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Excess current in superconducting Sr_2RuO_4

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We present results from point-contact measurements on Sr_2RuO_4 that show a linear dependence of the excess current as a function of temperature and applied magnetic fields over a surprisingly wide range of the phase diagram. We propose an explanation of this finding in terms of a *p*-wave triplet-pairing state with coupling to a low-energy fluctuation mode. Within this model we obtain a quantitative description of the temperature dependence of the excess current. The impact of surface effects on order parameter and excess current is addressed.

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I. INTRODUCTION

The discovery of superconductivity below $T_c \sim 1.5$ K in Sr_2RuO_4 has quickly triggered a large amount of interest because of the unconventional properties[1] and the initially proposed analogy[2] to ^{3}He. The enhanced specific heat, magnetic susceptibility, and electronic mass indicate the presence of significant correlations.[3–8] For a more detailed overview see Refs. 1, 8, and 9. The exact symmetry of the superconducting order parameter (OP) (Refs. 10–15) and notably the pairing mechanism[16–20] are still controversial. Andreev spectra are sensitive to the OP symmetry[10,21] and are thus an adequate experimental probe to yield clarifying information. The shape of the differential conductance dI/dV vs voltage V curves previously obtained from point-contact (PC) measurements in superconducting Sr_2RuO_4 where satisfactorily reproduced by an analysis of a *p*-wave pairing state with OP $\boldsymbol{d}(\boldsymbol{k}) = \hat{\boldsymbol{z}}(k_x \pm i k_y)$.[22]

Another, frequently ignored, property is the so-called excess current. This extra current occurs only in metallic junctions as a consequence of the Andreev-reflection process at the normal metal-superconductor interface. In contrast, junctions in the tunnel regime show no excess current. It has been shown that the excess current in *s*-wave superconductors is proportional to the superconducting gap[23] and consequently contains further information on the superconducting state. Here we focus on excess-current measurements in Sr_2RuO_4. In particular, we present experimental results for the excess current in applied magnetic fields and find a systematic linear behavior as a function of field over a surprisingly wide range. This finding is compared with experimental excess-current data from Ref. 22, which exhibit a strikingly linear dependence as well, but as a function of temperature. We show that these two findings imply a well-defined functional relationship between the excess current and the OP, and discuss the resulting implications in the framework of the *p*-wave picture[10,11,22] extended to include effects of low-energy fluctuations.[24,25]

Our measurements also suggest the presence of a normal-conducting surface layer in Sr_2RuO_4. We model such a layer by an enhanced scattering rate near the surface and obtain qualitative agreement with the experimental PC spectra within the *p*-wave picture.

II. EXPERIMENT: LINEAR FIELD DEPENDENCE

Our measurements were performed on two single crystals grown both by a floating zone technique in different groups. T_c was obtained via bulk resistivity measurements. One crystal, labeled No. 5 (Ref. 26) shows a midpoint transition temperature $T_c^{50\%} = 1.02$ K with a transition width $\Delta T_c^{90\%-10\%} = 0.035$ K and the other, No. C85B5 (Ref. 27) has $T_c^{50\%} = 1.54$ K and $\Delta T_c^{90\%-10\%} = 0.15$ K. Heterocontacts between superconducting Sr_2RuO_4 and a sharpened Pt needle as a counterelectrode were realized inside the mixing chamber of a ^{3}He/^{4}He dilution refrigerator. Measurements were performed with predominant current injection $j || ab$ and applied magnetic field $H || c$ within an accuracy of about 5°–10° relative to the crystallographic axis of Sr_2RuO_4. The differential resistance dV/dI vs V was recorded by a standard lock-in technique. The differential conductance dI/dV is obtained by numerical inversion of the measured dV/dI data. For purpose of an excess-current analysis, we focus on high transmission contacts, which exhibit a double-minimum structure in the differential resistance, i.e., a double-maximum in the differential conductance dI/dV vs V (see inset of Fig. 1). The excess current was determined by numerical integration of dI/dV vs V after subtraction of a smooth normal-conducting background

$$I_{\mathrm{exc}} \propto \int_{-\infty}^{\infty} \left(\left.\frac{dI}{dV}\right|_{\mathrm{S}} - \left.\frac{dI}{dV}\right|_{\mathrm{N}} \right) dV. \tag{1}$$

$(dI/dV)|_{\mathrm{S}}$ and $(dI/dV)|_{\mathrm{N}}$ denote the spectra in the superconducting and normal state, respectively.

