Site-selective $^{63}$Cu NMR study of the vortex cores of Tl$_2$Ba$_2$CuO$_{6+\delta}$

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Abstract

We report site-selective $^{63}$Cu NMR studies of the vortex core states of an overdoped Tl$_2$Ba$_2$CuO$_{6+\delta}$ with $T_c = 85$ K. We observed a relatively high density of low-energy quasi-particle excitations at the vortex cores in a magnetic field of 7.4847 T along the $c$ axis, in contrast to YBa$_2$Cu$_3$O$_{7-\delta}$.

Key words: A. oxides, A. superconductors, D. nuclear magnetic resonance (NMR), D. superconductivity

1. Introduction

The vortex core magnetism of high-$T_c$ cuprate superconductors has attracted great interests. This is the first report of site-selective $^{63}$Cu NMR study for the vortex core states of an overdoped Tl$_2$Ba$_2$CuO$_{6+\delta}$ (TL2201) with $T_c = 85$ K. Although a quadrupole Cu nuclear is coupled by an electric field gradient in TL2201, we noticed that the central transition line ($I_z = 1/2 \leftrightarrow -1/2$) of the Cu (spin $I = 3/2$) NMR at a magnetic field $H$ along the maximal principal axis ($c$ axis) of the electric field gradient tensor is purely magnetic. As to YBa$_2$Cu$_3$O$_{7-\delta}$ (Y1237) with $T_c = 92$ K, both $^{17}$O and $^{63}$Cu nuclear spin-lattice relaxation rates $1/T_1$ inside the vortex cores are reported to be enhanced more largely than those outside the cores only below about 20 K [1,2,3]. For TL2201, we observed that the $^{63}$Cu NMR $1/T_1$ near the vortex cores is enhanced more largely than that away from the cores just at $T_c$ and shows a Korringa-like behavior from $T_c$ to 10 K.

2. Experiments

A powder sample was magnetically aligned along the $c$ axis and was characterized more than ten years ago [4] and recently [5].

Magnetization $M$ was measured by a superconducting quantum interference device (SQUID) magnetometer. The irreversible temperature $T_{irr}$ was defined as a bifurcation temperature of $M/H$ after cooled at a zero magnetic field (ZFC) and at finite magnetic fields of $H = 10$ mT − 5.0 T (FC). Typical magnetic susceptibility $M/H$ at 10 mT and 2.0 T is shown in Fig. 1(a). The $T_{irr}$ was found to be quickly suppressed as the magnetic field $H$ was increased. The irreversible line of TL2201 in Fig. 1(b) is similar to that of Bi$_2$Sr$_2$CaCu$_2$O$_8$ (Bi2212). The anomaly observed in TI NMR at 20 K and at 2.0 T is associated with a vortex freezing effect across the irreversible line [5].

Site-selective $^{63}$Cu NMR experiments were performed by a phase-coherent-type pulsed spectrometer while cooling in a magnetic field of $H = 7.4847$ T. The $^{63}$Cu NMR frequency spectra were measured with quadrature detection. The nuclear spin-echoes were recorded as functions of frequency $\nu$ while $\nu$ was changed point by point. The $^{63}$Cu nuclear spin-
the coexistence of vortex solid and liquid, similarly to
K shift is due to a superconducting diamagnetic shift
a reduced Knight shift composed of two spectra with a finite spin shift and
T Below
Fig. 1. (a) Magnetic susceptibility $M/H$ after cooled at a zero magnetic field (ZFC) and at finite magnetic fields of $H = 10$ mT and 2 T (FC) along the $c$ axis. (b) A magnetic phase diagram on an irreversible line along the $c$ axis. Open circles are the irreversible temperatures at the fixed fields. Closed circles are the irreversible fields at the fixed temperatures.

lattice relaxation curves $^{63}p(t) \equiv 1 - M(t)/M(\infty)$ (recovery curves) of the nuclear spin-echo amplitude $M(t)$ were measured by an inversion recovery technique, as functions of time $t$ after an inversion pulse.

