Anomalous magnetic-field dependence of neutron depolarization near T_c in ceramic $YBa_2Cu_3O_{7-\delta}$

V. L. Aksenov, E. B. Dokukin, V. K. Ignatovich, S. V. Kozhevnikov,
E. I. Kornilov, Yu. V. Nikitenko, and A. V. Petrenko
*I. M. Frank Neutron Physics Laboratory, Joint Institute for Nuclear Research,
141980 Dubna, Moscow Region*

Yu. V. Bugoslavskiĭ and A. A. Minakov
Institute of General Physics, Russian Academy of Sciences, 117942, Moscow, Russia

(Submitted 12 January 1995)
Pis'ma Zh. Éksp. Teor. Fiz. **61**, No. 4, 294–298 (25 February 1995)

The depolarization of neutrons as they pass through the yttrium ceramic $YBa_2Cu_3O_{7-\delta}$ has been studied at temperature s near T_c in external fields up to 10 kOe. There is an interval of magnetic fields in which the polarization exhibits an irregular behavior not seen previously. Spectral changes in the transmitted beam indicate that dynamic processes arise in the vortex lattice in the region of irregular behavior.© *1995 American Institute of Physics.*

Its magnetic moment and high penetrating power make the neutron irreplaceable for studying magnetic structures in cases in which the average magnetization is not known accurately. This comment applies, in particular, to research on type-II superconductors, in which there is much interest in the magnetic field distribution in the mixed state and in the interaction of the vortex lattice with pinning centers.

Previous experiments on neutron depolarization (e.g., Refs. 1–4) have focused on the low-temperature region ($T<0.5T_c$). In the study which we are reporting here, and which is a continuation of the experiments of Ref. 5, the temperatures were near the superconducting transition ($T>0.85T_c$), and the external magnetic field was higher than in Ref. 5, up to 10 kOe. At these fields, high-T_c superconductors exhibit several new properties, which have yet to be fully explained.

This study of the $YBa_2Cu_3O_{7-\delta}$ superconducting ceramic was carried out on an SPN-1 polarized-neutron spectrometer at the IBR-2 high-flux beam reactor of the Neutron Physics Laboratory of the Joint Institute for Nuclear Research. The experimental procedure is described in Ref. 5. The test sample was a ceramic superconductor $YBa_2Cu_3O_{7-\delta}$ with $T_c=90.4$ K, a transition width of 1.0 K, and density of $\rho=4.9$ g/cm^3. It had the shape of a parallelepiped. Its dimensions, the direction of the magnetic field, the polarization direction, and the beam direction are all shown in Fig. 1. This sample had texture; the (001) crystallographic axis of the crystallites was oriented predominantly along the a direction of the parallelepiped.

In the experiments we measured the polarization of the neutron beam, $P(H,T,\lambda)$, at the exit from the polarization analyzer as a function of the neutron wavelength λ, the strength of the external magnetic field H, and the sample temperature T:

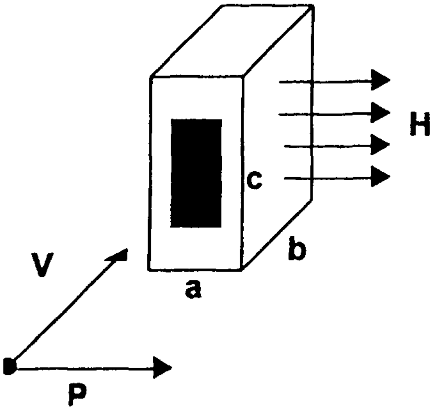

FIG. 1. Experimental geometry. P—Neutron polarization direction; v—beam propagation direction; H—external magnetic field. The dimensions of the sample are $a \times b \times c = 4.1 \times 19 \times 52$ mm. The black region represents the neutron beam, with dimensions $a \times c = 2 \times 26$ mm.

$$P(H,T,\lambda) = \frac{N^{+}(H,T,\lambda) - N^{-}(H,T,\lambda)}{N^{+}(H,T,\lambda) + N^{-}(H,T,\lambda)} . \tag{1}$$