Figure 1 shows the observed magnetic field dependence of the normalized excess current (symbols) across several PC's in Sr_2RuO_4 measured at temperatures $0.04 < T/T_c < 0.20$, together with a linear guide to the eye (line). Each symbol represents one PC either on sample No. 5 (open symbols) or No. C85B5 (filled symbols). The normalization val-

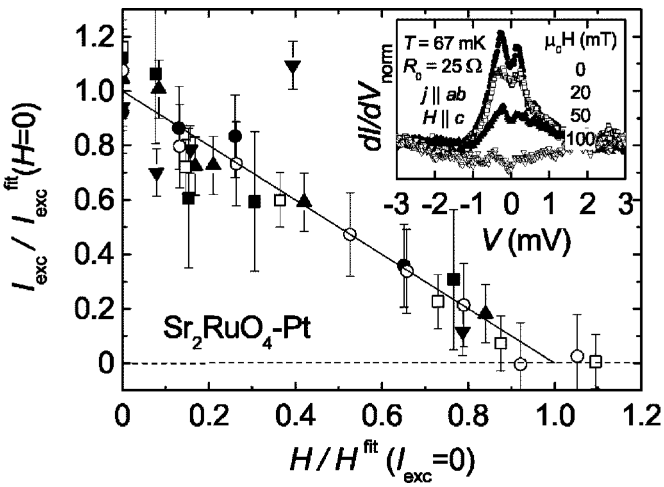

FIG. 1. Field dependence of the normalized excess current across several point contacts (PC's) in Sr_2RuO_4. The magnetic field H is aligned almost parallel to the c axis, and the current across the PC is applied in the ab plane. Each symbol represents one PC on one of the two studied samples. The full line is a guide to the eye. For explanation of $I_{exc}^{fit}(H=0)$ and $H^{fit}(I_{exc}=0)$ see text. The inset shows for one PC typical dI/dV curves from which the excess current was determined as a function of magnetic field.

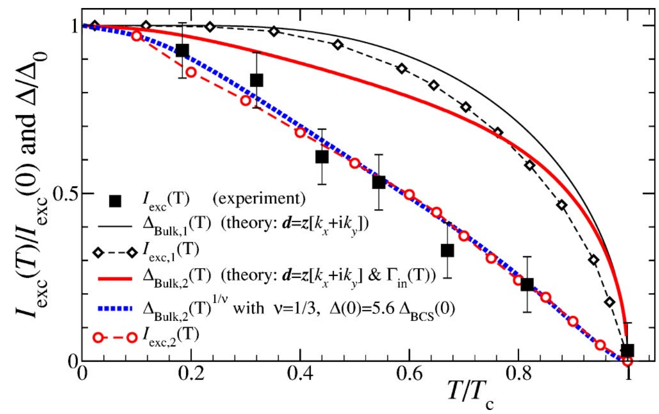

FIG. 2. Temperature dependence of the normalized excess current across a point contact in Sr_2RuO_4. Experimental results (squares) are taken from Ref. 22. Open symbols show the results of our calculation for the excess current from a p-wave analysis, without (diamonds) and with (circles) the effects of an inelastic scattering channel $\Gamma_{in}(T)$. The dashed thick curve illustrates the scaling relation $I_{exc,2}(T) \propto \Delta_{Bulk,2}(T)^{1/\nu}$ for the inelastic scattering model.

ues $I_{exc}^{fit}(H=0)$ and $H^{fit}(I_{exc}=0)$ are defined as those points where a linear regression of the $I_{exc}(H)$ vs H data intersect the axes and have been determined for each PC separately.

The data in Fig. 1 clearly are consistent with a linear dependence of the excess current on the applied magnetic field. Note that the result is quite universal since it is found in both samples in spite of their different value of T_c. As will be outlined now, the observed equivalence of the linearity in the field and temperature dependence implies a well-defined functional dependence of the excess current I_{exc} on the superconducting gap Δ.

