Field-Induced Uniform Antiferromagnetic Order Associated with Superconductivity in Pr$_{1-x}$LaCe$_x$CuO$_{4-\delta}$

Ryosuke KADONO*, Kazuki OHISHI†, Akihiro KODA, Shanta R. SAHA‡, Wataru HIGEMOTO†, Masaki FUJITA§ and Kazuyoshi YAMADA‡

Institute of Materials Structure Science, High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305-0801
†Advanced Science Research Center, Japan Atomic Energy Research Institute, Tokai, Naka, Ibaraki 319-1195
‡Institute for Materials Research, Tohoku University, Sendai 980-8577

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Strong correlation between field-induced antiferromagnetic (AF) order and superconductivity is demonstrated for an electron-doped cuprate superconductor, Pr$_{1-x}$LaCe$_x$CuO$_{4-\delta}$ (PLCCO). In addition to the specimen with $x = 0.11$ (which is close to the AF phase boundary, $x \simeq 0.10$), we show that the one with $x = 0.15$ ($T_c \simeq 16$ K at zero field) also exhibits the field-induced AF order with a reduced magnitude of the induced moment. The uniform muon Knight shift at a low magnetic field ($\sim 10^6$ Oe) indicates that the AF order is not localized within the cores of flux lines, which is in a marked contrast with theoretical prediction for hole-doped cuprates. The presence of anomalous non-diagonal hyperfine coupling between muons and Pr ions is also demonstrated in detail.

KEYWORDS: electron-doped cuprates, superconductivity, magnetism, $\mu$SR

1. Introduction

The question whether or not the mechanism of superconductivity in electron-doped ($n$-type) cuprates is common to that in hole-doped ($p$-type) cuprates is one of the most interesting issues in the field of cuprate superconductors, which is yet to be answered. Theoretically, in the single band models such as the Hubbard model or $t$-$J$ model, the electronic state of a hole on the CuO$_2$ plane ($3d^9\overline{L}$) is approximated by the Zhang-Rice singlet between a local Cu$^{2+}$ spin and the hole on the oxygen atoms, which is projected to the state of a spinless hole ($3d^8$) on the copper ions. This approximation makes the electronic state of holes and electrons virtually equivalent between $p$-type and $n$-type cuprates, leading to the prediction of “electron-hole symmetry”. In reality, there is a limited number of compounds known to date as $n$-type, among which those belonging to the $T^*$ phase, represented by Nd$_{2-x}$Ce$_x$CuO$_4$ (NCCO), have been most actively studied. The $T^*$ structure is similar to that of the T phase represented by La$_{2-x}$Sr$_x$CuO$_4$ (with reconfiguration of oxygen atoms) and thereby the latter is regarded as the $p$-type partner. Experimentally, it has been known for decades that the magnetic phase diagram as a function of doping exhibits significant electron-hole asymmetry between those two classes; while the antiferromagnetic (AF) order is strongly suppressed by small amount ($x \leq 0.06$) of doping in $p$-type La$_{2-x}$Sr$_x$CuO$_4$, the AF phase dominates over a wide region of doping (e.g., $0 \leq x \leq 0.14$ in NCCO), sharing a boundary with the superconducting phase. In view of the $t$-$J$ model, it is argued that this asymmetry can be understood by considering the difference in the actual electronic state in such a way that the higher order hopping (transfer) terms are introduced to the original models.

