Fluxon Pinning in the Nodeless Pairing State of Superconducting YBa$_2$Cu$_3$O$_7$

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Positive-muon spin rotation (µ$^+$SR) spectroscopy and magnetic moment measurements were used to probe fluxon (or vortex) formation in the superconducting mixed state of a high-purity YBa$_2$Cu$_3$O$_7$ crystal. Random potentials caused by crystal-lattice defects pin fluxons. A fluxon lattice forms in an external magnetic field, and changes of thermal activation lead to fluxon pinning and depinning. The root second moment of the local magnetic field distribution ($\sigma$) determined by µ$^+$SR contains information on the magnetic penetration depth and the pinning. Fluxon pinning leads to temperature-dependent transverse displacements of the fluxons that decrease $\sigma$ and also fluctuations in the separation between fluxons that tend to increase $\sigma$. By accounting for the field-dependent and temperature-activated fluxon disorder, it is found that the experimental results for the penetration depth are consistent with a superconducting order parameter of a strong-coupling two-fluid model, confirming that the superconductivity is nodeless with s-wave superconducting pairing. Quantitative results for fluxon displacements are discussed within the context of the fluxon field-temperature phase diagram.

Key words: High-T$_c$ superconductivity, s-wave pairing, fluxon lattice, vortices, penetration depth

INTRODUCTION

The cuprate compound YBa$_2$Cu$_3$O$_7$ is a member of a class of oxide superconductors with a relatively high value of the phase transition temperature, T$_c$ $\approx$ 90 K. It is a type-II superconductor with an upper critical magnetic field $H_{c2}(0)$ $\approx$ 100 T.1 Fundamental to understanding the superconducting properties of this superconductor, and the physics of high-T$_c$ oxides in general, is (1) determining the layer(s) in which the superconducting holes and associated electrons reside, and (2) finding the symmetry of the hole-pairing state and the energy gap function:

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either nodeless (s-wave) or noded (d-wave). Most authors believe that the superconducting layer is the cuprate plane, although the demonstration recently that Sr$_2$YRuO$_6$, which has no cuprate planes, superconducts at $\approx$ 49 K casts doubt on that identification.2 On the one hand, theoretical interest in d-wave pairing has been stimulated recently by the inference that high-T$_c$ superconductivity requires Cu d-states.3,4 But, on the other, Cu-doped Sr$_2$YRuO$_6$ appears to superconduct without CuO$_2$ planes.2,5

Nature of a Correct Theory

The nodeless-gap (s-wave) part of the theory is confirmed by positive-muon spin rotation (µ$^+$SR) spectroscopy, and complements early studies of the
superconducting penetration depth, $\lambda$, in YBa$_2$Cu$_3$O$_7$ by $\mu$+SR. These studies found that the temperature dependence of $\lambda(T)$ approaches a constant at low temperature with zero slope. Bardeen, Cooper, and Schrieffer (BCS) predicted this behavior for ordinary (low-temperature) superconductors. Similar behavior of $\lambda(T)$ was found for ac diamagnetic screening in thin films. All of this is consistent with a nodeless energy gap, wherein low-lying excitations of the superconducting condensate vanish exponentially at low temperatures. However, the electron-phonon scattering mechanism of conventional BCS theory is too weak to explain the high (90 K) critical temperatures, so a theory of YBa$_2$Cu$_3$O$_7$ must look into mechanisms other than phonons that presumably will involve intermediary quasi-particles more energetic than phonons, such as excitons.

