Experimental studies of the pairing symmetry in Sr_2RuO_4: Single-particle tunneling, Josephson effects, and phase-sensitive measurements

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Abstract

We have carried out several experiments aimed at determining the symmetry of the superconducting order parameter of Sr_2RuO_4. These experiments include measurements of single-particle tunneling spectra, the Josephson coupling between In or Pb and Sr_2RuO_4, and the critical current of superconducting quantum interference device (SQUID) samples involving $Au_{0.5}In_{0.5}$ and Sr_2RuO_4. Our junction resistance and critical current measurements on the SQUID samples show that high-quality Josephson junctions have been achieved.

Key words: Sr_2RuO_4; pairing symmetry; spin-triplet; Josephson effect

While evidence for spin-triplet pairing in Sr_2RuO_4 has been mounting [1], truly phase-sensitive measurements on superconducting quantum interference effect devices (SQUIDs) are still lacking. Such measurements were key to establishing d-wave pairing symmetry for the high-T_c superconductors [2].

We have carried out several experiments directly probing the symmetry of the superconducting order parameter of Sr_2RuO_4 using single-particle and Josephson tunneling. An early experiment in $Pb/Sr_2RuO_4/Pb$ junctions (Fig. 1a) revealed a temperature dependence of the critical current which suggests that the pairing symmetry in Sr_2RuO_4 is unconventional (non-s-wave) [3].

We have also measured the Josephson coupling between In and Sr_2RuO_4 using samples prepared by pressing In wire, an s-wave superconductor, onto the surface of a Sr_2RuO_4 crystal (Fig. 1b). The Josephson coupling between Sr_2RuO_4 and In was found to be strong along the plane but vanishingly small along the c-axis. The observation of this selection rule in the Josephson coupling provided further evidence that Sr_2RuO_4 is unconventional. In particular, within the p-wave scenario, this suggests that the symmetry of the order parameter is that of the Γ_5^- state [4].

Recently, we have observed Andreev surface bound states (ASBSs) in the 3 K and bulk phases of Sr_2RuO_4 [5]. The 3 K phase in is the interface region between Sr_2RuO_4 and the pure Ru embedded in Sr_2RuO_4 (Fig. 1c). (Although Ref. [5] reports data obtained in break junctions, Au/Sr_2RuO_4 junctions as shown in the Fig. 1c were found to show similar results.) The formation of ASBSs indicates that the phase of the superconducting order parameter is orientation-dependent [5]. The details of the tunneling spectrum showing a zero-bias conductance peak are consistent with what is expected for a spin-triplet order parameter [6].

In a phase-sensitive experiment, we detect quantum interference effects in a SQUID: either a specific pattern in the modulations of the critical current through the SQUID, or the spontaneous formation of half of a flux quantum in the ring. A phase-sensitive SQUID configuration for testing p-wave symmetry specifically was proposed in 1987 [7]. In our implementation of this

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proposal, we prepare two Josephson junctions on parallel but opposite faces of Sr_2RuO_4 (Fig. 1d). The conventional material forms one part of the loop and the Sr_2RuO_4 the rest. If Sr_2RuO_4 has p-wave pairing, the two junctions will have Josephson coupling constants with opposite signs. In its ground state, such a SQUID will spontaneously generate a half-flux, which can be detected by a scanning SQUID magnetometer. Additionally, the interference between the junctions can be observed by measuring the magnetic field dependence of the critical current. The result of p-wave pairing should be a minimum at zero applied field (rather than a maximum as is the case for a conventional SQUID).

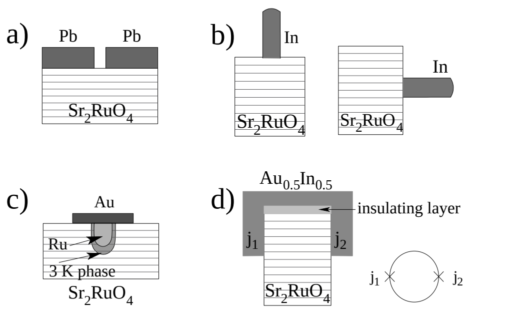

Fig. 1. Schematic of sample configurations. a) $Pb/Sr_2RuO_4/Pb$ junction; b) In/Sr_2RuO_4 junctions; c) $Au/Ru/Sr_2RuO_4$ junction; and d) $Au_{0.5}In_{0.5}/Sr_2RuO_4$ SQUID. Horizontal lines in the Sr_2RuO_4 crystals represent the ab plane.

The data in this paper was obtained on a SQUID sample made using a 1000 Å-thick $Au_{0.5}In_{0.5}$ film and an Al_2O_3 insulating layer. Details of the sample preparation will be published in the future. Two important details must be noted, however. First, this film composition was chosen because $Au_{1-x}In_x$ is the only material found so far with which Josephson coupling to Sr_2RuO_4 can be achieved when deposited by thermal evaporation. Deposition of a film, as opposed to pressing of a bulk material such as In, is necessary because this is the only way the SQUID area can be small enough to detect interference in I_c or the spontaneous half-flux by SQUID magnetometry [8]. Second, Ru inclusions, which are formed in the crystal during crystal growth, are present in all crystals we have examined so far. Their presence would introduce uncertainty in the crystal orientation at the junction so the samples were carefully prepared to avoid any Ru inclusions.

The junction resistance vs. temperature for several SQUID samples showed tunneling character, with no feature between 1.5 K and 3 K. Such a feature would have been an indication that one or more Ru inclusions were involved in the Josephson coupling between Sr_2RuO_4 and $Au_{0.5}In_{0.5}$. As shown in the inset of Fig. 2, Josephson coupling between $Au_{0.5}In_{0.5}$ and the bulk phase of Sr_2RuO_4 is indeed present, as indicated by the observation of a supercurrent. The normal state

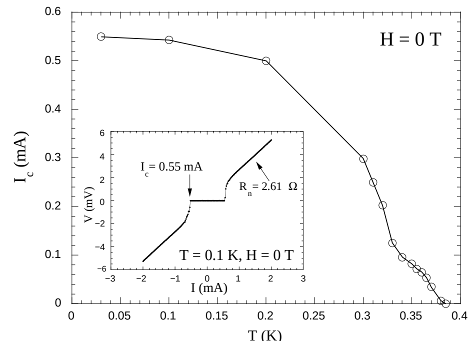

Fig. 2. $I_c(T)$ for a $Au_{0.5}In_{0.5}/Sr_2RuO_4$ SQUID as shown in Fig. 1d. The temperature dependence near T_c is $(Tc - T)^{1/2}$. The inset is an example of V(I) (at 0.1K) showing the zero-voltage current.

resistance, calculated from the slope of the curve at high voltages, incorporates some of the film resistance, which accounts for the unusually high value of I_cR_N.

Figure 2 shows the dependence of the critical current on temperature. The two bumps in the curve most likely reflect a different critical temperature for each junction in the SQUID. The temperature dependence of I_c is $(T_c - T)^{1/2}$ near T_c, as expected from Ginzburg-Landau theory [9].

The dependence of the critical current on applied field was also measured (data not shown). The junction critical field was only several Gauss, indicating that junction area is quite large. However, no interference pattern was observed, most likely due to the relatively large self-inductance of the device which may overwhelm the I_c oscillations. Magnetometry measurements using a scanning SQUID are yet to be carried out.

We acknowledge discussions with J. Kirtley, C.C. Tsuei, M. Sigrist, M. Rice, V. Yakovenko, and financial support from NSF.

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