However, the recent observation of superconductivity in a new class of $T^*$ compounds, La$_{2-x}$RE$_x$CuO$_4$ ($RE = $ Sm, Eu, etc., $T_c = 21$–25 K) suggests that there might be no such symmetry between $p$-type and $n$-type cuprates. The new $T^*$ phase compound exhibits superconductivity without carrier doping (both rare earth and La ions are trivalent), which leads to a speculation that it might not be crucial to have the AF insulator phase as a basis in modeling the $n$-type cuprates. Since the presence of the AF insulator (or, the Mott insulator) phase is presumed to be an essential feature of $p$-type cuprates in a certain class of theoretical models, the absence of the electron-hole symmetry would be a sign that the $n$-type cuprates may have their own mechanism for superconductivity independent of the $p$-type partners. As a matter of fact, there is increasing number of experimental evidence that they are different in many respects. For example, the resistivity ($\rho$) in the normal state of $n$-type cuprates follows a quadratic temperature dependence ($\rho \propto T^2$) which is common to ordinary metals, whereas a linear dependence is observed in optimally doped $p$-type cuprates. This is further supported by the recent NMR study of an $n$-type cuprate, Pr$_{1-x}$LaCe$_x$CuO$_{4-\delta}$ (PLCCO, $x = 0.09$), where the metallic Korringa law is observed upon the removal of superconductivity by applying an external magnetic field above the upper critical field ($H_{c2} \simeq 50$ kOe). Besides these, a commensurate spin fluctuation is observed in the superconducting state of an $n$-type cuprate, which is in marked contrast with the incommensurate spin fluctuation commonly found in $p$-type cuprates.

The response to the external magnetic field is another potential clue to understand the ground state property of cuprates which are typical type II superconductors. They fall into a flux line lattice (FLL) state under a magnetic field (> $H_{c1}$, the lower critical field), where the superconducting order parameter is locally suppressed in the center of flux (vortex cores). In such a situation, the $t$-$J$ model pre-
dicts that the local carrier density would be partially proportional to the order parameter so that the quasi-stationary AF correlation may develop in the vortex cores. A similar tendency is also predicted by the Hubbard model or that based on SU(5) symmetry. Interestingly, the recovery of quasi-stationary AF state under a moderate magnetic field has been reported to occur in a whole variety of $p$-type cuprates including La$_{2-x}$Sr$_x$CuO$_4$ (LSCO), YBa$_2$Cu$_3$O$_{7-\delta}$ (YBCO), YBa$_2$Cu$_3$O$_6$ (Y$_{1248}$), and Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (BSCCO). The primary issue in those results is whether or not the field-induced AF state is localized in the vortex cores. In this regard, while neutron diffraction is not sensitive to the local structure over such a large length scale (vortices with a core size of $\sim 10^2$ Å, separated by $10^2$–$10^3$ Å), local spin probes like nuclear magnetic resonance (NMR) and muon spin rotation ($\mu$SR) are sensitive to the local modulation of internal fields induced by the AF cores. Indeed, although the case is not strong, there is certain evidence that such AF vortex cores may be realized.

In this paper, we present detailed report on the field-induced antiferromagnetism in an $n$-type cuprate, Pr$_{1-x}$LaCe$_x$CuO$_{4-\delta}$, probed by $\mu$SR. A part of the work on a specimen with $x = 0.11$ ($T_c \approx 26$ K) has been reported in the earlier paper, where we demonstrated that the response to external field is markedly different from that found in $p$-type cuprates; it is characterized by a uniform shift ($\Delta B \sim 10$ Oe) of the internal field under an extremely low external magnetic field ($\sim 10^2$ Oe). More interestingly, $\Delta B$ exhibits unambiguous correlation with the occurrence of superconductivity; it develops only below $T_c$ with an external field lower than $\sim 40$ kOe. Here, we report new result on the specimen with $x = 0.15$ ($T_c \approx 16$ K) which is situated deep in the superconducting phase from the phase boundary to the AF phase ($x \approx 0.10$). While the observed response to the external field is quite similar to that for $x = 0.11$, the magnitude of the effect is considerably reduced. These observations suggest that the field-induced AF correlation coexists microscopically with superconductivity in PLCCO.

