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Spin-orbit scattering in $d_{x^2-y^2}$ superconductors

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We show that spin-orbit scattering off an isolated magnetic impurity in a singlet $d_{x^2-y^2}$ superconductor generates a d_{xy} order parameter with locally broken time-reversal symmetry. A consequence of the induced d_{xy} component are orbital charge currents and a magnetic field in the vicinity of the magnetic impurity.

Keywords: Spin-orbit scattering, magnetic impurities, broken time-reversal symmetry, unconventional superconductors.

The identification of the symmetry of the superconducting state of many of the high T_c cuprates with a spin-singlet “d-wave” orbital symmetry is widely accepted^{1,2}. This phase preserves time-reversal ($\mathcal{T}$) symmetry, but breaks the reflection symmetry along the $[110]$ mirror plane, as well as $\frac{\pi}{2}$ rotations in a tetragonal crystal. As a consequence $d_{x^2-y^2}$ pairing correlations are particularly sensitive to scattering of quasiparticles on the Fermi surface. We show that an isolated impurity in a $d_{x^2-y^2}$ superconductor generates a complex d_{xy} order parameter (OP) with locally broken $\mathcal{T}$ symmetry; the signature of this effect is an induced orbital charge current near the impurity and a localized magnetic field in the vicinity of the impurity.

Recent transport experiments reported evidence for low temperature phases associated with a secondary OP at surfaces of YBCO³, and in the bulk of Ni-doped Bi-2212⁴. The latter anomaly was interpreted as the signature of a second supercon-

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ducting phase with a fully gapped quasiparticle spectrum and a mixed symmetry OP of the form $d_{x^2-y^2} + id_{xy}$ due to magnetic impurities^{5,6}. The electronic and magnetic structure near an impurity located near the surface of a superconductor can now be studied with atomic resolution at low temperature by scanning tunneling microscopy (STM)⁷.

We solved the linearized Eilenberger transport equation in the presence of an isolated magnetic impurity [details will be published elsewhere⁸, see also Ref.⁹]. We separated the scattering potential $\hat{v}$ into channels for nonmagnetic (u), spin-spin exchange ($\mathbf{m} = J\mathbf{S}_{\text{imp}}$), and spin-orbit scattering ($\mathbf{u}_{\text{so}}$) between the orbital momentum of the quasiparticle and the impurity spin, $\mathbf{S}_{\text{imp}}$, as well as the self-coupling ($\mathbf{w}_{\text{so}}$) to the quasiparticle spin, $\hat{\mathbf{S}}$,¹⁰

$$\hat{v}(\mathbf{p}_f, \mathbf{p}'_f) = u(\mathbf{p}_f, \mathbf{p}'_f) + \mathbf{m}(\mathbf{p}_f, \mathbf{p}'_f) \cdot \hat{\mathbf{S}} + i[\mathbf{u}_{\text{so}}(\mathbf{p}_f, \mathbf{p}'_f) \cdot \mathbf{S}_{\text{imp}} + \mathbf{w}_{\text{so}}(\mathbf{p}_f, \mathbf{p}'_f) \cdot \hat{\mathbf{S}}]\hat{\tau}_3.$$

The induced OP was self-consistently determined from the gap equation with the pairing interaction $V(\mathbf{p}_f, \mathbf{p}'_f) = V_{x^2-y^2} \cos(2\phi) \cos(2\phi') + V_{xy} \sin(2\phi) \sin(2\phi')$. The dominant, attractive interaction is $V_{x^2-y^2}$, and the subdominant interaction is V_{xy} . We neglected an s -wave pairing channel. The V_{xy} is repulsive or too weak to nucleate a bulk d_{xy} OP.

The existence of an id_{xy} OP implies that the equilibrium superconducting state breaks $\mathcal{T}$ symmetry *locally* near the impurity, in addition to broken [110] and [100] reflection symmetries. The signature of the $d_{x^2-y^2} \pm id_{xy}$ state is the equilibrium charge current and magnetic field distribution near the impurity^{11,12,9,13}. For the intricate orbital charge current pattern see Fig. 1.

The magnitudes of the induced id_{xy} OP and magnetic field near an impurity depend on parameters characterizing the interaction between quasiparticles and the magnetic impurity. Not much is known about these interactions. Thus, measurements of the induced OP or magnetic field near an impurity can provide direct information about the coupling of the quasiparticle orbital momentum to the impurity moment. We express the impurity induced OP, current density and magnetic field in terms of a few key material parameters of the impurity. We used the normalized quantities $\delta\Delta_2^{(n)}(\mathbf{r}) = \delta\Delta_2(\mathbf{r})/\mathcal{E}$, with $\mathcal{E} = \pi S_z N_f \lambda_{so}^2 / \xi_0^2$, $\delta\mathbf{j}^{(n)}(\mathbf{r}) = \delta\mathbf{j}(\mathbf{r})/(c\mathcal{B})$ and $B_z^{(n)}(\mathbf{r}) = B_z(\mathbf{r})/\mathcal{B}$, with $\mathcal{B} = \frac{e}{c} N_f v_f \mathcal{E} = \frac{\Phi_0}{4\pi\lambda^2} \frac{\mathcal{E}d}{\pi\hbar v_f}$, which are of order unity.

We estimated the magnitude of the induced OP and magnetic field for Ni impurities in Bi-2212 as follows: The coupling parameter for Ni^{2+} ions is estimated from the spin-orbit coupling energy for free Ni^{2+} ions¹⁴, $\lambda_{so}^2 \sim (30 \text{ meV} \cdot a_0^2)^2$. The in-plane penetration depth of $\lambda \approx 200 \text{ nm}$, the interlayer spacing, $d \approx 1.5 \text{ nm}$, the in-plane lattice constant, $a_0 \approx 5.4 \text{ \AA}$, and the Fermi velocity, $v_f \sim 100 \text{ km/s}$, provide a determination of the density of states per Cu-O bilayer, $N_f = c^2 d / (4\pi e^2 v_f^2 \lambda^2)$. This gives an estimated energy scale for the induced d_{xy} gap of $\mathcal{E} \sim 0.1 \text{ meV}$, and a magnetic field scale of $\mathcal{B} \sim 0.3 \mu\text{T}$. An induced d_{xy} gap of order $0.1 \text{ meV} \approx 1 \text{ K}$, is the right order of magnitude to account for a $d_{x^2-y^2} \pm id_{xy}$ phase order transition at lower temperature, $T^* \sim 150 \text{ mK}$, as observed in 0.6% and 1.5% Ni-doped Bi-2212^{4,5}.

Fig. 1. Spin-orbit scattering induced orbital currents near the magnetic impurity at $\mathbf{r} = \mathbf{0}$ and at low temperatures ($T = 0.1T_c$).

In conclusion, spin-orbit scattering induces a robust $d_{x^2-y^2} + id_{xy}$ state, which locally breaks $\mathcal{T}$ symmetry in the vicinity of a magnetic impurity. The signature of the spontaneously broken $\mathcal{T}$ symmetry manifests itself as a complex pattern of circulating charge currents near the local maxima of the d_{xy} order parameter.

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