Here $N^{\pm}$ is the intensity of the neutrons detected with the spin flipper on and off, i.e., with the neutron spin directed along and opposite the field, respectively. The ranges of λ, H, and T in these experiments were $0.5 < \lambda < 15$ Å, $0 < H < 10$ kOe, and $77 \leqslant T \leqslant 94$ K. Information on the magnetic processes which occur inside the sample in its superconducting state was extracted from the ratio

$$P(\lambda) \equiv \frac{P(H,T,\lambda)}{P_0(T_0,\lambda)} , \tag{2}$$

where the subscript zero refers to measurements at the temperature $T = T_0 = 250$ K. The quantity $P(T_0,\lambda)$ is independent of the external field, since the ceramic is nonmagnetic in its normal state. In addition to the spectral polarization $P(\lambda)$ in (1), we used the integrated polarization P, which is given by expression (1) with $N^{\pm}(H,T,\lambda)$ replaced by $N^{\pm}(N,T)$:

$$N^{\pm}(H,T) = \int N^{\pm}(H,T,\lambda) d\lambda .$$

The results are illustrated in Fig. 2 with plots of the integrated polarization P/P_0 measured at $T = 86$ K, as the magnetic field is increased (a) and reduced (b). In addition to the polarization minima at $H = H_1$ and $H = H_2$, which were discussed in detail in Ref. 5, there is an interval of magnetic fields, from $H_3 = 4.1$ kOe up to the maximum field attainable on this apparatus, 10 kOe, in which the $P(H,T)$ behavior is irregular. On the return pass (as the field is reduced), the minima on the $P(H,T)$ curve are deeper, indicating a hysteresis. The irregular behavior terminates at the same value, $H_3 = 4.1$ kOe (Fig. 2b). As the field is reduced further, below 4 kOe, the value of $P(H,T)$ is close to one. This result means that the Abrikosov vortices in the sample are parallel to the external field at $H < H_3$.

Figure 3 shows the temperature dependence of the field $H_3(T)$ (curve 1). Shown for comparison here is the temperature dependence of the critical field, $H_R(T)$ (curve 2),

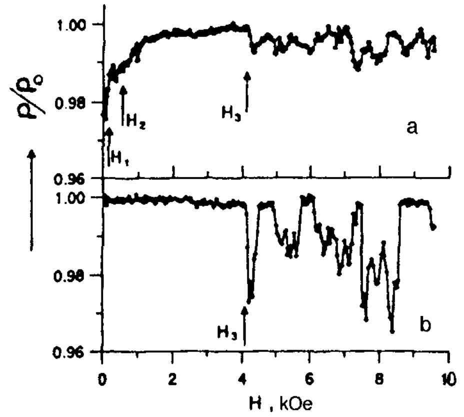

FIG. 2. Integrated polarization versus the external field at $T=86$ K. a—As the field is increased; b—as it is reduced.

measured for the same sample. At this critical field a resistance $r=0.01r_n$ arises in the sample (r_n is the resistance in the normal state) at an alternating current $I=1.8$ mA at a frequency of 35 Hz.

The temperature dependence $H_3(T)$ is approximately linear:

$$H_3(T)=H_3(0)(1-T/T_c)^x, \tag{3}$$

with $x=1.1$ and $H_3(0)\approx 84$ kOe. The temperature dependence of H_R is also approximately linear, with $H_R(0)\approx 310$ kOe. Relation (3) can be interpreted as the melting line of a vortex lattice, which has been seen in many other experiments.[6,7] Opinion is still divided regarding the nature of the melting line of a lattice of magnetic vortices. The interaction of vortices with pinning centers and with each other is amenable to only a qualitative analysis; the same is true of the nature of the thermal excitations in an Abrikosov vortex. The melting line can be described over a fairly broad range of temperatures ($0.8T_c<T\leq T_c$) by an expression $H(T)=H(0)(1-T/T_c)^x$, but different theories predict different values for x. For example, the theory of vortex-lattice melting in Ref. 8 predicts $x=2$; the theory of a thermally activated vortex flux[9] (the TAFF model) predicts $x=3/2$; and the theory of a vortex-glass–vortex-liquid transition[10] predicts $x=4/3$. A fit of the $H_3(T)$ curve to Fig. 3 yields a value $x=1.1$, which agrees best with the predictions of the theory of a glass–liquid transition. On the other hand, the ratio

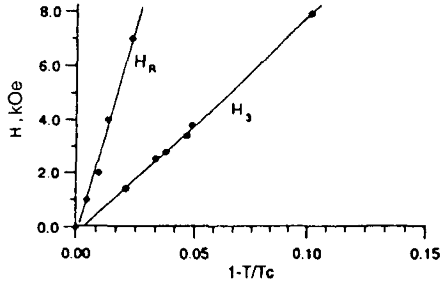

FIG. 3. Temperature dependence of the magnetic fields H_R and H_3 (the notation is explained in the text proper). The lines are simply drawn through the experimental points.