III. SCALING RELATION FOR I_{exc}

Consider the modulus of the superconducting OP near the field dependent critical temperature $T_c(H)$ as a function of the reduced temperature $t(H)=1-[T/T_c(H)]$ at a given magnetic field

$$\Delta_H(T)|_{t\ll 1}=A_H t^{\nu}. \tag{2}$$

The mean-field exponent (p-wave approach) is $\nu=1/2$ while in the recently introduced third-order transition picture[28] one has $\nu=1$. The proportionality factor A_H depends on the magnetic field H. In order to find the resulting field dependence of the OP modulus consider the phenomenological interpolation formula

$$\frac{H_{c2}(T)}{H_{c2}(T=0)}=1-\left(\frac{T}{T_c(H=0)}\right)^2 \tag{3}$$

determining the upper critical magnetic field H_{c2} as a function of temperature. Equation (3) with $\mu_0 H_{c2}(T=0)=1.5$ T and $T_c(H=0)=1.5$ K reproduces the experimental data[29–31] satisfactorily. The inverse of Eq. (3) determines $T_c(H)$. Defining the reduced field $h(T)=1-[H/H_{c2}(T)]$ at a given temperature and expanding Eq. (3) for $t\ll 1$ one finds the relation

$$t(H)\frac{T_c^2(H)}{T_c^2(0)}\approx\frac{1}{2}\frac{H_{c2}(T)}{H_{c2}(0)}h(T) \tag{4}$$

between the reduced temperature and the reduced field. Consequently the reduced field dependence of the gap at a given temperature is

$$\Delta_T(H)|_{h\ll 1}=A_H\frac{[H_{c2}(T)/2]^{\nu}}{[H_{c2}(0)-H]^{\nu}}h^{\nu}. \tag{5}$$

For $A_H=$const the prefactor of the right-hand side of Eq. (5) implies anomalies for low temperatures near the critical field, notably $\lim_{h\to 0}[\lim_{T\to 0}\Delta_T(H)]\neq 0$. Since $\Delta_T(H)$ and I_{exc} are closely related (Ref. 23 and below), the observed linearity in Fig. 1 requires that the divergence is compensated by the prefactor[28] through $A_H\sim[H_{c2}(0)-H]^{\nu}$ and hence

$$I_{exc}=\text{const}\times\Delta^{1/\nu}. \tag{6}$$

Equation (6) marks a central result as it imposes a necessary condition on any theoretical approach to the superconductivity in Sr_2RuO_4 in order to satisfy Eqs. (2) and (5) together with the experimental observations in Figs. 1 and 2. In the light of this scaling relation we discuss the widely accepted triplet p-wave pairing scenario, which we extend to include effects of low-lying bosonic fluctuations.

IV. PAIR-BREAKING BY LOW-FREQUENCY BOSONIC FLUCTUATIONS

The *p*-wave analysis of the PC spectra applied in Ref. 22 yields the BCS temperature dependence for the superconducting gap in Sr_2RuO_4, shown as $\Delta_{\mathrm{Bulk},1}$ (thin full line) in Fig. 2. The resulting temperature dependence of the excess current, determined from the calculated conductance for Andreev-type spectra, in the framework of the *p*-wave analysis is also shown in Fig. 2 as $I_{\mathrm{exc},1}$ (diamonds). The calculations are performed for a mean free path of 15 coherence lengths ($\xi_0 = v_f/2\pi T_c$) and for a diffusely scattering surface modeled as in Ref. 22. It is clear that this model is insufficient to describe the experimental data (squares in Fig. 2). Nevertheless, it is interesting to note that unlike in the *s*-wave case in unconventional superconductors the excess current is not necessarily proportional to the OP; we find near T_c a temperature variation of the excess current linear in *t*, in contrast to the $t^{1/2}$ variation of the OP. This is because impurities and disorder strongly affect the surface properties of unconventional superconductors.[32]

