ANTIFERROMAGNETISM INDUCED IN THE VORTEX CORE OF $Tl_2Ba_2CuO_{6+\delta}$ PROBED BY SPATIALLY-RESOLVED ^{205}Tl-NMR*

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Magnetism in the vortex core state has been studied by spatially-resolved NMR. The nuclear spin lattice relaxation rate T_1^{-1} of ^{205}Tl in nearly optimal-doped $Tl_2Ba_2CuO_{6+\delta}$ ($T_c = 85$ K) is significantly enhanced in the vortex core region. The NMR results suggest that the suppression of the d-wave superconducting order parameter in the vortex core leads to the nucleation of islands with local antiferromagnetic (AF) order.

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1. Introduction

The relation between superconductivity and magnetism has been a central issue in the physics of high-T_c superconductors (HTSC). The strong antiferromagnetic (AF) fluctuation plays a crucial role in determining many physical properties of HTSC [1]. Closely related to this problem, the microscopic structure of the vortex core in the d-wave superconductors turns out to be a very interesting subject. A new class of theories has emphasized the importance of the magnetism arising from the strong electron correlations.

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Though STM measurements can probe the local density of states with atomic resolution, they do not directly reflect the magnetism. Neutron scattering experiments on $La_{2-x}Sr_xCuO_4$ have reported recently that an applied magnetic field enhances the AF correlation in the SC state [2]. However, the relation between the observed AF static ordering and magnetic excitations within the vortex core is still not clear, because the neutron experiments lack spatial resolution.

Recent experimental [3–5] and theoretical [6] NMR studies have established that the frequency dependence of nuclear spin-lattice relaxation rate, T_1^{-1} in the vortex state serves as a probe for the low energy excitation spectrum. Up to now, however, all of these spatially-resolved NMR measurements have been carried out at the ^{17}O sites [3–5], at which the AF fluctuations are filtered.

In this paper we obtain local information on the AF correlations in the spatially-different regions of the vortex lattice by the spatially resolved NMR imaging experiment on ^{205}Tl nuclei in nearly optimal-doped $Tl_2Ba_2CuO_{6+\delta}$. This attempt is particularly suitable for the above purpose because T_1^{-1} at the Tl site can monitor AF fluctuations sensitively This is owing to the fact that the Tl atoms are located just above the Cu atom and there exist large transferred hyperfine interactions between Tl and Cu nuclei through apical oxygen (see the inset of Fig. 1). On the basis of the results of the NMR imaging, we have established a clear evidence of the AF vortex core state. [7]

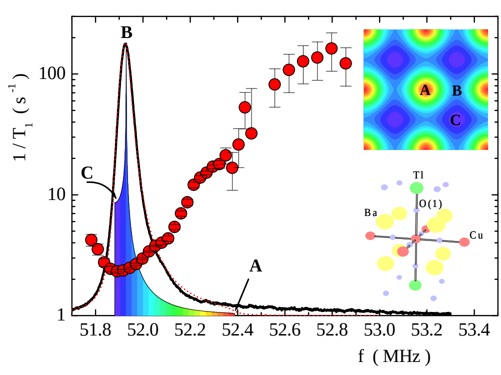

Fig. 1. ^{205}Tl-NMR spectrum and frequency dependence of $^{205}T_1^{-1}$ (filled circles) at 5 K. The thin solid line depicts the histogram at particular local fields of the Redfield pattern with $\xi = 18$ Å and $\lambda_{ab} = 1700$ Å. The upper inset shows the image of the field distribution in the vortex square lattice. A-position represents the vortex core, B is at the field corresponding to the saddle point of the vortices, and C-point is at the center of the vortex square lattice. The lower inset shows the crystal structure of $Tl_2Ba_2CuO_{6+\delta}$.

2. Experimental

High quality $Tl_2Ba_2CuO_{6+\delta}$ with $T_c = 85\,K$ has been synthesized under a high oxygen pressure atmosphere. NMR measurements were carried out on the c-axis oriented polycrystalline powder in the external field of $H = 2.1\,T$ along the c-axis. As shown in Fig. 1, a clear asymmetric pattern of the NMR spectrum, which originates from the local field distribution associated with the Abrikosov vortex lattice (the Redfield pattern), is observed below 50 K.