As demonstrated earlier in the specimen with $x = 0.11$, the presence of non-diagonal hyperfine (HF) coupling parameter is confirmed in the new specimen by the muon Knight shift and susceptibility measurements with both field parallel and perpendicular to the $ab$-plane. This establishes that muon probes the in-plane susceptibility of CuO$_2$ planes under a field normal to the planes, where the Pr ions are coupled to the Cu ions by the superexchange interaction and exert local field to muon throughout the non-diagonal HF coupling. Thus, the occurrence of in-plane polarization associated with the field-induced AF phase leads to the shift of the internal field along $c$-axis, which is mediated by the Pr ions. We show that this model provides a consistent account of the field-induced antiferromagnetism of CuO$_2$ planes observed by neutron diffraction in the specimen with $x = 0.11$. The success of the present model strongly suggests that the interpretation of data in the preceding work reporting a similar result in Pr$_{2-x}$Ce$_x$CuO$_{4-\delta}$ is inappropriate, leading to a highly overestimated size of Cu moments in the field-induced AF state.

2. Experimental

Single crystals of PLCCO with sizable dimensions were prepared by the traveling-solvent float zone method to obtain the specimen for $x = 0.11$ ($\delta \approx 0.02$, $T_c \approx 26$ K) and $x = 0.15$ ($\delta \approx 0.05$, $T_c \approx 19$ K), the details of which have already been published elsewhere. A large volume fraction and the sharp onset of Meissner diamagnetism near $T_c$ (see below) demonstrated the high quality of these specimens. The $\mu$SR measurements were conducted on the M15 beamline at TRIUMF, Canada. As illustrated in Fig. 1, a slab of PLCCO crystal (measuring about 5 mm×8 mm×0.5 mm) with the tetragonal $c$-axis perpendicular to the plane of the specimen was loaded onto a He gas-flow cryostat and a magnetic field ($\mathbf{H} = (0, 0, H_z)$) was applied parallel to the $c$-axis (where $z \parallel c$). Additional set of measurements were made on the specimen with $x = 0.15$ under a field parallel to the $ab$-plane. In a transverse field (TF) geometry, the initial muon polarization was perpendicular to $\mathbf{H}$ so that the muon probed the local field $B_z$ by spin precession at a frequency $\gamma_B B_z$ (with $\gamma_B = 13.553$ MHz/kOe being the muon gyromagnetic ratio). Detailed zero-field (ZF) $\mu$SR measurements on the same specimen at various levels of oxygen depletion indicated a weak random magnetism similar to the case of Pr$_{2-x}$Ce$_x$CuO$_{4-\delta}$, which is identified as being due to the small Pr moments.

3. Result and Discussion

3.1 Anomalous Muon-Pr Hyperfine Interaction in PLCCO

The muon hyperfine parameter ($A_\mu$) is deduced from a comparison between the magnetic susceptibility ($\chi$) and the muon Knight shift ($K_\mu$) in the normal state. In the following, we assume that the crystal $c$-axis (= tetragonal axis) is always parallel with the Cartesian $z$-axis, while the $ab$ direction is arbitrarily chosen in the $xy$ plane. Then, provided that the external field is parallel to the $c$-axis, their relation in rare-earth metallic compounds is generally expressed as

$$K_\mu^z \simeq K_0 + A_\mu \chi_c \frac{1}{N_{AB}} = K_0 + (A_c + A_{\text{dip}}^z) \chi_c \frac{1}{N_{AB}},$$

where $K_0$, $A_c$ denote the respective contributions from the $T$-independent Pauli paramagnetism and from the polarization of conduction electrons by the Rudermann-Kittel-Kasuya-Yoshida (RKKY) interaction, $\chi_c$ denotes the susceptibility along the tetragonal axis, $N_A$ is the Avogadro number, $N_B$ is the Bohr magneton, and $A_{\text{dip}}^z$ is the relevant component of the dipole tensor,

$$A_{\text{dip}}^{\alpha \beta} = \sum_i \frac{1}{r_i^3} \left( 3 \alpha \beta_i - \delta_{\alpha \beta} \right) \alpha, \beta = x, y, z,$$

