Superconducting anisotropy in the electron-doped high-$T_c$ superconductors Pr$_{2-x}$Ce$_x$CuO$_{4-y}$

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Abstract

We report superconducting anisotropy measurements in the electron-doped high-$T_c$ superconductors (HTSCs) Pr$_{2-x}$Ce$_x$CuO$_{4-y}$ (PCCO, $x = 0.15$ and 0.17) with an applied magnetic field ($H_0$) up to 28 T. Our results show that the upper critical field [$H_{c2}(T)$] of PCCO is highly anisotropic and as the temperature $T \to 0$, the value of it at $H_0 \parallel c$ [$H_{c2,\parallel}(0)$] is far less than the Pauli limit. The low temperature anisotropic character of PCCO is found to be rather similar to that of hole-doped cuprate HTSCs, but apparently larger than that of typical Fe-based superconductors. This study also proves a new sensitive probe of detecting rich properties of unconventional superconductors with the use of the resonant frequency of an NMR probe circuit.

Keywords: upper critical field, superconductivity, anisotropy, superconductors, high-$T_c$

(Some figures may appear in colour only in the online journal)

1. Introduction

The determination of superconducting anisotropy with the values of upper critical field ($H_{c2}$), coherence length ($\xi$, $\sim$ vortex core diameter) and penetration depth ($\lambda$) that characterize the superconducting state of high-$T_c$ superconductors (HTSCs), including the electron-doped cuprate superconductors, is crucial for the understanding of high-$T_c$ superconductivity. The superconducting anisotropy coupled with short coherence length in hole-doped high-$T_c$ cuprates gives rise to a complex mean-field field-temperature ($H - T$) phase diagram [1–3], which has a $H_{c2}(T)$ line separating the normal state from a mixed superconducting phase that includes a vortex liquid (reversible) and a vortex solid (lattice or glass, irreversible) with a penetrating magnetic field. These observations have been largely reported by the measurements of dc magnetic susceptibility on hole-doped La$_{2-x}$Ba$_x$CuO$_4$ [2, 4] current-voltage ($I$–$V$) on Y$_1$Ba$_2$Cu$_3$O$_{7-x}$ [2, 5] and magnetoresistance on electron-doped cuprate $R_{1.85}$Ce$_{0.15}$CuO$_{4-x}$ ($R = \text{Nd, Sm, Pr}$) [6–8] Fe-based superconductors K$_x$Fe$_2$Se$_2$ [9] LaFeAsO$_{1-x}$F$_{1-x}$ [10] and many other type-II superconductors [11–14].

Recent studies show that the superconducting anisotropy in the hole-doped cuprates Y$_1$Ba$_2$Cu$_3$O$_{7-x}$ [15–17] and La$_{2-x}$Eu$_x$Sr$_x$CuO$_4$ [16] is rather large and has a significant doping and/or in-plane field dependence, while the anisotropy in the Fe-based superconductors is generally smaller at low temperatures but has a rather strong temperature dependence. [18, 19] However, it is not clear for the electron-doped cuprate superconductors as very few of them were reported. [6, 8, 20]

On the other hand, controversy and inaccuracy exists [21] for the measurements of the superconducting anisotropy due
to the limitations of the techniques used for the measurements, the requirement of high magnetic field and the methods used to extract the values of $H_{c2,\perp}(T)$ and $H_{c2,\parallel}(T)$ [here $H_{c2,\perp}(T)$ and $H_{c2,\parallel}(T)$ are the values of $H_{c2}(T)$ with the magnetic field ($H_0$) applied at $H_0 \perp c$ and $\parallel c$, respectively, 1, etc.]

Conventional techniques for measuring the superconducting anisotropy use the electrical resistivity ($\rho$), [2, 8, 22, 23] the imaginary part of the sample ac susceptibility ($\chi''$), [8] or SQUID dc susceptibility ($\chi'$) [24]. A problem with the resistivity measurements is that in HTSCs the resistive transition is usually quite broad and the extracted values of $H_{c2}$ and $T_c$ are actually the field and temperature relative to a fraction of the ‘normal-state’ resistivity, respectively. [6, 8, 25] Thus the values obtained from the behavior of the electrical resistivity have a substantial uncertainty because they depend on the percentage for the onset of the flux flow used to determine them, while the criterion for the values obtained from the susceptibility measurements usually has a sensitivity issue that based on the noise level [6, 8, 22]. Moreover, the vortex solid state could actually extend to a much broader range of magnetic field than what one would expect from the resistivity measurements [25]. Thus, novel measurement techniques are highly valuable, as indicated by recent Nernst effect measurements in both cuprate and Fe-based HTSCs [25–30].

