TITLE: MAGNETIC FIELD MICROPORBE IN SUPERCONDUCTORS CARRYING A CURRENT

MASTER

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ABSTRACT

A new technique to probe local magnetic fields inside superconductors utilizing the Mössbauer Effect (ME) is reported. The ME nucleus responds to the local magnetic field resulting in a modified hyperfine ME spectrum from which the local field and its direction may be deduced. Concentrations of a few ppm of the radioactive probe nucleus are sufficient; the allowable depth of the probe depends on the attenuation of the ME γ ray. For ^{57}Fe (^{57}Co parent) in superconductors the field acts directly on the nuclear moment and the resulting sensitivity is only a few kG. For a thin probe consisting of ^{57}Co in Pd the response is enhanced by the "giant" localized moment providing a sensitivity at 1 K of better than 100 G. Results of such a probe placed at various locations across a commercial Nb_3Sn tape carrying a current are reported and compared with calculations of the field profile using several models. For thin tape geometries the usual models prove to be inadequate.

INTRODUCTION

In a type II superconductor the local current density is a function of both pinning forces and the local magnetic field. Because the local field is dependent on the actual current distribution, the critical state field and current profiles (as well as the average critical current density) depend on geometry. The ability to predict these profiles depends on the correctness of the critical-state model used and can contribute to an understanding of the influence of pinning forces on current transport. Large aspect-ratio rectangular geometries are particularly advantageous to the study of field profiles of superconductors carrying a current because in this geometry the differences between critical state models are more apparent. In contrast, all models give identical external field profiles for a cylindrical geometry.

Previous field-profile measurements were performed with fairly large and distinctly three-dimensional probes sensitive to only one component of the field. Thorel's¹ technique used small coils; other techniques have employed Hall probes.² Both methods require either a knowledge of field direction or a combination of measurements before the magnitude of the field can be extracted from the data.

Our technique is based on the Mössbauer Effect (ME) whereby the effective magnetic field on the Mössbauer nucleus may be deduced from the ME hyperfine spectrum. The hyperfine spectrum arises from transitions between the first excited state and the ground state of the ME nucleus resulting in γ rays having precise energies and intensities reflecting the environment of the nucleus. For ^{57}Fe (whose parent is ^{57}Co) the 14.4 keV γ rays may originate from within

the host (up to 100 microns deep in Nb_3Sn) and are analyzed by observing the transmission intensity of a resonant absorber as a function of its Doppler velocity. For a resolved spectrum the direction of the magnetic field may be determined from the relative intensities of the various lines. The sensitivity to a magnetic field acting on the nuclear magnetic moments in ^{57}Fe is only a few kG and limits the precision with which the field may be observed inside the superconductor. Also any perturbation in the superconductor localized about the probe nucleus must be considered even though the ^{57}Fe concentrations necessary for a measurement may be quite low (~ 1 -100 ppm).

Alternatively, ^{57}Fe in many host materials develops a large local moment which greatly enhances the local field at the nucleus.⁴ For ^{57}Fe in Pd the enhancement is quite large providing sensitivities proportional to T^{-1} of better than 100 G at 1 K.⁵ Although such a probe is not microscopic it can be quite small; data reported here were taken with a 25 micron thick Pd probe so that field measurements were made very close to the surface; complete field profiles will later be obtained as a function of probe position outside the superconductor.

EXPERIMENT

We report here the transport-current-induced magnetic field profile deduced from ME probe measurements near the surface of a 12.7 mm wide by 100 micron thick commercially prepared Nb_3Sn tape. The copper cladding was left on the tape so that the center of the probe was about 40 microns from the center of the Nb_3Sn as shown in Fig. 1. A DC toroidal transformer was constructed to induce the high currents required.

Fig. 1. Upper — Cross section of the experimental arrangement with position of the Hall probe, the width of ME probe and the width of the tape to scale. Lower — Cross section of the tape and ME probe with thicknesses to scale.

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The primary windings had a circular cross section to eliminate stray fields. A one turn secondary of Nb₃Sn tape was wound through the toroid, and a joint, found to be superconducting, was formed by butting the tape ends together, removing the two copper layers for a few cm near the joint and soldering similar Nb₃Sn tapes to either side across the joint. No resistance attributable to the soldered Nb₃Sn interfaces was detected and the critical current in the secondary is not believed to be limited by the joint characteristics.

The probe itself was prepared by plating about 1 millicurie of ⁵⁷Co onto high purity Pd foil followed by a 3 hour diffusion at 930°C. The active portion of the probe was about 2 mm x 1.12 mm x 25 microns. The response of the probe to an applied magnetic field confirmed the results reported⁴ earlier. In the absence of a magnetic field no line broadening was observed down to 1.1 K indicating that the probe remained paramagnetic.

