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Unusual magnetic and superconducting characteristics in multilayered high-$T_c$ cuprates: $^{63}$Cu NMR study


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We report unusual magnetic and superconducting (SC) characteristics in multilayered CuO$_2$ planes in Hg- and Cu-based high-$T_c$ cuprates through the $^{63}$Cu-NMR measurements. These compounds, in which the number of CuO$_2$ planes ($n$) ranges from 3 to 5 in a unit cell, include crystallographically inequivalent outer (OP) and inner (IP) CuO$_2$ planes that are surrounded by pyramidal and square oxygen, respectively. The Knight shift ($^6$K) at the OP and IP exhibits respective characteristic temperature dependence, consistent with its own doping level. Using an experimental relation between the spin part in $^6$K at room temperature and the doping level in a CuO$_2$ layer $N_h$, we show that $N_h$(OP) at the OP is larger than $N_h$(IP) at the IP for all the systems and its difference $\Delta N_h=N_h$(OP)$-N_h$(IP) increases as either a total carrier content $\delta$ or $n$ increases. At $\Delta N_h$'s exceeding a critical value, the pseudogap behavior in the normal state is seen alone at the IP, and a bulk SC transition does not set in simultaneously at the IP and OP. A SC nature at the OP becomes consistent with its own doping level in a CuO$_2$ layer. The former and latter are associated with an increase in $\Delta N_h$. It is a rather remarkable aspect that a $T_c$ is not always reduced even though these multilayered high-$T_c$ compounds are heavily overdoped. This arises, we show, because the IP remains underdoped and keeps a high value of $T_c$, while the OP is predominantly overdoped. This may be a microscopic origin for the lowest anisotropic SC characteristics reported to date in Cu-based multilayered high-$T_c$ compounds.

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I. INTRODUCTION

Extensive investigations have recently been made on various multilayered high-$T_c$ cuprates that include three or more CuO$_2$ layers in a unit cell. Their superconducting (SC) characteristics have been reported to depend closely on the doping level in the CuO$_2$ layer $N_h$ and on the number of CuO$_2$ planes $n$ per unit cell. In most of high-$T_c$ compounds, $T_c$ varies as a bell-shaped curve with $N_h$ and exhibits a maximum value $T_{c,max}$ at $N_h$(optimum)$\sim$0.2. In (Cu,C)Ba$_2$Ca$_2$Cu$_3$O$_{10+y}$ ($n=4$ Cu1234), however, $T_c$=117 K was reported to be almost independent of the doping level even though in the heavily overdoped region. This feature is believed to lead to the lowest anisotropic SC characteristics reported to date that is promising for an application use. It is an unsettled issue why a $T_{c,max}$ increases monotonically with increasing $n$, but saturates at either $n=3$ or 4, which is suggested to be the optimum number of $n$ that maximizes $T_c$. A cause for the suppression in $T_{c,max}$ for $n\sim$4 is not fully understood yet.

In mono-layered or bi-layered CuO$_2$ planes, $N_h$ is uniform at the crystallographically equivalent CuO$_2$ planes. This is, however, not the case in multilayered compounds for $n\sim$3 in which there exist crystallographically inequivalent outer (OP) and inner (IP) CuO$_2$ planes. The former and latter are characterized by a pyramidal (five) and a square (four) oxygen coordination, respectively. Extensive NMR studies suggested that respective local doping levels $N_h$(OP) and $N_h$(IP) differ at the IP and OP. Their $T$ variations of $1/T_1$ and Knight shift were confirmed to be the same. On the other hand, as a difference $\Delta N_h=N_h$(OP)$-N_h$(IP) becomes larger, disparate SC and magnetic behaviors were reported at the OP and IP for an overdoped Cu1234 ($n=4$). Namely, the normal-state magnetic behaviors for the IP and OP are characteristic of underdoped and overdoped compounds, respectively. An SC gap fully develops at the IP below $T_c$=117 K, but it increases gradually and linearly at the OP down to $T_c=60$ K. Thus, it was recognized that the SC and magnetic properties in multilayered compounds are intimately affected by a possible variation in $N_h$(IP) and $N_h$(OP) as well as by a total doping level per unit cell $\delta$.

