ELSEVIER

Physica C 341–348 (2000) 1299–1300

PHYSICA C

www.elsevier.nl/locate/physc

# Four-fold anisotropy of the basal plane magnetization of $YNi_2B_2C$: nonlocal effects*

L. Civale[a], A. V. Silhanek[a], J. R. Thompson[b,c], K. J. Song[c], C. V. Tomy[d], and D. McK. Paul[d]

[a]Comisión Nacional de Energía Atómica, Centro Atómico Bariloche 8400 Bariloche, Río Negro, Argentina
[b]Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831-6061
[c]Department of Physics, University of Tennessee, Knoxville, Tennessee 37996-1200
[d]Department of Physics, University of Warwick, Coventry, CV4 7AL, UK

We present studies of the vortex state magnetization $M$ of a single crystal of the nonmagnetic borocarbide superconductor $YNi_2B_2C$. With magnetic field $\boldsymbol{H}$ applied in the square basal plane of the tetragonal unit cell, $M$ has a four-fold anisotropy. This $\pi/2$ periodicity occurs deep in the superconductive mixed state, with an unusual field dependence, for a range of temperatures $T < T_c$. The observations are well explained by a generalized London model incorporating non-local electrodynamics, using parameters from complementary experiments.

Borocarbide superconductors are remarkable materials. For example, "clean" single crystals exhibit transitions in the vortex lattice between hexagonal, rhombohedral, and square symmetries, as cited recently.[1] These features in the flux lattice have been attributed to nonlocal electrodynamics,[2,3] which arises when the electronic mean free path is large relative to the coherence length $\xi$. In the non-magnetic borocarbide $YNi_2B_2C$, the equilibrium magnetization (with magnetic field $\boldsymbol{H} \parallel$ c-axis) deviates from the classical, local London dependence on field, $M_{eq} \sim \ln H$; the deviations have been quantitatively accounted for[4] by introducing non-local electrodynamics into the London description.[5]

More recently, we have shown that nonlocality strongly influences the response of the material to magnetic fields applied within the square basal plane. Now, the *local* London model for the mixed state introduces material anisotropy via a second rank mass tensor $m_{ij}$. However, in the square basal plane of these tetragonal materials, the masses $m_{aa} = m_{bb}$ are equal, implying that the properties in the *ab* plane should be isotropic. In contrast, non-local corrections should lead to a four-fold anisotropic response in the *ab* plane. Indeed, we have observed[1] in the mixed state of $YNi_2B_2C$ an oscillation of $M_{eq}$ with $\pi/2$ periodicity, with an unusual sign reversal as $H$ increases. Furthermore, we show that this behavior obtains in a wide temperature range well below the transition temperature $T_c = 14.5$ K. The results quantitatively agree with the non-local London description introduced by Kogan et al.[5]

The present studies were conducted on the same 17 mg single crystal of $YNi_2B_2C$ as used previously.[1,4] The crystal is a slab, roughly elliptic with axes along the two equivalent (110) directions. The c-axis was aligned with the rotation axis, so that $\boldsymbol{H}$ could be rotated within the basal plane. Two SQUID magnetometers (5 and 7 tesla magnets) were used.

Figure 1 shows the dependence of $M_{eq}$ on the in-plane angle $\varphi$, at $T = 7$ K. For $H = 30$ Oe (lower panel), the crystal was in the Meissner state. Hence the angular variation with periodicity of $\pi$ arises solely from shape anisotropy. The top frame in Fig. 1 shows high field data with $H > H_{c2}$ (which depends only weakly on $\varphi$). This normal state paramagnetism with periodicity $\pi/2$ decreases rapidly as $H/T$ decreases.[1] Generally, it is much smaller than the superconducting contribution, except close to $H_{c2}$.

Most important is the magnetization deep within the mixed state, as illustrated in the center frame of Fig. 1. These results show that $M$ has a four-fold symmetry in the entire field range of the

* A.S. is member of CONICET. Collaboration between UTK and CAB was supported in part by a UTK Faculty Research Fund. Research at the ORNL is supported by the U.S. Dept. of Energy under contract number DE-AC05-96OR22464 with Lockheed Martin Energy Research Corp.

