Antiferromagnetic vortex core of $Tl_2Ba_2CuO_{6+\delta}$ studied by ^{205}Tl-NMR

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Abstract

We report an experimental evidence of the vortex core antiferromagnetism by spatially-resolved NMR measurement on ^{205}Tl of $Tl_2Ba_2CuO_{6+\delta}$.

Key words: NMR ; vortex core ; High-T_c superconductor ; antiferromagnetism

High-T_c superconductivity appears by hole-doping into the Mott insulator in which strong antiferromagnetic (AF) correlations exist. Characteristic of the vortex core state of the high-T_c superconductor is quite different from that of the normal core in the conventional BCS superconductor [1]. Some theories based on SO(5) [2] and t-J [3] models predict that the superconducting (SC) vortex core could be in AF order state. Recent neutron scattering experiments by Lake *et.al.* suggested the AF order in the vortex core [4,5]. Thus, the microscopic information of the electronic state in the vortex core has been attracted much attention.

Although many experiments of STM and neutron scattering can prove local information of the vortices, these experiments have not been enough to clarify the interesting issues. Main reason is that the STM experiments lack sensitivity to magnetism, though they provide the local density of state (LDOS) with atomic resolution, and that the neutron experiments lack spatial resolution for the vortex structure.

Interestingly, a recent spatially-resolved NMR has been developed a powerful method to monitor bulk properties of the vortex core state.[6,7]. Reflecting the distributed field in the vortex state, NMR spectrum is asymmetric, showing so-called the Redfield pattern.

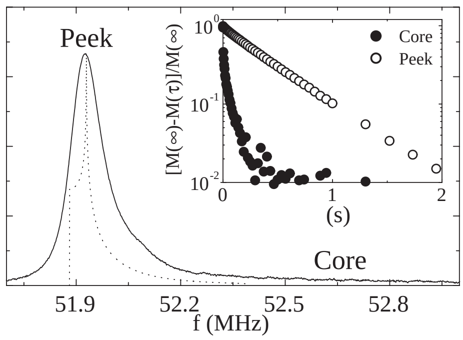

Fig. 1. ^{205}Tl NMR spectrum with T=5K, H=2.1T (Solid line). The dashed line is simulated Redfield-pattern. Inset is recovery curve from saturation of the nuclear magnetization at the spectrum peek (○) and the vortex core (●) at T=5K.

The magnetic field is highest at the vortex core, and thus the NMR signals of the core region appear at high frequency. Therefore, we can separate the NMR signals from the vortex core region and SC region. Previous measurements give successfully spatial-dependent nuclear spin-lattice relaxation time T_1 of the planer ^{17}O in $YBa_2C_3O_7$ [8,10] and $YBa_2C_4O_8$ [9].

T_1 is expressed in terms of dynamical susceptibility,

$$\frac{1}{T_1} = \frac{\gamma^2 k_B T}{2\mu_B^2} \sum_{\boldsymbol{q}} \left| A\boldsymbol{q} \right|^2 \frac{\mathrm{Im}\chi\left(\boldsymbol{q}, \omega\right)}{\omega}$$

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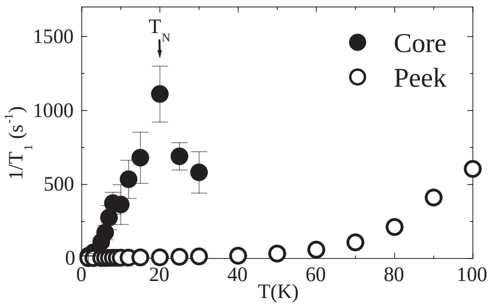

Fig. 2. Temperature dependence of T_1 of $Tl_2Ba_2CuO_{6+\delta}$. Filled circles are obtained at the vortex core, and open circles are at the spectrum peek.

Here $A\boldsymbol{q}$ is hyperfine coupling constant. Transferred hyperfine coupling constant at the O site is expressed

$$^{17}_{Plane}A_q = 2C\cos\frac{q_x a}{2}$$

as the planer oxygen site, ^{17}O, is located at the center of two Cu sites. As the Tl site in $Tl_2Ba_2CuO_6$ is located above the Cu site,

$$^{205}_{Tl}A_q = D\exp\left(iq_z R_{\mathrm{Cu-Tl}}\right)$$

is given. Thus, AF fluctuations of the planer Cu spins at $\boldsymbol{q} = (\frac{\pi}{a}, \frac{\pi}{a})$ are filtered in T_1 of plane ^{17}O site, but the Tl site can monitor those AF fluctuations. It should be point out that the transfer hyperfine coupling constant between the Cu and Tl is large. For these reasons, the oxygen site is suitable to obtain LDOS in the plane site, but it is not suitable to detect AF fluctuations. On the other hand, the Tl site is good probe for monitoring the AF fluctuations of the planer Cu spins.

In this paper, we report spatially-resolved NMR on the ^{205}Tl of optimally-doped $Tl_2Ba_2CuO_{6+\delta}$ to confirm antiferromagnetism of the vortices. Polycrystalline powder sample was aligned along the c-axis with applied magnetic field. At low temperature, we observed asymmetric spectrum (Fig.1), which originated from field distribution of the vortex state. Below T=20K, we observed large spectrum broadening near the vortex core region which is not explained only based on the broadening of the Redfield pattern.

We tried spatially resolved T_1 measurement at constant filed of H=2.1T, and succeeded to measure T_1 at the SC region and vortex core region separately. As shown in Fig.1, the recovery curve of nuclear magnetization in the vortex core is faster than that of the SC region. Characteristics of the SC region are that the recovery curve obeys a single exponential. On the other hand, the recovery curve of the vortex core region dose not obey single exponential, but $\exp\left(-\sqrt{t}\right)$. This indicates that the T_1 near the vortex core region distribute inhomogeneously. Here, T_1 is defined as a time that relaxation curve decreases to e^{-1}.

As shown in Fig.2, T_1^{-1} in the SC region is very similar temperature dependence as that obtained previously by conventional T_1 measurement. On the other hand, T_1 of the vortex core region is quit different from that of SC region, namely T_1^{-1} of the vortex core region are at least 100 times as large as that of SC region. As decreasing temperature, T_1^{-1} becomes large, shows a peek at 20K and then decrease largely below 20K. Thus the origin of the peculiar temperature dependence of T_1^{-1} is not due to the enhancement of the LDOS, but due to the evolution of magnetic fluctuations.

The present experiment shows some interesting results: the T_1^{-1} enhancement in the vortex core, the broadening of the spectrum near the vortex core at low temperature, the T_1^{-1} peek of the vortex core at T=20K, and the relaxation curve like $\exp\left(-\sqrt{t}\right)$ near the vortex core region. These results show the feature of the local antiferromagnetism of the vortcies. The T_1^{-1} enhancement and the spectrum broadening are originated from AF fluctuations of the local Cu spins induced in the vortex core. And the T_1^{-1} peek indicates an AF order of the Cu spins at T_N=20K. As the local and short-range magnetic ordering occurs inside the vortex core, T_1 process near vortices are distributed, showing $\exp\left(-\sqrt{t}\right)$ dependence.

In summary, we conclude that the local AF ordered state is realized in the vortex core below T_N=20K in $Tl_2Ba_2CuO_{6+\delta}$. Lastly, we would like to point out that an applied magnetic field dependence of T_1 is crucial for further understanding of the microscopic electronic structure of the vortex core in HTSC.

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