In this paper, we report extensive $^{63}$Cu-Knight shift $^6$K measurements on two series of multilayered compounds, HgBa$_2$Cu$_{3n-1}$Cu$_n$O$_{2n+2+y}$ and CuBa$_2$Ca$_{n-1}$Cu$_n$O$_{2n+4-y}$ with $n=3$, 4 and 5 and different hole content $\delta$. The $^6$K at the IP and OP exhibits respective characteristic temperature dependence, consistent with its own doping level. Local doping levels $N_h$(IP) and $N_h$(OP) at the IP and OP are separately extracted from the spin part in $^{63}$Cu-Knight shift, $K_s$(RT) at room temperature (RT). We remark that the highest $T_c$=133 K to date in Hg1223 ($n=3$) is because both the IP and OP are nearly optimally doped. $N_h$(OP) is shown to increase predominantly, whereas $N_h$(IP) remains in an underdoped region, when either $n$ or $\delta$ increases. As a difference $\Delta N_h=N_h$(OP)$-N_h$(IP) increases, disparate magnetic and SC behaviors are found at the IP and OP such that the pseudogap behavior is seen alone at the IP, and a bulk SC transition does not set in simultaneously at the IP and OP.
The SC nature at the OP becomes consistent with a mean-field behavior only below $T_{c2}$ that is significantly lower than $T_c$. It is a notable aspect that $T_c$ is not reduced even though these multilayered high-$T_c$ compounds are heavily overdoped.\textsuperscript{1} We remark that this arises because the IP remains underdoped and keeps a high value of $T_c$, even though the OP is predominantly overdoped.

### II. EXPERIMENTAL RESULTS AND DISCUSSION

All the multilayered compounds used in this study were prepared by a high-pressure synthesis technique as described elsewhere.\textsuperscript{12} Crystal structures and lattice parameters are reported to be nearly the same in these Hg- and Cu-based compounds.\textsuperscript{13–15} Powder x-ray diffraction experiment confirmed that the samples consist of almost a single phase.\textsuperscript{12} A SC transition temperature, $T_c$, was determined at an onset temperature below which diamagnetic signal appears in dc susceptibility. The $T_c$ of all the samples is listed in Table I. For NMR measurements, the powder samples, which were aligned along the $c$ axis at an external magnetic field of $H = 16$ T, were fixed with the stycast 1266 epoxy. The NMR experiments were performed by the conventional spin-echo method at 174.2 MHz ($H \sim 15.3$ T) and a $T$ range of 4.2–300 K.

Figure 1 indicates typical NMR spectra for the central transition $(1/2\rightarrow -1/2)$ in a series of (Cu,C)Ba$_2$Ca$_{n-1}$Cu$_n$O$_{2n+4-y}$ with $n = 3$, 4 and 5. All the spectra consist of well separated two peaks. Since the relative intensity after $T_2$ correction of the sharper peak increases with increasing IP layers, the sharper low-field peak and the broader high-field peak are assigned to come from the IP and OP, respectively. This assignment is consistent with the previously reported three-layer Tl$_2$Ba$_2$Ca$_2$Cu$_3$O$_{10}$ (Tl2223) where the intensity of the broader and low-field peak is exactly twice of that for the sharper and high-field peak.\textsuperscript{7} The fact that the spectral width is much narrower for the IP than for the OP reveals that some disorder is smaller at the IP than at the OP. This may be because the IP is far from the charge-reservoir layer where some randomness is introduced due to doping holes.

In general, the observed Knight shift, $K(T)$ consists of a $T$-independent orbital part $K_{orb}$, and a $T$-dependent spin part $K_s(T)$ that is proportional to the uniform susceptibility $\chi_s$. Taking into account that $K(T)$ is anisotropic, it is expressed

![Figure 1](image-url)

**FIG. 1.** $^{63}$Cu-NMR spectra at $H \parallel c$ axis and $T = 160$ K for $n = 3$ Cu1223, $n = 4$ Cu1234, and $n = 5$ Cu1245. Here $n$ is the number of CuO$_2$ planes. A sharp peak at a high-field side comes from the IP, whereas a broad one at a low-field side from the OP. Here the IP and OP are the inner and outer CuO$_2$ plane, respectively, as indicated in the inset.
as $K_n(T) = K_{a}(T) + K_{orb,a}(a=ab$ and $c)$. The $K_n(T)$ in underdoped compounds decreases with decreasing $T$ due to both effects of the development of antiferromagnetic spin correlations and the opening of pseudogap. On the other hand, $K_n(T)$ in the overdoped ones is nearly $T$ independent. It is noteworthy that $K_n(RT)$ at RT increases as $N_h$ increases in high-$T_c$ compounds.