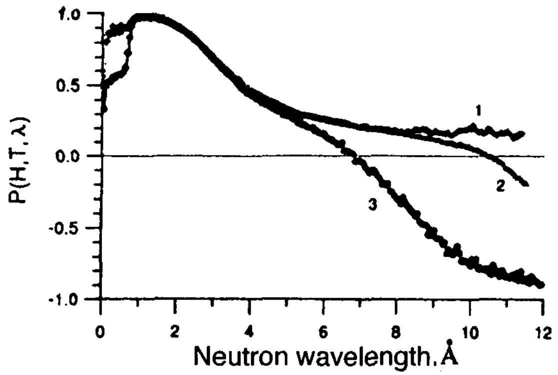

FIG. 4. The polarization spectrum $P(H,T,\lambda)$. 1—$T=250$ K; 2—$T=86$ K ($H=H_{\max}=9$ kOe); 3—$T=86$ K ($H=H_{\min}=8.4$ kOe).

$H_3(0)/H_{c2}(0)\approx 0.27$ agrees best with the ideas of Ref. 11 regarding the melting of a vortex lattice. From that paper we have $H_m(T)\approx 0.2H_{c2}(T)$ $(H_R\approx H_{c2})$.

The behavior of high-T_c materials near the melting line has been studied experimentally by a variety of macroscopic methods (there have been measurements of the magnetization, of the susceptibility in alternating and static fields, of current–voltage characteristics, of noise, and of the change in the frequency shift of mechanical vibrations which are excited). The results of these experiments do no more than confirm the existence of a line $H_m(T)$ which separates different phases of the magnetic-vortex system. On the other hand, the values of the exponent x found in different experiments range from 1 to 2, but they are quite different, so again it is not possible to draw conclusions about the validity of one theory or another. Furthermore, macroscopic methods deal with only the response of the entire volume of the superconductor to an external agent or with surface defects. The use of polarized neutrons makes possible a more-detailed study of the behavior of the Abrikosov vortices inside a superconductor, e.g., the bending of these vortices by thermal factors, structural factors, or external agents.

Our experiments show that the deformation of the lines is not static. This point is demonstrated by Fig. 4, which shows three curves for the polarization as a function of the neutron wavelength λ. Curve 1 corresponds to $P_0(\lambda)$; curve 2 shows $P(\lambda)$ corresponding to the point of the maximum, $H_{\max}=9$ kOe, of the curve in Fig. 2b; and curve 3 shows $P(\lambda)$ corresponding to the point of the minimum, $H_{\min}=8.4$ kOe, on the curve in Fig. 2b. There are some anomalous features here: the change in sign and the increase in the absolute value of the polarization at large wavelengths, as shown by curve 3. Such changes in the polarization spectrum could be explained only by inelastic scattering with spin flip and neutron cooling.

Figure 5 shows the ratios of integrated intensities $R^{\pm}=N^{\pm}(H,T)/N^{\pm}(T_0)$ at $T=86$ K and at $T=250$ K. In the anomalous region we see surges in the intensity when the flipper is on. In this case a large fraction of the neutrons incident on the sample are polarized opposite the field. Similar surges can also be seen at large values of λ in the spectrum corresponding to the resultant intensity of the two polarizations. This result is again evidence of inelastic scattering with spin flip.