After mounting the tape and completing the joint the source was attached to the surface of the tape with a very thin layer of Apiezon grease and its position was measured with a cathetometer to about 0.01 mm. The toroid-tape assembly was inserted into a ⁴He cryostat equipped with beryllium windows in the bottom to pass the 14.4 keV γ rays from the ME probe for analysis by a conventional ME analyzer. The γ -ray direction is perpendicular to the tape face. Temperature was maintained at 2.000 ± 0.005 K by a rubber-diaphragm manostat and measured using a W & T gauge. With the toroid and tape at 2 K the current was brought up in the toroid until the tape began to show losses which were detected by a calibrated Hall probe placed a sufficient distance from the tape to measure a pure θ field which is related to the total tape current, independent of local surface field variation. Once losses were evident, the tape was driven normal with a heater to reduce the supercurrent to near zero. The heater was then turned off and the primary current in the toroid was reduced to zero inducing a reverse persistent critical current in the tape without the need to keep the primary energized. The quality of the joint was such that in many hours of data collection no detectable decay was evident for tape currents of about 3000 A at 2 K for the tape and data reported here. After the persistent current was established the ME spectrum was accumulated for about 12 h, a time sufficient for good statistics. Then the toroid assembly was warmed to room temperature and without disturbing the tape, toroid, or Hall probe, the ME probe position was changed and remeasured and the whole cycle repeated. The persistent current dropped after each cycling so that after 7 runs the persistent current was about 90% of its initial value.

RESULTS AND DISCUSSION

Typical Mössbauer spectra for probe positions at the center and edge of the tape are shown in Fig. 2 and 3. The average field at the probe is found from the hyperfine splitting and the known response of the probe. Ideally, the spectrum consists of six resolved lines with intensity 3x1:1:x:3, where $0 < x < 4$ depending on the field direction with respect to the γ -ray analysis direction. Because of the finite width of the probe (1.12 mm) and because the field changed rapidly near the edge, the spectrum shown represents an average field over this width; the edge fields are probably somewhat higher than indicated by the average splitting.

Fig. 2. Mössbauer Effect spectrum of a dilute ⁵⁷Co in Pd source probe located at a center face of a 1.27 cm wide Nb₃Sn tape carrying about 3200 A. Source and tape temperature is 2.00 K. The Doppler velocity between the source and a K₄Fe(CN)₆ single-line analyzing absorber, given as the abscissa, corresponds to a velocity of ± 4.25 mm s⁻¹ with zero velocity at Channel 127. The typical statistical error associated with the number of counts in each channel is shown. In the absence of a magnetic field a narrow single line is observed. The spectrum shown was fit using the expected response of the six hyperfine lines in a small field.

Fig. 3. Mössbauer Effect spectrum, as above, except the ME probe was moved outward until the probe edge was coincident with the tape edge. A typical error in the data is shown. The computer fit shown suggests that the field is nearly perpendicular to the tape (parallel to the γ -ray direction). The broadening of the outer lines is presumably due to the field variation over the probe dimensions but other possible causes for broadening are under investigation.

In Fig. 4 the magnetic field deduced from the hyperfine splitting as a function of position for seven positions between center and edge of the tape is plotted. Because of possible edge damage, the effective edge of the tape is not precisely known. Although not shown here, the character of the spectrum for the probe outside the tape edge was significantly different, consisting mostly of a 4 line pattern where $x \neq 0$ indicating the field sampled was mostly aligned with the Y ray, i.e., the field is perpendicular to the tape face.

In order to better understand the data we also present field profiles for a large aspect ratio tape calculated from two models. For both models the assumption was made that there is no magnetization (H_{C1} is equal to 0.) and that the solutions are time independent so that the equation for the vector potential A of an infinitely long tape with current flowing parallel to the long axis is

$$\nabla^2 A(r) = \frac{4\pi}{c} \bar{J}(r) \quad (1)$$

where $\bar{J}(r)$ is the local current density in the tape and c is the speed of light. For the first calculation $\bar{J}(r)$ was chosen to be a constant.

For the second calculation Kim's⁷ critical-state model was used with $B_0 = 0$. The model became

$$\bar{J}(r) \times \bar{B}(r) = \frac{c}{4\pi} \bar{\alpha} \quad (2)$$

where $\bar{\alpha}$ was a vector of constant length whose direction was always perpendicular to $\bar{J}(r)$ and $\bar{B}(r)$. To find the field profile predicted by this model a numerical solution of the non-linear Poisson equation

$$\nabla^2 A(r) = \frac{\bar{\alpha}}{|\nabla \times A(r)|} \quad (3)$$

was obtained.

The approximation was made that the tape could be described as an assembly of 900 smaller tapes each with the same aspect ratio as the whole and that J was uniform in each of the smaller sections. A self-consistent solution for $\nabla \times A(r)$ (which equals $\bar{B}(r)$) was found using a computer; the results of both calculations are presented in Fig. 4 along with the data.

For the Kim model where the maximum current density is at the center of the tape and for the uniform current density calculation, the fields predicted at the center of the broad face of the tape are much higher than those measured and decrease with increasing distance from the surface. In contrast, the Hall probe saw a field of 910 gauss 5 mm from the surface of the tape while the Mössbauer probe indicated 260 gauss (or about H_{C1}) at the surface. This is consistent only with a current distribution having two maxima one on either side of the tape's center. If this is the case, the poor agreement between the data and the models is not surprising. At present, we do not have a critical state model that excludes current from the central region of the tape but we are attempting to include effects of H_{C1} , surface pinning and a more realistic picture of J_c vs B into the model. All of these changes will move current away from the center of the tape and possibly closer to the actual distribution indicated by the probe.

Fig. 4. Field profiles from the ME data, the Kim model and the uniform J model. Because of edge damage the effective width of the tape for the calculations was taken to be 11.7 mm rather than 12.7 mm. Calculations were made for a current in the tape of 3260 A. Errors in the data are estimated to be less than 10 percent. The data have been normalized to correct for small current and temperature variations.

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