0921-4534/00/$ – see front matter 
PII S0921-4534(00)00909-6

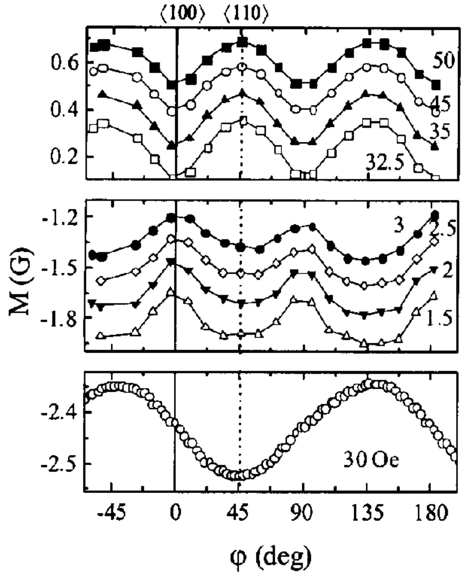


Fig. 1. The equilibrium magnetization in the basal plane of $YNi_2B_2C$ versus angle $\varphi$ of the field H. Values of H are in kOe; $T = 7$ K.

measurements. It is further apparent that the oscillations deep in the mixed state are inverted, relative to the normal state. In fact, the oscillation changes sign near 10 kOe. Furthermore, the amplitude of oscillation at $H$ = 1.5 – 3 kOe is as large as that in 50 kOe. This four-fold oscillatory behavior, including the change of sign, has been successfully modeled and explained using the nonlocal generalization of London theory.[5] A key feature of the modeling is an angular dependence of the characteristic field scale $H_0 \sim \Phi_0/\rho^2$, where $\rho \sim \xi_{BCS}$ is the nonlocality radius. This is the only added degree of freedom, as values for other parameters were taken from the earlier study[4] with $H \parallel c$. Other aspects of the analysis have been reported previously.[1]

To generalize these observations, we have measured the oscillation amplitude over a wide range of temperatures. For these measurements, we measured $M$ with $H \parallel$ <110> and $H \parallel$ <100>, which are the extrema of the oscillations. Selected results for the amplitude [$M$<110> – $M$<100>] are shown in Fig. 2 on a logarithmic field scale, for the temperatures shown. As $H$ decreases from high fields, the normal state signal decreases, passes through a peak near $H_{c2}$, then monotonically decreases and changes sign near 10 kOe. This

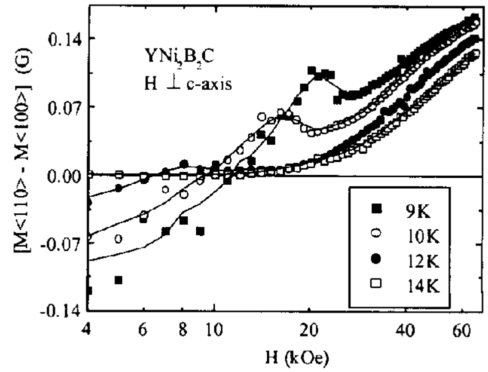


Fig. 2. Amplitude of the oscillations of the basal plane $M$, with $\pi/2$ periodicity, versus field $H$. Values for the temperature are shown; lines are a guide to the eye.

behavior is very similar to that observed in angular studies like those in Fig. 1. These experimental results show that nonlocality effects have a profound effect on these clean, intermediate-$\kappa$ superconductors and they emphasize the considerable utility of the generalized London theory. In a complementary study, Kogan et al.[6] investigated the angular dependence of the equilibrium magnetization in $LuNi_2B_2C$. The results were successfully analyzed via numerical integration of the nonlocal expressions.

In summary, we have demonstrated a four-fold anisotropy in the square basal plane of clean single crystal $YNi_2B_2C$, deep in the mixed state, for a range of temperatures and magnetic fields. This response is well explained by a generalized London model incorporating non-local electrodynamics, with parameters based largely on complementary experiments.

## REFERENCES

1. L. Civale et al., Phys. Rev. Lett. **83**, 3920 (1999).
2. Y. De Wilde et al., Phys. Rev. Lett. **78**, 4273 (1997).
3. V. G. Kogan et al., Phys. Rev. B **55**, R8693 (1997).
4. K. J. Song et al., Phys. Rev. B **59**, R6620 (1999).
5. V. G. Kogan et al., Phys. Rev. B **54**, 12386 (1996).
6. V. G. Kogan et al., Phys. Rev. B **60**, R12577 (1999).