Figures 2(a) and 2(c) show the $T$ dependence of $K_{n,ab}(T)$ at $H_{ab}$ plane for HgBa$_2$Ca$_2$Cu$_3$O$_{6.15+y}$ ($n=3$ Hg1223), and Figs. 2(b) and 2(d) for (Cu,C)Ba$_2$Ca$_2$Cu$_3$O$_{10-y}$ ($n=3$ Cu1223). Here all the doping levels are different. These compounds include one IP and two OP’s. Respectable Figs. 3(e), 3(f), and 3(g) indicate the $K_{n,ab}(T)$’s for HgBa$_2$Ca$_2$Cu$_3$O$_{10+y}$ ($n=4$ Hg1234), (Cu,Ni)Ba$_2$Ca$_2$Cu$_3$O$_{12-y}$, and (Cu,C)Ba$_2$Ca$_2$Cu$_3$O$_{12-y}$ ($n=4$ Cu1234) that include two IP’s and OP’s. Figure 3(h) indicates the $K_{n,ab}$ for (Cu,C)Ba$_2$Ca$_2$Cu$_5$O$_{14-y}$ ($n=5$ Cu1245) that includes two OP’s and three IP’s. The respective data in Figs. 2(a) and 2(c) are cited from the paper reported by Julien et al. In all the compounds, it is evident that $K_{a}(T)$ is larger for the OP than for the IP. In the $n=3$ Hg1223 [see Fig. 2(a)] and $n=4$ Hg1234 [see Fig. 3(e)], since the $K_{a}(T)$’s at the OP and IP decrease with decreasing $T$, both the IP and OP are expected to be underdoped. By contrast, in the $n=4$ Cu1234 [see Figs. 3(f) and 3(g)] and $n=5$ Cu1245 [see Fig. 3(h)], the $K_{n,ab}$ at the IP decreases with decreasing $T$, whereas the $K_{n,ab}$ at the OP that is largely enhanced is nearly $T$ independent down to $T_c$. This evidences that the OP is heavily overdoped, but the IP remains underdoped.

In order to see in detail the $T$ dependence of $K_{n,ab}$ below $T_c$ from Figs. 2(a–d) and 3(e–h), its $T$-derivative value $dK_{n,ab}(T)/dT$ for $n=3, 4$ and 5 compounds [see (a)–(h) in Table I]. The dotted line (arrow) shows $T_c$ ($t_a$). The solid arrow shows bulk $T_c$.

![FIG. 2. The $T$ dependence of the spin part in the $^{63}$Cu Knight shift $K_{a}(T)$ at $H_{c}c$ axis for the $n=3$ compounds with various doping levels [see (a)–(d) in Table I].](image1)

![FIG. 3. The $T$ dependence of $K_{n,ab}(T)$ for the $n=4$ and 5 compounds with various doping levels [see (e)–(h) in Table I].](image2)
an experimental relation of $N_h = 0.0462 + 0.502K_{s,ab}(RT)$. Note that the relation seen in Fig. 5 is valid irrespective of whether the CuO$_2$ plane is surrounded by the pyramidal or octahedral oxygen coordination.

Using this relation, we estimate $N_h$(OP) and $N_h$(IP) from the measured $K_{s,ab}(RT)'s$ that are presented in Figs. 2 and 3. Thus estimated values are indicated in Table I. Here we have assumed that the hyperfine coupling constant is independent of IP or OP, which was actually confirmed in three-layered Tl2223. Note that a total carrier content $\delta = (n - 2)N_h$(IP) + $2N_h$(OP) in a unit cell. In Fig. 6, $N_h$(OP), $N_h$(IP) and its difference $\Delta N_h = N_h$(OP) − $N_h$(IP) are plotted against an averaged hole content per a layer, $\delta_{av} = \delta/n$. In all the compounds, it is remarkable that $N_h$(OP) is larger than $N_h$(IP). Both $N_h$(OP) and $N_h$(IP) increase linearly with $\delta_{av}$. $\Delta N_h$ increases as $\delta$ or $n$ increases.

The present result on a systematic variation in $N_h$(OP) and $N_h$(IP) indicated in Fig. 6 is in good agreement with the theoretical prediction.\(^\text{19,20}\) For multilayered high-$T_c$ cuprates, Di Stasio et al. argued a carrier distribution at each CuO$_2$ plane by using a sheet-charge model that assumes two-dimensional sheets of charge.\(^\text{19}\) Alternatively, Haines and Tallon modified the former model to a point-charge model, in which the sheet charge electrostatic term is replaced by a Madelung energy.\(^\text{20}\) In both the models, a carrier distribution at each plane was calculated so as to minimize a total carrier energy expressed by a sum of band energy and electrostatic energy. Consequently, both the models showed that $\Delta N_h$ increases with increasing either $\delta$ or $n$, consistent with the present experiment. Considering an ionic configuration around the IP and OP, we may remark that the apical oxygen O$^{2-}$ that is close to the OP lowers electrostatic energy for holes presenting at the OP than at the IP. As $n$ increases, a distance between the IP and the apical oxygen becomes larger, and then their difference of electrostatic energy is enhanced, making $\Delta N_h$ increase.\(^\text{21}\)

As $\Delta N_h$ increases, it is evident that the IP and OP reveal the disparate SC and magnetic behaviors. For $\Delta N_h \approx \sim 0.07$, $T_c$, and $T^*$ are uniquely determined as seen in Figs. 4(a–e), but for $\sim 0.07 \leq \Delta N_h$, $T^*$ exists only for the IP and the SC gap at the OP begins to develop gradually below $T_c$ and follows the BCS mean-field behavior of $T$ dependence just below $T_{c2}$ that is far below the bulk $T_c$. These results suggest that either a magnetic or an electronic interlayer coupling between the IP and OP for $n \approx 4$ becomes progressively weaker as $\Delta N_h$ increases. Once $\Delta N_h$ exceeds a critical value of $\sim 0.07$, both the SC and magnetic properties are governed by the respective value of $N_h$(IP) and $N_h$(OP) that are underdoped and heavily overdoped, respectively.

