of effect in the N–I–S sample is illustrated in Fig. 1(b). We note that the suppression of $J_c$ in F–I–S becomes significant only near $T_c$, due to the diverging QP relaxation time [1]. In analogy to the simple QP relaxation through inelastic electron–phonon scattering [1], we may assume a relaxation process of spin-polarized QPs through the spin exchange interaction. The relaxation time is given by $\tau_s(T) \sim 3.7\tau_{ex}k_B T_c/\langle\Delta(T)\rangle$, where $\tau_{ex} \sim (\hbar/E_{ex})$ is the interaction time associated with the exchange energy $E_{ex} \sim 30$ K in YBCO [5]. Hence, for an average d-wave superconducting energy gap $\langle\Delta(T)\rangle \approx \varDelta_d[1-(T/T_c)]^{1/2}$ with $\varDelta_d \sim 20$ meV, we obtain

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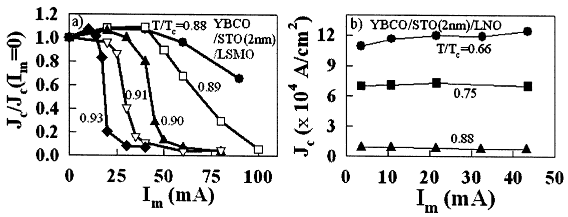


Fig. 1. (a) Effect of the spin-polarized quasiparticle current ($I_m$) on the $J_c$ of YBCO in an F–I–S heterostructure. (b) Independence of $J_c$ on injection in an N–I–S control sample.

$\tau_s \sim 3\times10^{-13}[1-(T/T_c)]^{-1/2}$ s. The spin diffusion length $\ell_s$ may be estimated by $\ell_s \approx \sqrt{\ell_0 v_F \tau_s}$, where $\ell_0$ is the electron mean free path, and $v_F$ is the Fermi velocity [1]. For $v_F \sim 10^5$ m/s and $\ell_0 \sim 20$ nm, we find that $\ell_s \sim 25$ nm for $T \to 0$ and $\ell_s \sim 80$ nm ( $\sim$ sample thickness) at $[1-(T/T_c)] \sim 0.01$. This estimate is consistent with the observed strong dependence of $J_c$ on $I_m$ in F–I–S only near $T_c$.

The main panel of Fig. 2(a) illustrates the differential conductance ($dI/dV$) versus bias voltage ($V$) data of YBCO, taken with a low-temperature STM, for c-axis tunneling at 4.2 K and under various $I_m$. The inset shows the dependence of QP density of states (DOS) on $I_m$ at the Fermi level ($V=0$). The spectra appear invariant for $I_m$ up to 35 mA [6], above which spectral smearing appears, showing excess QP-DOS near the zero bias, which is consistent with Cooper pair breaking. The threshold current $I_m^* \sim 35$ mA corresponds to an injection energy $(eI_m^* R_J) \approx 21$ meV, comparable to $\Delta_d$ for a measured junction resistance $R_J \approx 0.6\ \Omega$. At higher $I_m$, the QP-DOS may be fitted to an effective QP temperature ($T^* \sim 60$ K), even under negligible Joule heating [6]. In contrast, spectral studies of YBCO in the N–I–S sample exhibit no detectable dependence on the injection, as shown in the main panel and the inset of Fig. 2(b). These results suggest that spin-polarized QPs are strong "pair breakers". More investigation is underway to determine relevant physical parameters associated with the dynamic pair breaking and quasiparticle tranport in cuprate superconductors.

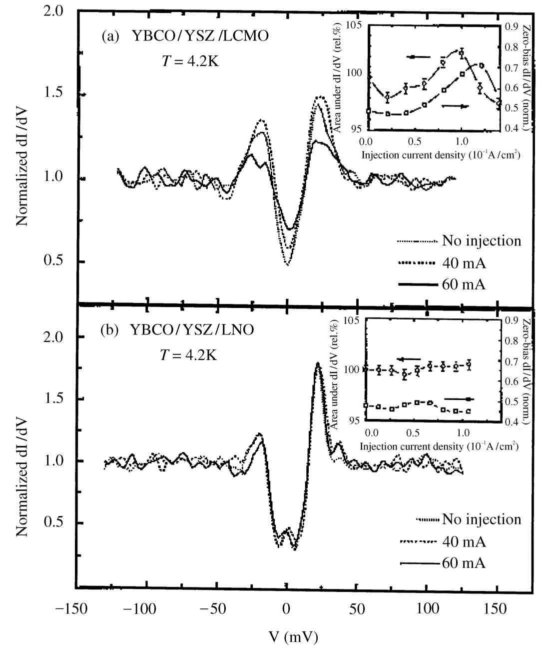


Fig. 2. STM spectroscopy data taken at 4.2 K on (a) F–I–S and (b) N–I–S samples under varying $I_m$, showing nonconserved spectral area and nonuniform zero-bias conductance for the former, (inset of (a)), and relative spectral invariance for the latter, (inset of (b)).

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