3. $^{63}$Cu NMR Results and Discussion

Fig. 2 shows temperature dependence of the central transition line ($I_z = 1/2 \leftrightarrow -1/2$) of the $^{63}$Cu NMR while cooling at $H = 7.4847$ T along the $c$ axis below 96 K. In the normal state, the positive Knight shift $K_c$ of the observed sharp line is the sum of an orbital shift $K_{c,\text{orb}}$ and a spin shift $K_{c,\text{spin}}$ [4]. Below $T_c$ down to 22 K, the $^{63}$Cu NMR spectra are composed of two spectra with a finite spin shift and a reduced Knight shift $K_c < K_{c,\text{orb}}$. The reduced shift is due to a superconducting diamagnetic shift $K_{c,\text{dia}}$ in a vortex lattice. These spectra indicate the coexistence of vortex solid and liquid, similarly to the $^{205}$TI NMR spectra at 2.0 T [5]. Below 22 K, the

Fig. 2 shows temperature dependence of the frequency distribution of the $^{63}$Cu NMR recovery curves $^{63}p(t)$ at 86 and 10 K. In the normal state at 86 K, a slight frequency distribution was observed, similarly to $^{17}$O NMR for YBa$_2$Cu$_4$O$_8$ [8], maybe due to slight misorientation of the powder grains. At 10 K, the relaxation is slower away from the vortex cores. The solid curves are the least-squares fits by theoretical functions of $p(t)=p(0)[0.1\exp(-t/T_1)+0.9\exp(-6t/T_1)]$ for a magnetic transition of $I_z = 1/2 \leftrightarrow -1/2$. Although the fits were not so satisfactory at 10 K, the relaxation rates $1/T_1$ were tentatively estimated from these fits.

Fig. 3 shows temperature dependence of frequency distribution of the estimated $1/T_1$. With cooling down, a larger frequency distribution of $1/T_1$ was observed. In contrast to the $^{205}$TI NMR [5], no clear effect of the vortex freezing was observed.

Fig. 4 shows temperature dependence of frequency distribution of $1/T_1$ at 85.68 MHz near the vortex cores and at 85.40 MHz
away from the cores. At \( T_c \), \( 1/^{63}T_1 \) away from the cores quickly decreases in a function of \( T^3 \). Below 20 K, it approaches a \( T \)-linear function. From \( T_c \) to 10 K, \( 1/^{63}T_1 \) near the cores shows a Korringa-like \( T \)-linear behavior. These results are different from those for Y1237 [1,2,3] but similar to the theoretical \( 1/^{63}T_1 \) due to the spatial distribution of a local density of electron states [9] and also to the Zn-induced effect on Y1237 [10]. The theory does not include antiferromagnetic correlation. Although \( 1/^{63}T_1 \) between \( T_c \) and 43 K might be affected by a direct process of overdamped motion of pancake vortices [11], the Korringa-like \( 1/^{63}T_1 \) in a vortex lattice below 32.5 K indicates a relatively high density of normal quasi-particle excitations inside the vortex cores in TL2201.

Fig. 6 shows the \( ^{63} \)Cu nuclear spin-lattice relaxation rate divided by temperature, \( 1/^{63}T_1 T \), for Y1237 reproduced from Ref. [3] and for TL2201. The difference in \( 1/^{63}T_1 T \) inside and outside the vortex cores is larger in TL2201 than in Y1237.

Scanning tunneling spectroscopy (STS) studies for Y1237 indicate the split of a zero-bias peak in the conductance spectra near the vortex cores at a

Fig. 4. Temperature dependence of frequency distribution of \( ^{63} \)Cu nuclear spin-lattice relaxation rate \( 1/^{63}T_1 \) (the right axis).

Fig. 5. Log-log plots of \( ^{63} \)Cu nuclear spin-lattice relaxation rate \( 1/^{63}T_1 \) as a function of temperature at 85.68 MHz around the vortex cores and at 85.40 MHz away from the vortex cores.
magnetic field [12]. The impurity Zn-substitution effects are known to induce the zero-bias conductance peak in the STS spectra near the Zn impurity [13] and the difference in $1/T_1$ near and away from the Zn just below $T_c$ [10]. Thus, the STS conductance spectrum for TL2201 might indicate the zero-bias conductance peak near the vortex cores, which is illustrated in the inset of Fig. 6(b). The nature of Andreev bound states at the vortex cores, e.g., the degree of the split of the zero-bias conductance peak near the vortex cores might depend on the degree of enhancement of underlying antiferromagnetic correlation.

4. Conclusion

We report for the first time the site-selective $^{63}$Cu NMR studies of the vortex core magnetism for TL2201 with $T_c = 85$ K at about 7.5 T along the c axis. The difference in $^{63}$Cu nuclear spin-lattice relaxation rate $1/T_1$ inside and outside the vortex cores was observed in TL2201 just below $T_c = 85$ K, in contrast to that in $1/T_1$ in Y1237 below about 20 K. The Korringa-like behavior of $1/T_1$ near the vortex cores indicates a high density of the normal quasi-particle excitations inside the vortex cores in TL2201.

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