# NQR study of hysteresis in $YBa_2Cu_3O_{7-x}$

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Experiments reveal that the effect of the pinned magnetic flux on the transverse relaxation time $T_2$ of the NQR of copper nuclei in the planes [Cu(2)] of the $YBa_2Cu_3O_{7-x}$ crystal structure is different from that for the chains [Cu(1)]. Possible reasons for this effect are discussed.

Discussions of the vortex structure in the high-$T_c$ superconductors have dealt with Josephson vortices at weak links between grains,[1] the weak links which arise at twin boundaries,[2] and the weak links which stem from the layered structure.[3] Although Bulaevski *et al.*[4] have concluded that the model of superconducting planes coupled by Josephson junctions which they developed does not fit $YBa_2Cu_3O_{7-x}$ perfectly, the coherence length perpendicular to the layers in this superconductor is short enough that one would expect some nontrivial features in the vortex structure.

  

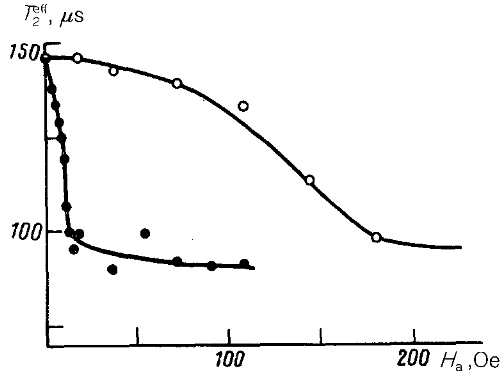


FIG. 1. $T_2^{eff}$ versus $H_a$ for Cu(2) nuclei ($T$= 15 K). ○—Cooling in a zero field (ZFC); ●—cooling in a field (FC).

In this letter we are reporting the use of the method of nuclear quadrupole resonance (NQR) of copper nuclei to study flux pinning. In contrast with other methods, the NQR method yields local information. In particular, it allows one to separately observe the effects on the nuclei in the planes [Cu(2)] and the chains [Cu(1)] of the structure, whose NQR lines have been well resolved.

The measurements were carried out by Hahn spin-echo method over the temperature interval 4.2–100 K with magnetic fields $H \leqslant 500$ Oe. The $YBa_2Cu_3O_{7-x}$ samples, with $T_c = 91$ K, were prepared by the ceramic procedure and then ground (the grain size was 3–10 μm).

Measurements were carried out in two regimes: (a) zero-field cooling (ZFC) from $T \geqslant 100\ K > T_c$, followed by measurements of the amplitude of the signals and the relaxation characteristics, the application of a field $H_a$, the removal of this field, and a repetition of the measurements; (b) cooling in a field $H_a$ (FC), removal of the field, and then measurements. Measures were taken to prevent uncontrolled magnetic fields.

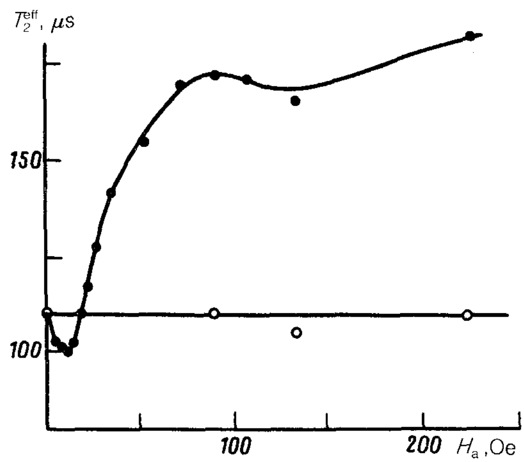


FIG. 2. $T_2^{eff}$ versus $H_a$ for Cu(1) nuclei ($T$= 15 K). ○—ZFC; ●—FC.

In particular, a welded cryostat, without solder rings capable of pinning magnetic flux, was used.

Within the measurement error, no effect of the magnetic history of the sample on the spin-lattice relaxation time $T_1$ was observed. On the other hand, at $T < T_c$ the magnetic history did affect the amplitudes of the echo signals (A) and also the rate of their decay as a function of the time interval ($\tau$) between the exciting pulses. The $A(\tau)$ curves are customarily used to determine the transverse (spin–spin) relaxation time $T_2$. Proceeding under the assumption that the $A(\tau)$ dependence is modified by a magnetic field (the external field or the field of the pinned flux), we characterize it by the quantity $T_2^{\mathrm{eff}}$, finding the value of this quantity formally by approximating $A(\tau)$ by an exponential function. The measurements showed that, while the $A(\tau)$ curve has characteristic oscillations in an applied field,[5] it is a single-exponential function, within the measurement error, after the removal of the field.