which is predominantly determined by the nearest-neighbor Pr ions (with index $i$) at a distance $r_i = (x_i, y_i, z_i)$ from the muon. Considering the earlier reports that the muon site is crystallographically unique and located near the oxygen atoms midway between the CuO$_2$ planes
contact-type non-diagonal hyperfine interaction, dominant component. Thus, we must introduce a Fermi by eq. (1) with the magnetic dipolar term as the pre-

coupling constants. Meanwhile, our simulation indicates 

dominantly occupied by Pr and La ions, the observed spec-

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two symmetrical satellite peaks with respect

proportional to $\mu_{xy}$, the in-plane Knight shift

is expected to be linear in $\chi_{ab}$, which is in line with eq.(4).

It is inferred from the Fourier analysis of the TF-

$\chi$-plane to reproduce the difference between those two

directions. The $K$-χ plot for $\chi_{ab}$ in Figs. 2(b) and 3(b) exhibits a linear relation with a small offset near the ori-

gin, from which we obtain

$$A^z_\mu = \frac{dK^z_\mu}{d\chi_{ab}} = -1.083(3) \text{kOe}/\mu_B = A_f$$

(7)

The value of $A_f$ is in reasonable agreement with that ob-

ained previously, i.e., $-969(2) \text{Oe}/\mu_B$ in the specimen with

$x = 0.11$. From the comparison with the calculated

value of the dipolar tensor, we have an estimated

size of field-induced Pr moment along the $ab$-axis at 20

Ko. $\mu_p \simeq (A^xy_\mu/A^xy_{\mu B}) \mu_B = 0.26(1)\mu_B$. Here, we note that $\mu_p$ is not a local spin but an effective dipole mo-

ment induced by the mixing of the $^3H_4$ multiplets under

an external field. Thus, it shrinks with decreasing field and thereby it is consistent with the previous observation of fairly small Pr moments inferred from zero field-µSR

study.31

It must be stressed that, while the origin of the above anomalous hyperfine interaction is not clear at this stage, the

diagonal term in eq. (5) plays a key role in probing

the in-plane polarization of Pr ions which are directly coupled to Cu spins in the CuO$_2$ planes. In the following, we propose a mechanism on how the in-plane polarization in the CuO$_2$ planes exerts additional field to muons sitting nearby the Pr ions.

3.2 Field-Induced Antiferromagnetic Order in the Superconducting State

In the flux line lattice state of the type II superconductors, implanted muons provide a random sampling of the spatial field distribution $B(r)$ so that the observed µSR time spectrum is described by a complex polarization

$$P_x(t) + iP_y(t) = \int n(B) \exp(i\gamma_B Bt + \phi) dB,$$

(9)

where $n(B)$ is the spectral density for $B(r)$ characterized by a negatively shifted peak corresponding to the

van Hove singularity, and $\phi$ is the initial phase of muon spin rotation.34 Meanwhile, as shown in Fig. 4, the µSR spectrum at $H_z = 200$ Oe exhibits a large positive shift of the peak frequency in the superconducting state of PLCCO, which is apparently opposite to that associ-

ated with $n(B)$. Such a positive shift, or so-called “paramagnetic Meissner effect”, is occasionally found in the magnetization of granular cuprate superconductors upon

field-cooling (FC) with a small field ($\leq 1$ Oe), which has been interpreted as a manifestation of $d$-wave paring.35

However, as shown in the inset of Fig. 4, the possibility of attributing the observed positive shift to the paramagnetic Meissner effect is ruled out by the magnetic

response observed in both FC and ZFC (zero field-cooling) magnetization measurements; the bulk magnetization exhibits no anomaly to anticipate such a reversed magnetization. The increase in the spin relaxation rate ($\Lambda$) may be understood by considering the inhomogeneous magn-

etic field distribution due to the FLL formation. These observations are common to the case with $x = 0.11$, and similar to what has been observed in Pr$_{2-x}$Ce$_x$CuO$_{4-\delta}$