For ^{205}Tl with nuclear spin of $I = 1/2$, the recovery curve from the saturation of the nuclear magnetization fits well to a single exponential relation of time τ after saturation pulses. In the vortex state, on the other hand, the feature of the recovery curves is strongly positional-dependent, and shows a $\sqrt{\tau}$ functional form at the core region. We defined T_1 as the time required for the nuclear magnetization to decay by a factor $1/e$.

3. Results and discussion

Fig. 1 shows the frequency dependence of $(^{205}T_1)^{-1}$ at 5 K. On scanning from the outside into the core (C→B→A), $(^{205}T_1)^{-1}$ increases rapidly after showing a minimum near the saddle point (B). The magnitude of $(^{205}T_1)^{-1}$ in the core region is approximately 80 times larger than that near the saddle point. This large enhancement of $(^{205}T_1)^{-1}$ is in striking contrast to $(^{17}T_1)^{-1}$ at ^{17}O sites reported in $YBa_2Cu_3O_7$ [3, 4] and $YBa_2Cu_4O_8$ [5],

Fig. 2 show the T-dependences of $(^{205}T_1T)^{-1}$ and $(^{205}T_1)^{-1}$ within the core and at the saddle point. Well above T_c, $(^{205}T_1T)^{-1}$ obeys the Curie–Weiss law. $(^{205}T_1T)^{-1}$ shows a broad peak at $T = T^*(\sim 120\,K)$, and then decreases rapidly without showing any anomaly associated with the SC transition at T_c, similar to other HTSC, which can be attributed to the pseudogap. Below 40 K, $(^{205}T_1T)^{-1}$ in the SC region is reduced largely and is nearly T-independent down to 4 K.

The T-dependence of $(^{205}T_1)^{-1}$ at the vortex core regime contains some key features for understanding the core magnetism. $(^{205}T_1)^{-1}$ exhibits a sharp peak at $T = T_N(= 20\ K)$. Below T_N, $(^{205}T_1)^{-1}$ decreases rapidly with decreasing T. The sharp peak of $(^{205}T_1)^{-1}$ at T_N seems to support the occurrence of a local AF ordering. We also point out that the appearance of the local AF ordering is also consistent with the $\sqrt{\tau}$ dependent nuclear magnetization decay curve. In fact, the $\sqrt{\tau}$ dependence has been observed when the microscopic imhomogeneous distribution of $(T_1)^{-1}$ due to strong magnetic scattering centers is present [8].

In summary, the spatially-resolved NMR provides a direct evidence that the AF spin correlation is extremely enhanced in the vortex core region, and the paramagnetic AF ordering transition of the Cu spins in the core

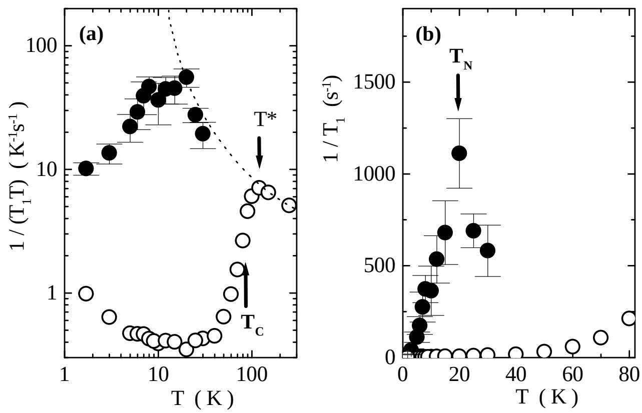

Fig. 2. Temperature dependence of $({}^{205}T_1T)^{-1}$ (a) and ${}^{205}T_1^{-1}$ (b) of ^{205}Tl in $Tl_2Ba_2CuO_{6+\delta}$. The filled circles represent the data at the vortex core and open circles represent the data at the saddle point. In (a) $T^* \sim 120$ K is the pseudo-gap temperature, and $T_c^* \sim 85$ K is the SC transition temperature. The dotted line represents the Curie–Weiss law which is determined above T^*. In (b) T_N is the temperature at which ${}^{205}T_1^{-1}$ at the vortex core exhibits a sharp peak.

region occurs at $T_N \sim 20$ K in $Tl_2Ba_2CuO_{6+\delta}$. The present results offer a new perspective on how the AF vortex core competes with the *d*-wave superconductivity.

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