A schematic for the determination of $H_{c2}$ and $T_c$, as well as associated parameters $H_m$ and $T_m$ using some of these experimental techniques including that for our NMR probe circuit resonance frequency measurements to be described in this report is shown in figure 1. Here $T_m$ ($H_m$) is the temperature (applied magnetic field) traditionally defined to be the temperature (field) at which the electrical resistivity begins to go to zero at the low temperature (field) side in the vortex regime upon decreasing temperature (field), or where the electrical resistivity starts to deviate from zero while upon increasing temperature (field). The value of $H_m$ is often called the irreversibility field, below which a vortex solid state appears. Similarly, the value of $T_m$ corresponding to the value of the field $H_m$ is the melting temperature of the vortex solid. Apparently, the correspondence between $T_m$ and $H_m$ is similar to that between $T_c$ and $H_{c2}$ in terms of the states of the material (note, the field corresponding to $T_c$ is $H_{c2}$, not $H_m$). Figures 1(a) and (b) exhibit those determinations from the measurements of the electrical resistivity ($\rho$) as swept by the applied magnetic field $H$ at a fixed temperature ($T = T_0$) and by the temperature $T$ at a fixed field ($H = H_0$), respectively.Similarly, figures 1(c) and (d) are those from the measurements of the Nernst signal ($\epsilon_N$) versus applied magnetic field $H$ at $T_0$ and our NMR probe circuit resonance frequency ($f_b$) versus $T$ at $H_0$ as described below, respectively.

In this paper, we report the superconducting anisotropy measurements on single crystals of the electron-doped HTSCs Pr$_{2-2x}$Ce$_x$CuO$_{2-\delta}$ (PCCO, $x = 0.15$ and 0.17) with applied magnetic field $H_0$ up to 28 T, using the resonant frequency ($f_b$) of a nuclear magnetic resonance (NMR) probe circuit, which can sensitively track the effect of the changes in the superconducting vortex phases on the shielding of the radio frequency (RF) magnetic field by the sample that is placed in the NMR coil.

Our main results are that the upper critical field $H_{c2}$ of PCCO is highly anisotropic with significantly smaller values of $H_{c2,\perp}$ than those of the hole-doped cuprate HTSCs, indicating a significantly smaller vortex liquid regime for the electron-doped than for the hole-doped cuprate HTSCs. As the temperature $T \to 0$, the upper critical field [$H_{c2,\perp}(0)$] at $H_0 \parallel c$ is far less than the Pauli limit [$H_{Pauli}(0)$]. Other anisotropies are the zero $T$ coherence length [$\xi_{ab}(0)$] and penetration depth [$\lambda_{ab}(0)$]. We reveal that the low temperature anisotropy of PCCO as reflected by the value of $\gamma$ [$\gamma = H_{c2,\perp}(0)/H_{c2,\parallel}(0)$] appears to be rather similar to that of the hole-doped cuprate HTSCs, but apparently larger than that of typical Fe-based superconductors. This experiment also proves a novel sensitive probe of detecting rich properties of unconventional superconductors with the use of the resonant frequency of a NMR probe circuit.

2. Experimental details

Single crystals of PCCO ($x = 0.15$ and 0.17) were grown with a flux technique [31, 32]. The samples used in this experiment are the same as those we used for the NMR measurements. The sample size for PCCO ($x = 0.15$) is $\sim 1.5 \text{ mm} \times 1.2 \text{ mm} \times 35 \mu\text{m}$ with a mass of 0.53 mg and the size of the PCCO ($x = 0.17$) sample is similar. The NMR coil (inductance $L_C$) was made from 50 $\mu\text{m}$ silver wire wound with
Figure 2. Sketch of the NMR probe circuit used for the superconducting anisotropy measurements on PCCO \((x = 0.15\) and 0.17). The symbols and operation are described in the section 2 text.

\(~\sim 20\) turns. It has a quality factor \((Q \sim 60)\) and is attached to a goniometer with the sample rotation axis that is \(\perp H_0\) and located in the lattice \(ab\)-plane. The measurements at high magnetic field were conducted at the National High Magnetic Field Laboratory (NHMFL) in Florida. A commercial network analyzer (NA) was used for detecting \(f_k\). The NMR probe was built by W G Clark’s group at UCLA. The measurements used a value of \(f_k \simeq 300\) MHz for the major two alignments \((H_0 \parallel c\) and \(H_0 \perp c\)), with a resolution of 50 kHz or 0.017%. Figure 2 shows the sketch of the NMR probe circuit used in the measurements. The components are the NMR coil (inductance \(L_C\)), its resistance \((R_C = 2\pi f L_C/Q)\), the series tuning capacitance \((C)\), the parallel matching inductance \((L_m)\) and its series resistance \((R_m)\). To include the effects of the sample in the coil, we use \(L_C = L_{CO} + L_{SO} + \Delta L_S = L_0 + \Delta L_S\), where \(L_{CO}\) is the inductance of the empty coil, \(L_{SO}\) is the change in \(L_C\) caused by the sample at the start of the measurement (frequency \(f_0\)), \(L_0 = L_{CO} + L_{SO}\) is the value of \(L_C\) at the start of the measurement and \(\Delta L_S\) is the change in \(L_C\) from the sample during the measurement. The real part of \(\Delta L_S\) \((Re[\Delta L_S])\) can be \(+\) or \(-\) (reduced or increased shielding). The imaginary part \((Im[\Delta L_S])\) is negative and represents the change in the rf losses associated with the dissipation from the shielding currents in the sample.

