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TITLE: HYPERFINE MAGNETIC FIELD MEASUREMENTS IN $ErRh_4B_4$

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HYPERFINE MAGNETIC FIELD MEASUREMENTS IN $ErRh_4B_4$*

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We report measurements of the hyperfine magnetic field in $ErRh_4B_4$ in zero applied field in a range of temperatures around the reentrant temperature T_{c2}. Using the Mössbauer effect of ^{57}Fe impurities as a hyperfine field microprobe, we find that the low temperature ferromagnetic order persists well above T_{c2} into the superconducting state in this compound, thereby providing direct evidence of coexistence between superconductivity and magnetic order.

In the late 1950's, Matthias *et al.*[1] discovered alloy systems which gave strong indications of coexistence of superconducting and magnetically ordered states. Subsequent studies employing Mössbauer effect microprobes (^{57}Fe nuclei)[2,3] confirmed the earlier findings and proved coexistence of superconductivity and some kind of spontaneous magnetic order.

In 1977, the superconducting and magnetic properties of the ternary compound $ErRh_4B_4$ were documented[4]. Among the most interesting of these properties is the reentrant behavior at the so-called reentrant temperature T_{c2}. [illegible] destroyed by a competing ferromagnetically ordered phase. [illegible] temperature [illegible] magnet [illegible] in nature.

We report here the results of our recent experimental investigation [illegible] Mössbauer effect (ME) [illegible] hyperfine magnetic field [illegible] $ErRh_4B_4$ [illegible] sample of [illegible] Argonne National Laboratory [illegible]. The [illegible] The ^{57}Co is expected to substitute for [illegible] Rh [illegible] average concentration [illegible] estimated to be less than 100 ppm.

The reentrant temperature of the doped sample was determined from measurements of the ac susceptibility. Hysteresis was observed in the data depending on whether the sample was warmed or cooled through T_{c2}. We also observed a trend in the data toward successively higher values of T_{c2} on cooling and successively lower values on warming, as the sample was repetitively cycled through the transition region. For this reason we quote ranges in which T_{c2} was measured on warming and cooling, respectively, 0.79 K to 0.75 K and 0.66 K to 0.71 K.

ME measurements were performed with the source cooled in a ^3He cryostat. A constant-acceleration-mode ME spectrometer was employed with a room temperature single-line potassium ferrocyanide absorber.

At all temperatures the ME spectrum is comprised chiefly of a slightly asymmetrical quadrupole doublet. A simple model, based on a single site, [illegible] hyperfine split quadrupole [illegible] characterize the data accurately. Indeed, the crystallographic data of [illegible] show that there are two non-equivalent Rh sites present in the ratio [illegible]. Our subsequent analysis of the ME data is therefore based on a model characterized by two non-equivalent sites A' and B' [illegible] ratio [illegible] for the [illegible] probe. The model also reflects our assumption that only one of the sites experiences a measurable hyperfine field as a result of the ferromagnetic ordering of the Er atoms in the host compound.

The details of the model are determined by [illegible] spectra accumulated at the extremes of the temperature range investigated. The 4 K [illegible] determines the isomer shift and quadrupole splitting of each of the two sites. Fits to spectra accumulated at the lowest temperature show that B' is the magnetically influenced site. The model can only be fully determined, however, with the introduction of the relative directions of the principal axes of the electric field gradient and the internal magnetic field at the B'

site. As these directions are not known, we take them to be colinear.

At intermediate temperatures, a fitting procedure determines the optimum hyperfine-magnetic splitting of the B' site quadrupole which is consistent with our fully determined dual-site model. The introduction of an additional B' site linewidth broadening allows a second degree of freedom to the fit. This eases the constraint imposed by our simple assumption regarding the relative directions of the hyperfine fields and also reflects the possiblity that all B' sites are not precisely equivalent.

The results of fits to the intermediate temperature ME spectra exhibit several interesting features. Most notable, the B' site remains non-magnetic at all temperatures above approximately 1 K. Below this temperature, however, the magnetic splitting increases significantly, reaching a saturation value of 0.067 mm s^{-1} (corresponding to 0.21 ± 0.02 T) at a temperature of approximately 0.6 K. Linewidth broadening of the B' site component lines exhibits a quite similar temperature dependence. The linewidth increases from a nominal value of 0.34 mm s^{-1} at high temperatures to approximately 0.40 mm s^{-1} at saturation; this broadening roughly corresponds to 0.2 T.