(PCCO).29
More surprisingly, this additional shift exhibits a strong and non-linear dependence on the external field. The absolute magnitude of the shift, \(\Delta B_z = B^N_0 - B^S_0\) (frequencies divided by \(\gamma_\mu\), is shown in Fig. 5, where \(B^N_0\) and \(B^S_0\) denote the internal field felt by muon at 10 K and at temperatures above \(T_c\), respectively. It exhibits a steep decrease with increasing field, changing its sign to negative above \(\sim 1\) kOe in both cases of \(x = 0.11\) and 0.15. The field dependence of \(\Delta B_z\) below \(\sim 1\) kOe indicates that the change associated with the FLL state is completely masked by the anomalous positive shift. This is also consistent with a large magnetic penetration depth (\(\geq 3400\) Å) reported for PCCO, which would lead to a shift with much smaller amplitude than the observed one (e.g., \(\Delta B_z \sim -1\) Oe at \(H = 200\) Oe). Above \(\sim 2\) kOe, \(\Delta B_z\) is only weakly dependent on the field up to \(\sim 40\) kOe, where the gradual increase of the shift to the negative direction would be attributed to a small contribution of bulk demagnetization effect.

It might be argued that the observed behavior of \(\Delta B_z\) below \(\sim 1\) kOe is qualitatively similar to that reported for PCCO (\(H \leq 2\) kOe). However, while the latter suggests that \(\Delta B_z\) approaches asymptotically to zero at higher fields, our data indicates that there is a change of sign in \(\Delta B_z\); note that the lines in Fig. 5 representing the demagnetization effect do not cross zero when they are extrapolated to lower fields. As discussed below, this is not understood by the simple model proposed for the case of PCCO, but one has to consider a modulation (flip) of the hyperfine field \(A'_z\) induced by the external field. Here, it must be stressed that the hyperfine parameters reported in the previous section is deduced from the data obtained at 20 kOe. Unfortunately, \(K^2_\perp\) in the normal state is too small to be measured at such low fields. Provided that the change is described by the classical Langevin function, the entire field dependence including the flip is described in the following form,

\[
\Delta B_z(H_z) = B^+ \tanh(H_z/H_p) + c_d H_z + B_0, \tag{10}
\]

where \(B^+\) is the additional internal field induced by \(H_z\), \(H_p\) is the characteristic field with which the sign of \(A'_z\) changes, \(c_d\) is the residual demagnetization term, and \(B_0\) is the field offset. The result of fitting analysis using the above equation is shown by solid curves in Fig. 5, where the obtained parameter values are listed in Table I. The model reproduces data for both cases of \(x = 0.11\) and 0.15.

It is interesting to note that, apart from the steep change below \(\sim 2\) kOe attributed to the flip of \(A'_z\), the field dependence of \(\Delta B_z\) for \(x = 0.11\) is quite similar to that of field-induced \(z\)-moment revealed by neutron diffraction; they exhibit least dependence on the field below \(\sim 40\) kOe. This strongly suggests that the parameter \(B^+\) in eq. (10), which represents the amplitude of the internal field felt by muon, is proportional to the \(z\)-moment observed by neutron diffraction. Concerning the neutron result, one may recall vigorous debate on the origin of field-induced effect observed in NCCO, whether it is due to impurity phases or intrinsic to the CuO2 plane. In PLCCO, the possible contribution of impurity phases (Pr,Ce,La)2O3 has been investigated by the recent neutron diffraction experiment and they found no such effect below 70 kOe. It is known in PLCCO that the Cu spins have a non-collinear AF structure, lying within the ab-plane. Provided that the field-induced AF phase has the same non-collinear structure, the \(c\)-axis component of the dipolar field from the \(z\)-moments would be zero. Note, however, that this does not mean null shift, because the muon precession frequency is determined by the vector-sum of dipolar fields, so that the additional field along the \(ab\) plane, \(B_{xy}\), leads to a shift

\[
\Delta B = \sqrt{H_z^2 + H_{xy}^2} - H_z. \tag{11}
\]