As seen above, the *p*-wave scenario alone does not account for the observed temperature dependence of the experimentally obtained $I_{\mathrm{exc}}(T)$. This is true also for the overall magnitude of the bulk gap $\Delta(0) = 1.1$ meV$= 5.6 \times 1.76 k_B T_c$, extracted from tunneling spectra.[22] To reconcile the measured $\Delta(0)$ and $I_{\mathrm{exc}}(T)$ with a *p*-wave OP we consider an additional pair-breaking channel. It was shown by Millis *et al.*[24] that a low-frequency bosonic mode at a characteristic frequency ω_p described by an Einstein spectrum $A_p(\omega) = (\pi/2) J_p \omega_p \delta(\omega - \omega_p)$ leads to a *temperature dependent* pair-breaking parameter

$$\Gamma_{\mathrm{in}}(T) = \frac{(1-g)}{4} J_p \omega_p \coth\left(\frac{\omega_p}{2T}\right), \tag{7}$$

where g is the coupling-constant appearing in the gap equation. The assumptions are that $\omega_p < T_c \ll \omega_E$, ω_E being the frequency of the pairing mode, and that $A_p(\omega)$ is unaffected by the transition into the superconducting state. We performed calculations using the quasiclassical Green's functions technique and included the pair-breaking parameter as a self-energy within a self-consistent Born approximation, i.e., $\hat{\Sigma}_{\mathrm{in}}(\boldsymbol{R},\varepsilon,T) = \Gamma_{\mathrm{in}}(T) \langle \hat{g}(\boldsymbol{p}_f,\boldsymbol{R},\varepsilon) \rangle_{\boldsymbol{p}_f}$, where ϵ is the energy of the quasiparticles, $\boldsymbol{R}$ the position with respect to the interface, and $\boldsymbol{p}_f$ the Fermi momentum; the $\boldsymbol{p}_f$ average is over the Fermi surface. The Green's function $\hat{g}(\boldsymbol{p}_f,\boldsymbol{R},\varepsilon)$ is a functional of the self-energy $\hat{\Sigma}_{\mathrm{in}}(\boldsymbol{R},\varepsilon,T)$ in the usual way. The OP profile $\Delta(\boldsymbol{R},T)$ near the interface was then obtained by iterating the weak-coupling gap equation and $\hat{\Sigma}_{\mathrm{in}}(\boldsymbol{R},\varepsilon,T)$ until convergence.

For the excess current this model gives an excellent agreement with experimental data, as shown by $I_{\mathrm{exc},2}$ (circles) in Fig. 2 for $\omega_p = 0.5 T_c$ and $[(1-g)/4] J_p = 2\pi \times 0.25$. The almost linear temperature dependence over the whole temperature range is reproduced within our model, and furthermore, as shown as the dashed thick line in Fig. 2, the above introduced scaling relation between the calculated $I_{\mathrm{exc},2}(T)$ and the theoretically obtained OP $\Delta_{\mathrm{Bulk},2}(T)$ is fulfilled to remarkable accuracy with the scaling exponent $\nu = 1/3$.

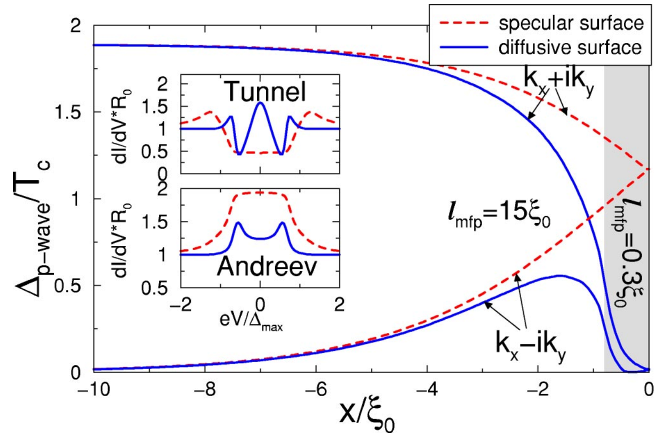

FIG. 3. Creation of a normal-conducting surface layer in a *p*-wave superconductor due to an increased scattering rate near the surface. For comparison, as dashed lines are shown the curves assuming a clean surface. The two OP components are the bulk $k_x + ik_y$ OP, and the subdominant $k_x - ik_y$ order parameter which is stabilized only within a few coherence lengths ($\xi_0 = v_f/2\pi T_c$) near the surface. Both OP components are suppressed in a layer with increased scattering, leading effectively to a normal-conducting surface layer. The calculations are for $T = 0.05 T_c$. The insets show the corresponding PC spectra (bottom) and tunneling spectra (top).

