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Observation of vortex coalescence, vortex chains and crossing vortices in the anisotropic spin-triplet superconductor Sr_2RuO_4

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Abstract

Scanning μSQUID force microscopy is used to study magnetic flux structures in single crystals of the layered spin-triplet superconductor Sr_2RuO_4. Images of the magnetic flux configuration above the $\vec{a}\vec{b}$-face of the cleaved crystal are acquired, mostly after field-cooling the sample. For low applied magnetic fields, individual vortices are observed, each carrying a single quantum of flux. Above 1 G, coalescence of vortices is discovered. The coalescing vortices may indicate the presence of domains of a chiral order parameter.

When the applied field is tilted from the $\vec{c}$-axis, we observe a gradual transition from vortex domains to vortex chains. The in-plane component of the applied magnetic field transforms the vortex domains to vortex chains by aligning them along the field direction.This behavior and the inter-chain distance varies in qualitative agreement with the Ginzburg–Landau theory of anisotropic 3D superconductors. The effective mass anisotropy of Sr_2RuO_4, $\gamma = 20$, is the highest observed in three-dimensional superconductors.

When the applied field is closely in-plane, the vortex form flux channels confined between the crystal-layers. Residual Abrikosov vortices are pinned preferentially on these channels. Thus the in-plane vortices are decorated by crossing Abrikosov vortices: two vortex orientations are apparent simultaneously, one along the layers and the other perpendicular to the layers.

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1. Introduction

Sr_2RuO_4 is a tetragonal, layered perovskite superconductor with a superconducting transition temperature (T_c) of 1.5 K [1]. Sr_2RuO_4 has been a subject of intensive interest in recent years because of the theoretical suggestion [2,3] that Sr_2RuO_4 is an odd-parity, spin-triplet superconductor. Abundant experimental evidence supporting the theoretical prediction has been obtained, as summarized recently [4,5]. A very recent phase-sensitive experiment [6] has established the odd-parity pairing symmetry in Sr_2RuO_4 by measuring the quantum interference pattern in superconducting quantum interference devices (SQUIDs) consisting of Sr_2RuO_4 and $Au_{0.5}In_{0.5}$, an s-wave superconductor. In addition, muon spin rotation (μSR) experiments have revealed [7] the presence of spontaneous currents in the superconducting Sr_2RuO_4, indicating the breaking of time reversal symmetry (TRS) below T_c. The TRS breaking implies that the Cooper pair has an internal orbital moment (chirality) giving rise to a superconducting order parameter with multiple components.

The crystal structure and the thermodynamic properties of the superconductor restrain the choice of the order parameter. The orbital component of the order parameter of the form, $(p_x \pm ip_y)$ is compatible with most experiments. The two possible realisations of the superconducting order

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parameter, $p_x + ip_y$ (p^+) and $p_x - ip_y$ (p^-), represent two possible chiral states [8] which are energetically degenerate. Consequently the presence of domains is expected in which the Cooper pairs posses different orbital angular momenta. Building on this form of the order parameter, the magnetization processes were explored by numerical simulations [9,10]. In a magnetic field the degeneracy between p^+ and p^- domains is lifted, favoring a domain with the Copper pair orbital moment aligned with the field. The favored domains will have a higher critical field H_{c2}, and a lower H_{c1}. Consequently, vortices will first appear in these domains. At the interface between the domains of opposite chiralities, walls will form [11]. The presence of domain walls has considerable influence on the vortex motion and pinning. For example, flux penetration should take place preferentially along the domain walls. These walls will act as preferential pinning sites for vortices. Vortices at these sites could decompose into fractional vortices decorating the domain walls. In analogy with the case of superfluid ^{3}He-A decorated domain walls are called vortex sheets [12,13].

