Non-local superconductivity and the vortex-state properties of YNi$_2$B$_2$C

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Abstract

The magnetization $M$ and heat capacity of clean, single crystal YNi$_2$B$_2$C superconductor have been studied with magnetic field $H||c$-axis. The magnetization $M(H)$ deviates from conventional predictions, but is accurately described by recent non-local London theory, with well-behaved parameters. We show that the Ginzburg-Landau parameters $\kappa_1$ and $\kappa_2$ increase considerably as $T$ decreases, similar to niobium, but with $\kappa(T_c) \approx 7$. © 2000 Elsevier Science B.V. All rights reserved.

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The nickel–borocarbide superconductors are a rich and complex system of materials. These tetragonal materials have received great attention because of their remarkable properties, including the coexistence of magnetism and superconductivity and phase transitions in the vortex lattice (from simple hexagonal to rhombohedral to square symmetry), even for YNi$_2$B$_2$C that contains no magnetic rare earth ions [1,2]. This strange behavior of the vortex lattice has been explained in terms of non-local London theory [3] or generalized Ginzburg–Landau theory [4]. The non-local electrodynamics strongly affects the equilibrium magnetization $M$, which deviates significantly from conventional local London predictions, but agrees well [5] with recently generalized non-local London theory [6].

Magnetic studies were conducted in a SQUID magnetometer. The 17 mg single crystal, grown by a high-temperature flux method, was studied at temperatures $T$ from far above $T_c$ (14.5 K) to 2–3 K, in magnetic field $H||c$-axis from zero to $H > H_{c2}$, the upper critical field.

The in-field heat capacity was investigated to provide independent measures of $H_{c2}(T)$ and, by integration, the thermodynamic critical field $H_{c}(T)$. We obtain $H_{c}(0) = 2550$ G.

In general, the magnetization $M(H, T)$ exhibited little magnetic irreversibility, enabling an analysis of the crystal’s equilibrium properties. The reversible $M$ has been analyzed using standard London theory [7] near $T_c$ and its non-local generalization [6] at lower temperatures. Nonlocal effects should be important when the BCS coherence length $\xi \approx 11$ nm is small compared with the electronic mean free path $\ell$, as is the case here with $\ell \approx 30$ nm. Indeed, $M(H)$ deviates significantly from local London theory, but it is well-described by non-local London theory, with well-behaved parameters; e.g., $1/\tilde{\kappa}^2(T) \sim (1 - \ell^2)$ with $\tilde{\kappa}(0) = 89$ nm. A further consequence of “cleanliness” and a large $\ell$ is that the Ginzburg–Landau parameters $\kappa_1$ and $\kappa_2$ should vary significantly with temperature. Variations in these quantities have been largely ignored in studies to date on borocarbide superconductors.

According to Maki theory [8], extensions beyond the constant-$\kappa$ approximation are needed for clean materials at lower temperatures. There one has $H_{c2} = \sqrt{2\kappa_1 H_c}$ and $4\pi dM/dH|_{H_{c2}} = 1/\beta\kappa=[2(\kappa^2 - 1)]$. Experimentally,
Fig. 1. (a) The Ginzburg–Landau parameters $\kappa_1$ and $\kappa_2$ for YNi$_2$B$_2$C with field $H||c$-axis versus reduced temperature $t = T/T_c$; $\kappa \approx 7$ at $T_c$. (b) For comparison, the same parameters measured in single crystal Nb, with $H||[001]$; $\kappa = 0.773$ at $T_c$.

we have $H_c$ and $H_{c2}$ from both magnetization and heat capacity measurements. Also, we have (background corrected) $M(H)$ curves extending into the normal state, which provide values for $\kappa_2$. The results for $\kappa_1$ and $\kappa_2$ for the single crystal of YNi$_2$B$_2$C are shown in Fig. 1 as a function of reduced temperature $t = T/T_c$. Each $\kappa_i$ is normalized by the (common) value $\kappa = 7$ at $T_c$. The deduced values of $\kappa_i$ increase significantly as $T$ decreases. For comparison, corresponding results are shown for a high purity, single crystal of Nb [9]. The behavior is remarkably similar for the low-$\kappa$ Nb and intermediate-$\kappa$ material YNi$_2$B$_2$C.

To conclude, the temperature dependence of $\kappa_1$ and $\kappa_2$ and the non-local London magnetization both point to significant effects of non-local electrodynamics in the YNi$_2$B$_2$C, consistent with its long electronic mean free path.

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References