In both the FC and ZFC regimes, the value of $T_2^{\mathrm{eff}}$ and the amplitude of the signal from the Cu(2) nuclei initially decrease substantially with increasing $H_a$ and then become independent of it (Figs. 1 and 3). The $T_2(H_a)$ dependence for the Cu(1) nuclei is completely different. For the nuclei (Fig. 2), $T_2^{\mathrm{eff}}$ is independent of $H_a$ in the ZFC case, while the FC case it in fact increases with $H_a$. The curve of $A(H_a)$ for the Cu(1) nuclei also has an ascending region (Fig. 3).

These results are stably reproducible with samples synthesized in various laboratories. No dependence of the measured properties on $H_a$ is observed at $T > T_c$. This result implies that the effects found here are not being influenced by possible magnetic inclusions or elements of the apparatus which might be magnetized. At the same time, independent data show that a pinning of magnetic flux does occur in high-$T_c$ samples at $T < T_c$ in the specified field.

For the Cu(2) nuclei, this behavior might be a consequence of the "slow beat" effect in the envelope echo $A(\tau)$ in a magnetic field $H$ (Ref. 5), for which the period is $\sim 1/(\gamma H)$. An averaging of these periods in the nonuniform field of the pinned vortices might reduce to a decrease in $T_2^{\mathrm{eff}}$. A decrease in the echo amplitude might then be due to either a decrease in $T_2^{\mathrm{eff}}$ or an excursion of some of the nuclei from resonance. For the Cu(1) nuclei, on the other hand, one is forced to assume that the fields acting

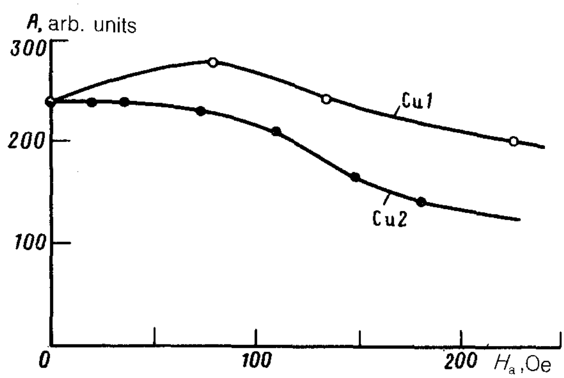


FIG. 3. Amplitude of the NQR signal versus $H_a$ for $\tau = 30$ μs ($T = 15$ K). O—Cu(1) nuclei; ●—Cu(2) nuclei.

on these nuclei are weaker by a factor of at least several units; i.e., we must assume that the fields of the pinned flux vary rapidly at the atomic scale. At first glance, this interpretation would seem to completely contradict the present understanding of the structure of vortices in superconductors, for which the typical size of the field decay region is equal to the penetration depth $\lambda$, which in turn is much larger than interatomic distances. However, if we think of $YBa_2Cu_3O_{7-x}$ as a set of superconducting $CuO_2$ planes coupled by Josephson junctions, then the "Josephson" vortices with $H$ parallel to the planes, with a normal core lying between the planes and stretching out in the direction of the planes, would have the minimum energy and the minimum $H_{c1}$ (Ref. 4). Most of the vortex superconducting current would then be concentrated in the nearest superconducting $CuO_2$ atomic planes (e.g., the planes between which there are yttrium ions), while the field outside these planes would fall off sharply. This picture of course requires a more rigorous analysis and substantiation. Alternative explanations must also be examined.

One way to interpret our results without being forced to make assumptions about microscopic irregularities of the vortex field might be to assume that the pinned flux is in a special orientation with respect to the axes of the gradient of the crystal electric field. However, an analysis of this possibility on the basis of the relations derived in Ref. 5 shows that it is not acceptable.

Other explanations require assumptions regarding local mechanisms which would act in different ways on the actual values of $T_2$ in the planes and the chains. It has been established[6,7] that the value of $T_2$ for the Cu nuclei in the planes increases sharply (it roughly doubles) upon the transition to the superconducting state, while the corresponding time for the Cu nuclei in chains is not affected. Bakharev *et al.*[6] have discussed a possible explanation which links this effect with an influence of the superconducting transition on fluctuations of the electron spin of the $Cu^{2+}$ ions in planes. In our case, we would assume that the appearance of the superconducting vortex currents, localized predominantly in planes, affects the spin dynamics of the spin moments of $Cu^{2+}$. We are not prepared to offer a specific model for this effect.

With regard to the weak increase in $A(H_a)$ and $T_2^{\text{eff}}(H_a)$ for Cu(1), we note that this behavior might be understood as resulting from changes in internuclear spin–spin interactions in the high-gradient magnetic field and interactions with the electron spins of paramagnetic impurities. The differences between the ZFC and FC regimes might be explained in the same way. In the latter regime, the vortex density should be greater at a given value of $H_a$; this conclusion agrees qualitatively with the observed differences.


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