Thus, one of the simplest models to explain the positive shift at a low external field is to consider the effect of dipolar fields along the \(ab\) plane. In the case of PLCCO, the in-plane component of the dipolar field has two possible values, \(|B_{xy}| \approx 784\) Oe/\(\mu_B\) or 365 Oe/\(\mu_B\) (depending on the relative order of moments between two CuO2 layers). In order to explain the shift of \(\sim 10\) Oe at \(H_z = 200\) Oe for \(x = 0.11\), we have to assume \(|B_{xy}| \approx 64\) Oe corresponding to the Cu moment size of \(0.1-0.2\) \(\mu_B\). Unfortunately, this is obviously too large to be reconciled with the result of neutron diffraction, where the moment size of Cu ions induced by the external field is estimated as \(\sim 10^{-2}\) \(\mu_B\). Moreover, as pointed out earlier, it does not explain the change in the sign of shift observed at higher fields. Therefore, it is unlikely that the Cu moments directly contribute to \(\Delta B_z\), in contrast to what has been suggested for the case of PCCO. On the other hand, it is inferred from neutron diffraction studies that there is a strong superexchange coupling between Cu and Pr ions in \(R_2CuO_4\) (\(R = Nd, Pr\)). More specifically, about 0.08 \(\mu_B\) of Pr moments is known to be induced by Cu moments with 0.4 \(\mu_B\) in \(Pr_2CuO_4\), having a non-collinear spin structure in both sublattices. In a mean-field treatment, the Cu ions exert an effective magnetic field on the Pr ions so that the moment size of the Pr ions is proportional to that of Cu ions, namely,

\[
\langle M_{Pr}\rangle \sim \chi_{ab}J\langle M_{Cu}(H_z)\rangle, \tag{12}
\]

where \(J\) is the Cu\(^{2+}\)–Pr interaction energy and \(\langle M_{Cu}(H_z)\rangle\) is the field-induced Cu moments. This would lead to an additional field at the muon site,

\[
\Delta B_z(Pr) \simeq A_f(H_z)\langle M_{Pr}\rangle, \tag{13}
\]

\[
A_f(H_z) \simeq A_f^0 \tanh(H_z/H_p). \tag{14}
\]

Thus, \(\Delta B_z(Pr)\) is induced by Cu ions which are polarized by an external field in the superconducting phase. Here, it is obvious that the presence of non-diagonal hyperfine coupling \(A_f\) between muons and Pr ions plays a key role. It serves as a mediator between the in-plane polarization of Pr ions and the hyperfine field along the c-axis on the nearby muons. Provided that the magnitude of \(A_f\) at lower fields is close to that determined at 20 kOe (\(\approx 1\) kOe/\(\mu_B\)), our estimation indicates that about 0.01\(\mu_B\) of Pr moments, which may be induced by \(\sim 0.05\mu_B\) of Cu moments, is sufficient to account for the amplitude of
$\Delta B_z$ in the specimen with $x = 0.11$. A similar estimation yields $\sim 0.02 \mu_B$ of Cu moments for $x = 0.15$. It would be due to this small moment size that the neutron diffraction were unsuccessful to detect the field-induced AF phase for the latter case.\textsuperscript{28}