The Mixed State

Studies of the superconducting mixed state in the bulk of a single-crystal specimen should be particularly helpful for elucidating the physics of high-temperature superconductivity. This phase of a type II superconductor (defined as $\kappa = \lambda/\xi > 2^{1/2}$, where $\kappa$ is the Ginzburg–Landau parameter and $\xi$ is the superconducting coherence distance) is induced when an external magnetic field penetrates as an array of quantized fluxons (flux quantum $\phi_0 = h/2e$), also known as vortices. The two-dimensional fluxon density (a-b plane) is $B_{\text{int}}/\phi_0$, where $B_{\text{int}}$ is the locally averaged magnetic induction (internal magnetic field). For a given value of the penetration depth, the precise form of the local magnetic field distribution function can be calculated exactly when the fluxons are assumed to form a two-dimensional lattice of regular symmetry in the a-b plane. Fluxons normally form a triangular lattice and produce a local magnetic field that is a maximum at the fluxon center, minimum at the triangle center, and has a saddle point, $B_{\text{sadd}}$, at the midpoint between nearest neighbors. The local magnetic field distribution exhibits a peak at $B_{\text{sadd}}$. Recent measurements of local magnetic field spectra by $\mu$+SR have determined the variation of the penetration depth with temperature and magnetic field. In orthorhombic YBa$_2$Cu$_3$O$_7$, the penetration depth is a diagonal tensor with three components, $\lambda_a$, $\lambda_b$, and $\lambda_c$. The component in the a-b basal plane, defined as $\lambda_{ab} = (\lambda_a \lambda_b)^{1/2}$, determines the local magnetic field distribution when the external field, $H$, is applied along the c-axis. Since $\lambda_a$ and $\lambda_b$ are unequal, the theoretical fluxon lattice is oblique (although nearly triangular). The c-axis field orientation is of special interest in this work, because superconductivity in YBa$_2$Cu$_3$O$_7$ is anisotropic and the supercurrents comprising fluxons flow mainly in sheets parallel to the crystallographic a-b plane.

Fluxon Pinning Phases

Fluxon pinning phenomena, which are responsible for the finite critical currents of type II superconductors, generally destroy the regular periodicity of the idealized fluxon lattice. Defects in the crystal structures of superconducting specimens cause fluxons to lie off lattice sites and to have self energies that vary with position. This effect is discussed phenomenologically in terms of fluxon pinning potentials and pinning forces. Theoretical models of fluxon configurations also take into consideration fluxon-fluxon interactions and the effects of thermal fluctuations. Flux pinning, which can be enhanced by deliberate introduction of defects through radiation damage, for example, becomes technologically advantageous for inhibiting fluxon movement and Joule heating in superconductors, which carry high current densities in a magnetic field. High critical currents are desirable for such applications as high-field magnets, low-dissipation power transmission and conversion, and magnetic levitation and propulsion. For studying the physics of the superconductivity, fluxon pinning effects must be dealt with consistently in data analyses.

Fluxons in the mixed state of a superconductor form phases that occupy regions in the temperature-magnetic field (T-H) plane that have been denoted as fluxon liquid, fluxon glass, and Bragg glass. Phases and phase boundaries have been characterized by the ordering and dynamical response of the fluxons. While a perfect two-dimensional lattice of straight fluxon lines is rarely observed, owing to the presence of pinning, the Bragg glass closely resembles the long-range order of the ideal crystal phase. Fluxon phases have conventionally been studied by observing fluxon motion driven either by time-varying magnetic fields or an applied transport current. In an early work, the $\mu$+SR method was used to analyze the local magnetic fields in a polycrystalline sample of YBa$_2$Cu$_3$O$_7$ in terms of a static critical-state model of fluxon pinning. A similar picture of static fluxon disorder was later applied to explain smearing of internal field distributions in a sample comprising a mosaic of YBa$_2$Cu$_3$O$_7$ crystals, while also confirming nodeless pairing with a modified two-fluid model. In the present work, we use a novel approach to studying pinning and depinning of fluxons that occur in near equilibrium with an external magnetic field in a single crystal of YBa$_2$Cu$_3$O$_7$. Information on fluxon states formed at constant magnetic field $H$ is determined from $\mu$+SR measurements of the local magnetic fields produced by the fluxons.

**LOCAL MAGNETIC FIELD**

For an external field applied along the c-axis, $H$, the distribution of the local magnetic induction in a regular fluxon lattice has a width that is defined rigorously as the square root of the variance in the local magnetic field. The theoretical value of this quantity, equivalent to the root second moment, is denoted here as $\sigma_0$. Calculation of $\sigma_0$ is approximated in the London model, i.e., in the extreme limit of a type II superconductor with $\kappa >> 1$, by the expression