Another effect of $\Gamma_{\mathrm{in}}(T)$ is that the enhanced scattering at higher temperatures reduces the observed T_c substantially from its ideal value while the gap at $T \to 0$ is much less affected, giving $\Delta(0)/k_B T_c$ ratios much larger than the BCS ratio 1.76. Our calculations give the correct absolute magnitude $\Delta(0) = 5.6 \Delta_{\mathrm{BCS}}(0)$. Notably, also the functional form of $\Delta(T)/\Delta(0)$ is modified compared to the pure *p*-wave case (see $\Delta_{\mathrm{Bulk},2}$, thick line in Fig. 2). The conductances calculated with the present model have the same qualitative features, both for the Andreev and the tunnel limit, as those displayed in Ref. 22, and can still account for the measured data.

V. NORMAL-STATE SURFACE LAYER

In order to obtain more detailed insight about the nature of the pairing state in Sr_2RuO_4 it would be instructive to quantify empirically the field dependence of A_H in Eqs. (2) and (5). Unfortunately, obtaining data from the necessary temperature scans at different fields for a given PC is difficult because of the sensitivity of the large background resistivity[22] in the dV/dI data to very small changes in the configuration. A possible reason for the presence of a large background can be found in a normal-state surface layer due to surface reconstructions[33] that leads to an additive resistivity in the PC as $\sigma^{-1}_{\mathrm{measured}} = R_N + \sigma^{-1}_{\text{N-S}}$. Here $\sigma^{-1}_{\text{N-S}}$ is the conductivity of the normal-superconductor interface, R_N is the normal layer resistivity, and typically $\sigma^{-1}_{\text{N-S}}/R_N \sim 10\%$. Note that the thickness of the normal-state surface layer appears to be independent of the sample quality since the observed values of $0.5\Omega \leqslant R_N \leqslant 25\Omega$ vary from PC to PC but are in the same range for both samples.

Such a normal-state surface layer has a natural explanation in a *p*-wave triplet scenario because the *p*-wave OP is very sensitive to scattering. We assume a region near the interface in which scattering is enhanced. In Fig. 3 we show the self-consistent OP, $\Delta(\boldsymbol{R},T=0.05T_c)$, for a mean free path of 0.3 coherence lengths in the shaded region, and of 15 coherence lengths elsewhere. The bulk OP is of the form k_x+ik_y, and near the surface a secondary OP component, k_x-ik_y, is induced. As can be seen from Fig. 3, both components are suppressed in the surface layer where scattering is enhanced, leading effectively to a normal-conducting layer near the interface.

The presence of a normal-state layer affects strongly PC and tunneling spectra. However, as we show in the insets of Fig. 3, the form of the spectra in the presence of a normal-state layer is in agreement with experiment (c.f. inset in Fig. 1 and Ref. 22). The excess current is reduced by such a surface layer (see lower inset in Fig. 3). Also, the tunneling spectra show a pronounced zero-energy anomaly in contrast to the clean surface. The temperature dependence of the excess current near T_c is only weakly affected by a normal-conducting surface layer, leaving the results discussed above unaltered.

VI. CONCLUSIONS

We presented excess-current measurements on the unconventional superconductor Sr_2RuO_4. The excess current exhibits surprisingly linear behavior both in temperature and magnetic field over a large range. Using these findings we derive a scaling relation between the excess current and the OP [Eq. (6)].

We discuss this result within the theory of *p*-wave spin-triplet superconductivity. We find that the excess current in unconventional superconductors is not necessarily proportional to the order parameter. In order to account for the wide range over which the linear behavior of the excess current holds experimentally we extend the pure *p*-wave theory to take into account scattering between quasiparticles and low-energy bosonic fluctuations, probably originating from spin fluctuations.[24] The extended theory yields a very good agreement with the measured excess current and yields a scaling exponent $\nu=1/3$. Furthermore it can account for the large $\Delta(0)/k_B T_c$ ratios obtained from PC measurements.[22] Finally, we show that surface effects should be considered for a satisfactory reproduction of the PC spectra.

In closing, we mention that a recent Ginzburg-Landau analysis, assuming a third-order phase transition induced by two-dimensional gapless excitations in the superconducting phase, yields the correct temperature dependence to account for the data, at least close to T_c.[25,28] As shown in Ref. 13 the *p*-wave channel of superconductivity may be only marginally dominant assuming that pairing in Sr_2RuO_4 is mediated by incommensurate spin fluctuations. In this case the presence of fluctuations in the OP is not unlikely.

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