The magnetic properties of superconductors depend strongly on their crystalline and electronic anisotropy. The general theoretical approach on vortex matter is based on the anisotropic Ginzburg–Landau (GL) theory. There the anisotropy is expressed in terms of the effective mass of the electron. For layered anisotropic superconductors, the out of plane effective mass m_c is much larger than the in-plane effective masses ($m_c \gg m_{ab}$). To describe this anisotropy the parameter $\gamma = (m_c/m_{ab})^{1/2} = \lambda_c/\lambda_{ab}$ [14] is used. For example in $NbSe_2$ $\gamma = 3.3$, in YBCO $\gamma = 5$–8 and in BSCCO γ is higher than 150, γ being dependent on the oxygen doping of the high T_c superconductors. Sr_2RuO_4 has also a layered structure, the RuO_2 planes are separated by 12.74 Å and has highly anisotropic properties [4]. Sr_2RuO_4 has a γ value of 20 situating it between YBCO and BSCCO on the anisotropy scale. We expect Sr_2RuO_4 to act more like a 3D superconductor as the c-axis parameter is three times smaller than the coherence length ξ_c. The Ginzburg–Landau parameter $\kappa = \lambda/\xi$ is around 2.3 when the magnetic field is applied along the c-axis direction and 46 for the in-plane direction. The physical properties of Sr_2RuO_4 are very rich due to its unconventional mechanism of superconductivity and its anisotropy. Scanning magnetic probe microscopy [15,16] is a means of choice to study this interplay.

2. μSQUID force microscopy and crystals

We use for magnetic imaging a high resolution scanning μSQUID microscope (SμSM) [17] working in a dilution refrigerator. The SμSM has an aluminum μSQUID as pickup loop of 1.2 μm diameter. The critical current of the μSQUID is a periodic function of the magnetic flux emerging perpendicularly from the sample surface. The images shown are maps of the critical current value of the μSQUID while it scans the surface. The magnetic fields are applied by a solenoid and a rotatable Helmholtz coil, the copper coils are at room temperature. The solenoid axis is parallel to the ab face of the sample and the Helmholtz coil generates a field perpendicular to the solenoid axis. Adjusting the relative angle and the magnitude of the two fields allows us to point the resultant field along any direction. The Sr_2RuO_4 single crystal was grown by a floating zone technique using an image furnace [18,19]. Specific heat measurements of crystals taken from the same single-crystal rod showed volume superconductivity below a temperature of 1.31 K and a transition width of less than 0.1 K. We used two different samples of plate like shape of this crystal, one having a thickness of 0.5 mm with an estimated demagnetization factor, N of 0.9 (sample 1) and the other 0.6 mm with $N = 0.7$ (sample 2). The sample is cleaved along the ab-plane and AFM images show flatness down to the order of 6 Å (Fig. 1), about twice as flat as surfaces of $NbSe_2$.

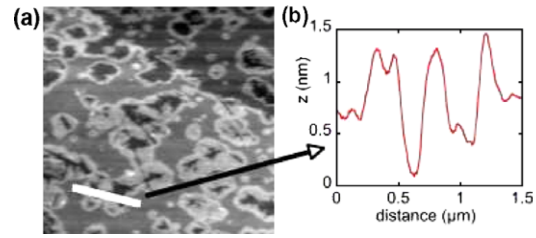

Fig. 1. (a) AFM Image of the surface of cleaved Sr_2RuO_4. (b) Line scan as indicated, the roughness is of the order of half the unitcell.

3. Coalescence, flux domains and crossing vortices

During the imaging, the μSQUID moved in a plane above a cleaved ab surface of the single crystal of Sr_2RuO_4. Individual vortices are seen [16] after cooling the crystal (sample 1) in a magnetic field of 0.1 G applied along the c-axis. The vortices disappear completely above $T = T_c = (1.35 \pm 0.05)$ K, in agreement with the T_c value determined previously in specific heat measurements. At these low fields Sr_2RuO_4 behaves as a usual type-II superconductor. The images of Fig. 2 were obtained after field-cooling (FC) sample 2 in fields between 2 and 7 G to a temperature of 0.35 K. At 2 G applied field, Fig. 2a, vortices are distinct, some of them are close together, at 6 G Fig. 2b a higher density of individual vortices is detected, locally coalescing flux regions form, and as the field increases further to 7 G, Fig. 2c the individual vortices have melted into flux domains. For comparison, we imaged a conventional s-wave superconductor $NbSe_2$ having a T_c of 7.2 K. $NbSe_2$ is a layered material, it is weakly anisotropic with an effective mass anisotropy (λ_c/λ_{ab}) of 3.3. The penetration depth for applied fields along c-axis λ_{ab} is 0.15 μm comparable with λ_{ab} of Sr_2RuO_4. A hexagonal vortex lattice is readily observed by the μSFM Fig. 2d, after field-cooling the sample in 5 G. The vortices are clearly distinct from one another. When the field is further increased the vortices