Scaling between \(L_{CO}\) and the characteristic impedance of the cable \((Z_0 = 50\Omega)\) is given by \(2\pi f L_{CO} = kZ_0\). Typically, \(0.5 < k < 2\) and \(L_{CO} >> L_{SO}, \Delta L_S\). The coil circuit (reactance \(Z_T\)) is connected by a coaxial transmission line to the NA, which sends a signal (amplitude \(V_m\), swept \(f\)) to the NMR coil circuit and receives the corresponding reflected signal \((V_{out})\). The values of \(L_C, C\) and \(L_m\) are chosen to make \(Z_T \simeq Z_0\) close to the frequency \((f_0)\) at which the measurement is started. It can be shown that at moderate and high values of \(Q\), this is done by making \(2\pi f_0 L_{CO} \simeq 1/(2\pi f_0 C)\) and \(2\pi f_0 L_m \simeq Z_0/\sqrt{Q}\).

The NA measures the reflection coefficient \((\Gamma(f) = [Z_T(f) - Z_0]/[Z_T(f) + Z_0])\) associated with \(V_m\) and \(V_{out}\) over a range of \(f\). By using the conditions above to obtain \(Z_T \simeq Z_0\) near \(f_0\), a minimum in the magnitude of \(\Gamma(f)\) occurs at the nearby frequency \(f_k\). At the start of the measurement, a slight adjustment is made in \(C\) to set \(f_k = f_0\). The value of \(f_k\) for each set of conditions is provided by the NA from the \(f\)-sweep of \(|\Gamma(f)|\) displayed on its screen. Our numerical analysis of \(|\Gamma(f)|\), shows that to a good approximation \([33]\) and over a fairly large range of \(Q\) and \(k\),

\[
f_k \simeq f_0 \left(1 - Re[LS]/2L_0\right).
\]

It also turns out that variations in \(Im[LS]\) and \(Q\) have a significant effect on the depth of the minimum in \(|\Gamma(f)|\), but have a negligible effect on \(f_k\). As shown below, when the sample is cooled down by \(~\sim 10\) K below \(T_c\), the value of \(f_k\) near 300 MHz in our measurements can be shifted from \(f_0\) up to \(~\sim 45\) MHz, which is much larger than the accuracy and resolution of the readings using the NA. This indicates that this method has a significant value in comparison with other measurement techniques.

An important consideration for the sensitivity in these measurements is that the sample fills the coil as much as possible. In this experiment, the sample fills about 60% of the volume of the NMR coil.

Another important aspect of the measurements reported here is that the RF magnetic field applied by the NA is small enough that it does not provide the RF induced flux lattice annealing (RIFLA) that may occur especially when pulsed NMR spin echo measurements are done. This RIFLA effect is discussed for thin NbTi wires [34] and for PCCO [35]. The physical basis of RIFLA is that at low temperature, when the flux lattice is created by turning on a magnetic field, or modified by rotating the direction of the applied field relative to the orientation of the sample, because of pinning of the flux lines to impurities in the sample, the flux lattice configuration may not have the lowest free energy. Under these circumstances, when a large amplitude RF signal is applied, it can shake the flux lines and their location can change to a lower free energy configuration, which also changes the local magnetic field in the sample. This configuration change increases the binding force of the flux lines, with the effect that their motion in response to an RF magnetic field can be reduced, leading to a reduction of the RF magnetic susceptibility of the sample and a corresponding change in the tuning parameters of the NMR probe circuit.

The RF power used for our NMR spin echo measurements (not shown in this report) is typically \(~\sim 200\) W and at low \(T\) leads to an initial reduction of the spin echo amplitude that gradually disappears as the number of measurements in a time sequence increases and the annealing stabilizes. Also, as shown in [35], there can be a substantial change in the probe circuit tuning frequency if the field is rotated with and without annealing the flux lattice during the measurement. On the other hand, the power provided by the NA is always \(~\sim 0.035\) W and is usually set to be much less. In this case, no change in the probe tuning frequency was observed with repeated sample rotations in the applied magnetic field. This verifies that our measurements reported here were not affected by RIFLA.