Figure 1 is a plot of the hyperfine magnetic field at the B' impurity probe sites as a function of temperature. Hyperfine magnetic fields were calculated by calculating the spectrometer velocity scale at saturation. Although relatively small at saturation, the hyperfine magnetic field and presumably the ferromagnetic order) persists to temperatures well above T_{c1}. In contrast to the general behavior observed with other measurement techniques, not only is superconductivity, as also [1] at resistance[2], neutron scattering and heat capacity[3] our measurements were unable to resolve any upper critical hysteresis in the hyperfine field as a function of warming the sample through the transition region. However these ME measurements have marginal sensitivity for observing hysteresis effects. That the hyperfine magnetic fields reported in this work are due to impurity-impurity magnetic ordering of the Fe atoms rather than to the host Er atoms seems doubtful in view of the extremely low Fe concentration. Relaxation time effects can also be ruled out for ^{57}Fe in this metallic system.

In conclusion, we have measured a temperature dependent hyperfine magnetic field at ME impurity probe sites in $ErRh_4B_4$. This field persists above the reentrant temperature of the compound into the superconducting state, thereby providing direct evidence of coexistence of a magnetically-ordered state and superconductivity in this material in a small temperature interval above T_{c2}.

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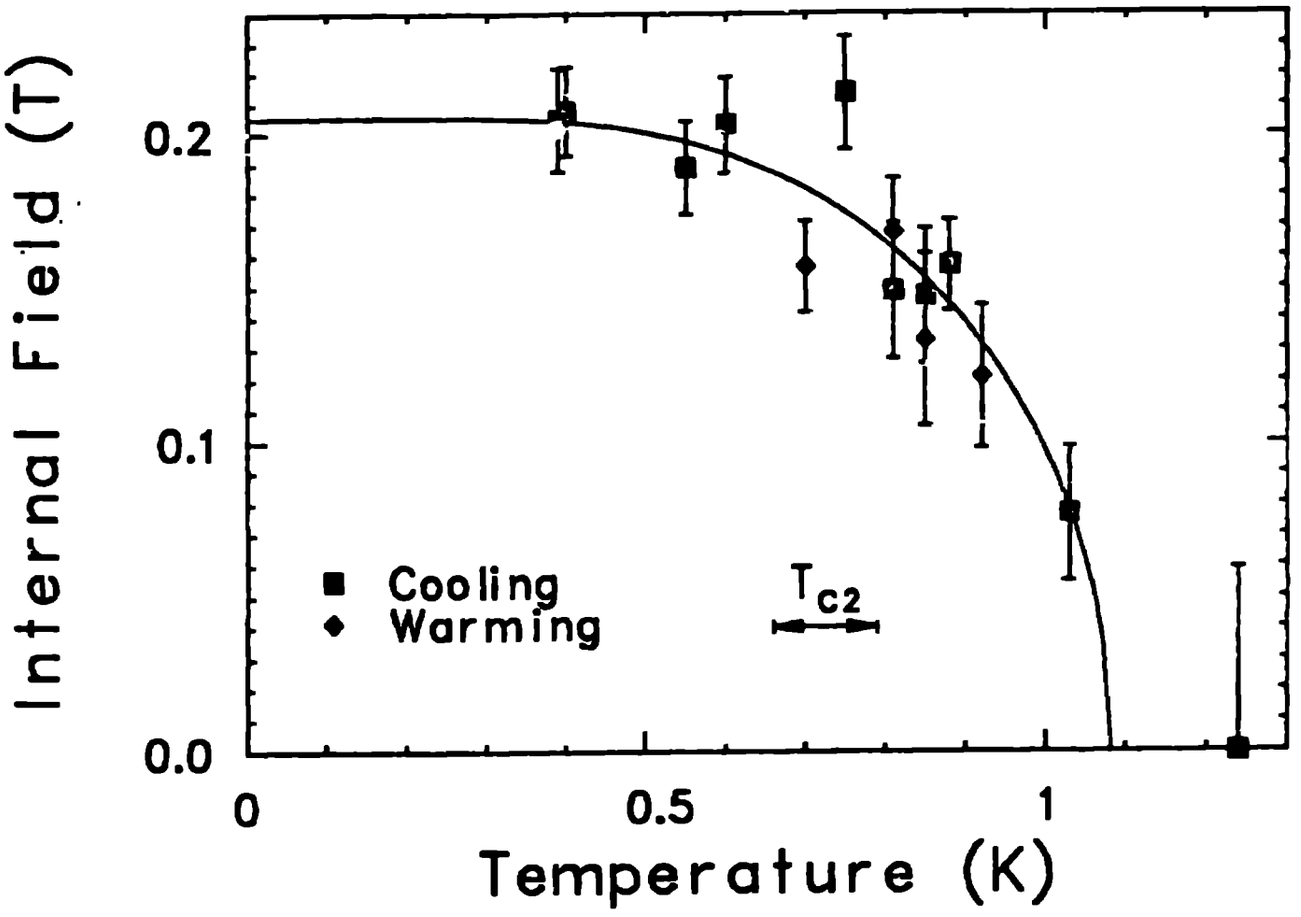

Figure 1. Internal magnetic field in $ErRh_4B_4$: the solid line is a molecular field fit to the data.