We would like to stress that the $\mu$SR results in the FLL state of $n$-type cuprates (including those in PCCO) are qualitatively different from those obtained by similar techniques for the case of $p$-type cuprates in two aspects. First of all, the effect of superconducting phase manifests itself in the well-defined frequency shift, whereas it is traceable only as an enhancement of spin relaxation\textsuperscript{22, 23, 25} or the change in the specific part of the field profile related to vortex cores\textsuperscript{21, 24} in $p$-type cuprates. This indicates that the induced polarization of Cu ions in $n$-type cuprates is quite uniform over the entire volume of the specimen, while it might be localized in the vortex core region in $p$-type cuprates. Secondly, the effect is highly nonlinear to the external field, as demonstrated by the fact that the strong influence of superconducting phase is observed at an external field as low as $10^2$ Oe where the density of magnetic vortices is very small (their distance being $\sim 4 \times 10^3$ Å). Considering that most of the implanted muons are probing the region outside the vortex cores in the specimen at this low field range, we conclude that the origin of the enhanced frequency shift in the superconducting phase is not confined in the vortex cores. In addition to the case of $x = 0.11$,\textsuperscript{27} the new result in the specimen with $x = 0.15$ confirms that the small polarization of Pr ions (and of Cu ions) is present over the entire volume of the specimen under an external field, which on the other hand suggests that the AF correlation becomes weak with increasing $x$. We emphasize that this is the most important finding of the present work, since it is only the local probes such as $\mu$SR that can investigate the homogeneity of the magnetic order in such a length scale.

As mentioned earlier, the theoretical models based on the strong electronic correlation (e.g., the t-J model\textsuperscript{15} or Hubbard model plus superconducting correlation\textsuperscript{16}) predict that the AF correlation tends to precipitate in the vortex cores in the FLL state. The present result indicates that such situation is not realized in PLCCO, as demonstrated by the data at 200 Oe where the contribution of vortex cores is negligible. On the other hand, it might be in favor of the quantum critical point scenario in understanding the competition between AF and superconducting phases.\textsuperscript{43} The observed effect in PLCCO might be understood by assuming that a parameter controlling the quantum criticality between the AF and superconducting phase is extremely sensitive to magnetic field. Considering the step-like response of CuO$_2$ planes to a magnetic field, developing exclusively in the superconducting state, will provide a strong criterion for identifying the true electronic ground state of $n$-type cuprates.

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Table 1. Fitting parameters obtained by analyzing data shown in Fig. 5 using eq. (10).

| x   | $B^x$ (Oe) | $H_p$ (kOe) | $c_d$ | $B_0$ (Oe) |
|-----|------------|-------------|-------|------------|
| 0.11| -9.6(2)    | 1.04(3)     | -0.13(2) | 6.9(2)     |
| 0.15| -3.6(1)    | 0.80(4)     | -0.059(9) | 2.74(9)    |

Fig. 1. A schematic view of experimental set-up around the specimen for TF-$\mu$SR measurement, where $P_\mu$ is the initial muon polarization and $H_z$ is the external magnetic field. The veto counter is used to eliminate background signals from muons which missed the specimen. Four positron counters are placed inside the cryostat to minimize the positron path, which is crucial to attain a high time resolution.
Fig. 2. (a) The muon Knight shift with $H$ parallel to the $c$-axis, where the solid curve is proportional to $\chi_{ab}$. (b) $K-\chi$ plot for the central frequency shown in (a). Inset: magnetic susceptibility vs temperature at $H=20$ kOe applied parallel ($\chi_c$) or perpendicular ($\chi_{ab}$) to the $c$-axis.

Fig. 3. (a) The muon Knight shift with $H$ parallel to the $ab$-plane, where the solid curve is proportional to $\chi_{ab}$. (b) $K-\chi$ plot for the central frequency shown in (a).
Fig. 4. Temperature dependence of the muon precession frequency (a) and transverse spin relaxation rate (b) at $H_z = 200$ Oe (where $T_c \approx 16$ K).

Fig. 5. Magnetic field dependence of the additional shift in the superconducting state, where $B_{S0}^N$ and $B_{N0}^N$ correspond to the internal field at 10 K and 35–40 K, respectively. Solid curve is a fitting result by the model described in the text.