Finally, we comment on a systematic variation in $T_{c}$ in the multilayered high-$T_c$ cuprates. In most of high-$T_c$ cuprates, it is known that $T_{c}$ for the $n = 1$ and $n = 2$ compounds reaches a maximum value around an optimum $N_h$(optimum) $\sim 0.2$. For the $n = 3$, 4, and 5 compounds, it is, however, hard that both the OP and IP are optimally doped because the electrostatic energy that is mainly generated by the apical oxygen is lower at the OP than at the IP. In the $n = 3$ Hg1223, $T_{c} = 133$ K was reported to exhibit the highest $T_{c}$ to date. In this compound, it is noteworthy that $N_h$(IP) $\sim 0.2$ is just optimized and $N_h$(OP) $\sim 0.25$ is comparable to $N_h$(optimum) as shown in Fig. 6. This suggests that the highest value in $T_{c}$ to date is because the IP is optimally doped. This may be because the disorder at the IP is relatively small as seen in Fig. 1 and the plane is flatter than the...
OP.\textsuperscript{13–15} It would be expected that its $T_c$ increases further, reaching a record of high $T_c$, if $N_h$(OP) were reduced to $\sim$ 0.2. In the $n = 4$ Hg1234 where the OP and IP reveal the similar SC and magnetic behaviors as seen in Fig. 4(e), its $T_c$ = 123 K is relatively higher than in Cu1234 [see Fig. 4(f)]. This is because a large decrease in doping level between the IP and OP makes an interlayer coupling weaker in the latter. We suggest that a large $\Delta N_h$ reduces a bulk $T_c$. We propose that (i) an optimum hole doping at the IP and (ii) a decrease in $\Delta N_h$ are important factors for obtaining a further high $T_c$ in multilayered cuprates.

### III. Conclusion

In summary, we have studied through the $^{63}$Cu Knight-shift measurements the magnetic and SC characteristics in the multilayered high-$T_c$ cuprates, HgBa$_2$Ca$_{n-1}$Cu$_n$O$_{2n+2+y}$ and CuBa$_2$Ca$_{n-1}$Cu$_n$O$_{2n+4-y}$. Here the number of CuO$_2$ planes $n$ ranges from $n = 3$ to 5 and a total doping level $\delta$ varies from under- to over-doped region. Local doping levels $N_h$(IP) and $N_h$(OP) at the IP and OP have been separately extracted from the spin part in $^{63}$Cu-Knight shift $K_s$(RT) at room temperature. The highest $T_c$ = 133 K to date in Hg123 ($n = 3$) was shown to arise because both the OP and IP are nearly optimally doped. As either $\delta$ or $n$ increases, the OP is predominantly overdoped, whereas the IP remains underdoped. As a difference $\Delta N_h = N_h$(OP) $-$ $N_h$(IP) increases, the disparate magnetic and SC behaviors were found at the IP and OP such that the pseudogap behavior is seen alone at the IP, and a bulk SC transition does not set in simultaneously at the OP and IP. The energy gap at the OP seems to develop following the BCS mean-field type of $T$ dependence below $T_c$ that is significantly lower than $T_c$. A $T_c$ is not reduced even though these multilayered high-$T_c$ compounds are heavily overdoped,\textsuperscript{1} because the OP remains underdoped and keeps a high value of $T_c$, while the OP is heavily overdoped. This may be a microscopic origin for the lowest anisotropic SC characteristics ($\gamma \sim 1.4$) reported to date in Cu-based multilayered high-$T_c$ compounds.\textsuperscript{2} We propose that a homogeneous carrier distribution over all the CuO$_2$ planes is one of most important conditions to raise $T_c$, and to realize this, it may be efficient to reduce any difference in the electrostatic energy between the IP and OP. In this context, a replacement of the apical O$^{-2}$ by F$^{-1}$ is promising in reducing it as actually realized in the Ba$_2$Ca$_3$Cu$_4$O$_{10-\delta}$F$_\delta$ system.\textsuperscript{22} This study is now underway.

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\textsuperscript{22}A. Iyo, K. Tokiwa, and H. Ihara (private communication).