Microscopic coexistence of antiferromagnetism and superconductivity in $HgBa_2Ca_4Cu_5O_y$: Cu-NMR study

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Abstract

We report a coexistence of superconductivity and antiferromagnetism in five-layered compound $HgBa_2Ca_4Cu_5O_y$ (Hg-1245) with $T_c = 108$ K trough Cu-NMR measurements. This compound is composed of two kinds of CuO_2 planes in a unit cell, three inner planes (IP) and two outer planes (OP). The OP is optimally-doped, undergoing a superconducting (SC) transition at $T_c = 108$ K, whereas the IP is strongly underdoped, doing an antiferromagnetic (AF) transition below $T_N \sim 60$ K.

Key words: Multilayered high-T_c cuprates ; NMR ; Antiferromagnetism

1. Introduction

Multilayered high-T_c cuprates, which have more than three CuO_2 planes in a unit cell, include two kinds of CuO_2 planes. As indicated in the inset of Fig. 1, an outer CuO_2 plane (OP) has a pyramidal five-oxygen coordination, whereas an inner plane (IP) has a square four-oxygen one. Nuclear magnetic resonance (NMR) experiments suggested that the OP and the IP differ in the doping level (N_h) [1–3]. We have reported that N_h(OP) at the OP is larger than N_h(IP) at the IP for the multilayered cuprates and its difference $\Delta N_h = N_h(\mathrm{OP}) - N_h(\mathrm{IP})$ increases as either a total carrier content or the number of CuO_2 layers (n) increases. [4] It is expected that multilayered cuprates with large n may provide a rather interesting possibility to unravel the electronic states at the underdoped IP's without any significant disorder, because they are apart from the hole-reservoir layers.

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2. Experimental results and discussions

Polycrystalline sample was prepared by the high-pressure synthesis technique as described elsewhere [5]. Powder x-ray diffraction experiment indicates that the sample consists of almost a single phase. A $T_c = 108$ K was determined from the dc susceptibility. For NMR measurements, the powdered sample was aligned along the c-axis at an external magnetic field of $H = 16$ T. The NMR experiments were performed by the conventional spin-echo method at 174.2 MHz ($H \sim 15.3$ T).

Figs. 1 indicate the T dependence of $^{63}K_{ab}$ for $H \perp c$ and $1/T_1T$ for $H \parallel c$, respectively. In general, $K(T)$ consists of the T independent orbital part, K_{orb}, and the T dependent spin part, $K_s(T)$ that is proportional to the uniform susceptibility, χ_s. K_s(IP) decreases, whereas $1/T_1T$(IP) increases monotonically with decreasing T down to 150 K, below which the NMR signals at the IP and the IP* disappear suddenly. This is because the low-energy spectral weight in dynamical response function $\chi(\mathbf{q} = \mathbf{Q}, \omega)$ is rapidly enhanced

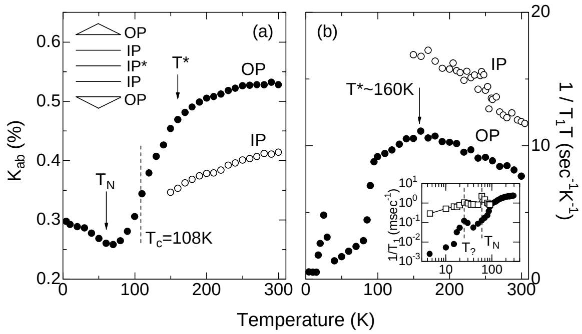

Fig. 1. T dependence of (a) Knight shift K_{ab} for $H \perp c$, and (b) $(1/T_1T)$ for $H \parallel c$.

around $\omega \sim 0$, demonstrating that the IP's are in a quite underdoped regime. Here $\mathbf{Q}$ is the AF wave vector $(\pi/a, \pi/a)$. The growth of low-energy magnetic excitations towards an AF ordering is considered to prevent the emergence of pseudogap. K_s(OP), on the other hand, decreases below $T^* \sim 160$ K, followed by a rapid decrease around $T_c = 108$ K which is indicative of bulk superconductivity at the OP. Remarkably, K_s(OP) and $1/T_1T$(OP) exhibit a pseudogap behavior below $T^* \sim 160$ K. We note that the $1/T_1$ at the OP is distributed below T_c. The inset of Fig. 1(b) shows the T dependences of $(1/T_1)$. Its short component (open square) indicates the peaks at $T_N \sim 60$ K and $T_? \sim 25$ K, whereas its long component shows the peak at $T_? \sim 25$ K. Along with the results that the OP's spectral width broadens at low T, the peak in $1/T_1T$(OP) appears at T_N, and K_s(OP) increases below T_N, the IP's are expected to order antiferromagnetically below T_N. The peak at $T_? \sim 25$ K may arise from another magnetic transition or some vortex dynamics.

Fig. 2 shows ^{63,65}Cu-NMR spectra at $H = 0$ and 1.4 K, which evidences for the AF ordering at the IP and IP*. The nuclear quadrupole frequencies at the IP and the OP's, ν_Q(IP) and ν_Q(OP) are estimated from the NMR experiments at high T as $^{63}\nu_Q$(IP) = 8.37 MHz and $^{63}\nu_Q$(OP) = 16.05 MHz, respectively (not shown). These frequencies are not consistent with the observed one. Therefore, all these spectra are affected by the presence of internal field $H_{\rm int}$ associated with the onset of AF order. Actually, four peaks in $f = 55 - 110$ MHz are understood as the central peaks ($1/2 \leftrightarrow -1/2$ transition) of ^{63,65}Cu at the IP and IP*. A ratio of ^{63,65}Cu-NMR intensity at low frequency to high frequency ($I_L/I_H \sim 2$) suggests that the two peaks at low (high) frequencies are arising from the IP (IP*). Each observed frequencies allow us to estimate the respective AF moments at the IP and IP* are $M(\text{IP}) \sim 0.30\mu_B$ and $M(\text{IP}^*) \sim 0.37\mu_B$ by using hyperfine coupling constant of $(A - 4B) \sim 207\text{kOe}/\mu_B$. [6,7]

The spectra in $f = 10 - 40$ MHz are arising from the OP. The calculated spectra to be consistent with the experiment are indicated in the figure, allowing us to estimate $\nu_{\rm Q} \sim 16$ MHz and $H_{\rm int} \sim 0.54$ T. It is expected that the AF spin polarization at the IP induces $H_{\rm int}$(OP) via the hybridization between the 4s(IP) state and the 4s(OP) and/or $3d_{3z^2-r^2}$(OP) state, making it possible to couple magnetically along the c-axis via the SC OP-Hg-OP layers.

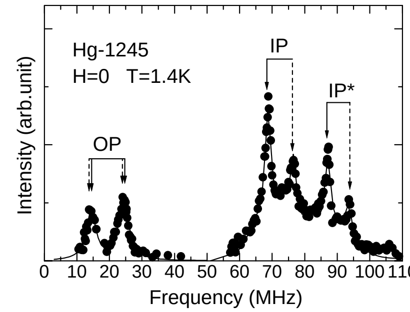

Fig. 2. A zero-field ^{63,65}Cu-NMR spectra at 1.4 K.

3. Summary

We revealed that the optimally-doped OP undergoes the bulk SC transition at $T_c = 108$ K and the strongly underdoped IP's do the AF transition below $T_N \sim 60$ K in $HgBa_2Ca_4Cu_5O_y$. The AF spin polarization at the IP is found to induce an internal field at the OP. It is an interesting issue to address how the alternate stacking of two disparate electron phases can keep a high value of $T_c \sim 108$ K.

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