Comparison of the spectra of neutrons transmitted through the sample above T_c and

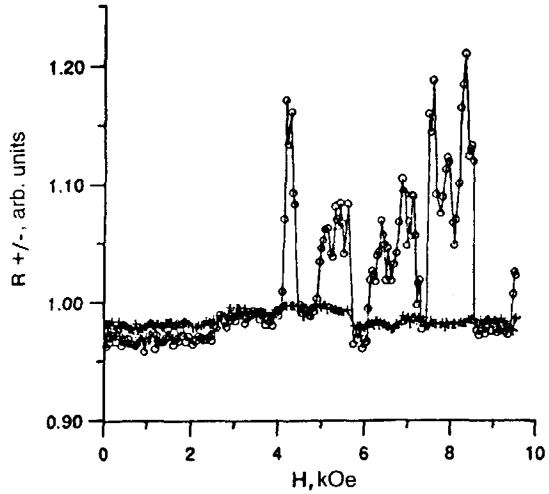

FIG. 5. Integrated intensities of the neutron beams with spin along the field (+, R^+) and with spin opposite the field (O, R^-) at $T=86$ K, divided by the corresponding intensities at $T=250$ K.

at the polarization minimum in the anomalous region yields an estimate of the energy transfer in the course of inelastic scattering: ≈20 meV.

The magnetic interaction of a neutron with matter can be described, in general, by

$$V(q) \propto \mu_i(\delta_{ij} - q_i q_j / q^2) B_j(q,\omega) = \boldsymbol{\mu} \cdot \{\mathbf{q} \times [\mathbf{q} \times \mathbf{B}(\mathbf{q},\omega)]\},$$

where i and j specify the Cartesian components of the corresponding vector, and $\boldsymbol{\mu}$ is the magnetic moment of the neutron. We have written out only that part of the interaction which corresponds to a wave-vector transfer $\mathbf{q}$ and an energy $\hbar\omega$. According to the experimental geometry, the observed inelastic scattering is accompanied by a transfer of momentum parallel to the momentum of the incident particles. Consequently, the inelastic scattering which is observed is accompanied by the appearance of excitations along a direction perpendicular to the axis of Abrikosov vortices. Furthermore, since spin flip should occur in the course of inelastic scattering, the vector $\mathbf{q} \times [\mathbf{q} \times \mathbf{B}(\mathbf{q},\omega)]$ should be perpendicular to the magnetic field. Correspondingly, the magnetic induction $\mathbf{B}(\mathbf{q},\omega)$, which describes the perturbation associated with the excitation of the vortex lattice, should be perpendicular to both the external field and the beam direction. Such a perturbation could arise only from a bending of an Abrikosov vortex.

It follows that inelastic scattering is accompanied by the onset of bending excitations of vortices which are propagating in the direction perpendicular to the Abrikosov lattice. The irregular change in the cross section for this scattering upon a change in the external field may result from a dependence of these excitations on the distance between vortices and fluctuations which develop near the melting line of the vortex lattice.

In summary, the anomalous magnetic-field dependence of the polarization of the neutron beam may be due to inelastic scattering of neutrons by magnetic vortices accompanied by spin flip and the transfer of excitation of a bending nature in the direction perpendicular to the system of vortices.

This study was carried out within the framework of projects 94-02-04011 and 93-02-2535 of the Russian Fund for Fundamental Research and under Grant NJZ000 of the International Science Foundation.

[1] R. J. Papoular and G. Collin, Phys. Rev. B **38**, 768 (1988).
[2] M. N. Volkov, R. P. Dmitriev, N. K. Zhuchenko *et al.*, Zh. Tekh. Fiz. **59**(6), 186 (1989) [Sov. Phys. Tech. Phys. **34**, 702 (1989)].
[3] R. P. Dmitriev, R. Z. Jagood, N. K. Zhuchenko *et al.*, Z. Phys. B **83**, 155 (1991).
[4] W. Roest and M. Th. Rekveldt, Phys. Rev. B **48**, 6420 (1993).
[5] V. L. Aksenov, E. B. Dokukin, Yu. V. Nikitenko *et al.*, Physica Scripta T **49**, 650 (1993).
[6] E. H. Brandt, J. Supercond. **6**, 201 (1993).
[7] W. A. Feitz and W. W. Webb, Phys. Rev. **178**, 657 (1969).
[8] A. Houghton, R. A. Pelcovits, and A. Sudbo, Phys. Rev. B **40**, 6763 (1989).
[9] P. H. Kes, J. Aarts, J. van den Berg *et al.*, Supercond. Sci. Technol. **1**, 242 (1989).
[10] D. S. Fisher, M. P. A. Fisher, and D. A. Huse, Phys. Rev. B **43**, 130 (1991).
[11] G. Blatter, M. V. Feigel'man, V. B. Geshkenbein *et al.*, Preprint ETH-TH/93-9, (1993), p. 237.

Translated by D. Parsons