3. Experimental results

Figure 3 shows the measured values of \(f_k\) versus \(T\) for the single crystal of PCCO \(x = 0.15\) at several applied magnetic
fields $H_0 \perp c$ up to 28 T. Similar result for the sample PCCO $x = 0.17$ at $H_0 \perp c$ is shown in figure 4. The result of $f_R$ versus $T$ for $H_0 \parallel c$ is shown in figure 5, as an example for PCCO $x = 0.15$.

As shown in figures 3–5, $f_R$ almost linearly increases with $T$ below $T_c$ where the flux-flow starts as indicated by the arrows ($f_R$ saturates upon cooling down to low enough temperatures (not shown here)). For PCCO $x = 0.15$, the value of $f_R$ at $B_0 \perp c$, $f_{R,1c} \sim 303.5$ MHz above $T_c$ (figure 3) which is in the normal state (note, there is no frequency deviations above temperatures $T > T_c$). Below $T_c$ it reaches $\sim 308.0$ MHz by decreasing $T$ to $\sim 10$ K at 9 T, for example. Thus this indicates that the circuit resonant frequency has a shift of up to $\sim 4.5$ MHz due to the change of the sample susceptibility. Other effects that contribute to the shift are estimated to be very small since the range of temperature change is rather narrow.

Generally, there are two major factors that could cause a change in the inductance $L_S$ of a conducting sample. One is the conductivity of the sample and the other is the RF (or ac) susceptibility of the sample. Here we had ruled out the possibility from the changes in the sample coil itself, as we tested it with measurements when the sample is removed from the NMR coil. The loss of density of states at the Fermi level, for example, when the sample enters the flux lattice (glass) state, will affect the conductivity and cause $\text{Re}[L_S]$ to decrease. Thus it is expected that $f_R$ will go up on traversing from the normal to the superconducting state, as seen from equation (1) and by the data (figures 3–5).

Noticeably, at $H_0 \parallel c$ the increase of $f_R$ below $T_c$ is much slower, and the applied magnetic field $H_0 \parallel c$ corresponding to its $T_c$ is also significantly smaller than those at $H_0 \perp c$. The anisotropy of the sample magnetic susceptibility should play a significant role for these differences.

Figure 6 shows the values of the upper critical field $H_{c2}$ versus $T$ obtained from the data as shown in figures 3–5, in which the values of $H_{c2}$ corresponds to the values of $H_0$ with $T = T_c$ as indicated by the arrows in the figures. At low temperatures, the values of $H_{c2,1c}$ are significantly larger than those of $H_{c2,1c}$, indicating a high anisotropy.

4. Discussion

In this section, the zero temperature values of the upper critical field $H_{c2}(0)$ along with the zero temperature values of coherence length $\xi(0)$ and penetration depth $\lambda(0)$ of PCCO are extrapolated and compared with those of typical hole-doped HTSCs and Fe-based superconductors.

Since $T_c$ (not $T_m$) is what we obtained here from the temperature-swept $f_R$ measurements at each fixed applied magnetic field $H_0$ and the corresponding field to it is $H_{c2}$ (not $H_m$), the irreversibility field $H_m$ (or $T_m$) is apparently not of interest here.

As shown in figure 6, at $H_0 \parallel c$ the $H_{c2,1c}$ versus $T$ curve has an anomalous shape (a concave upward curvature), which
has been widely observed in both hole- and electron-doped cuprate HTSCs [6–8, 12, 22, 25, 36–39] and many other systems as well, where there is no evidence of saturation as $T \to 0$. The mechanism is still unknown. More peculiarly, hole-doped cuprate HTSCs even show [12, 22] a divergence of $H_{c2,\perp}(T)$ at low $T$.

However, for the electron-doped HTSCs, it is generally agreed [6, 29] that as $T \to 0$ the upper critical field $H_{c2,\perp}(T \to 0) = H_{c2,\perp}(0)$ with no evidence of divergence. Considering this, one can fit the data more appropriately as [40]

$$H_{c2,\perp}(T) \approx H_{c2,\perp}(0) \left[1 - T/T_c\right]^{\alpha},$$

rather than using the Werthamer, Helfand and Hoben berg (WHH) formula [41]

$$H_{c2}(0) = -0.693 T_c (dH_{c2}/dT)_{T_c},$$

where equation (2) is consistent [40] with the Ginsburg-Landau theory [2].

Here in equation (2), $T_c = 22$ K and $20$ K for $x = 0.15$ and 0.17, respectively. This gives a result of $\alpha \approx 2.0$ and $H_{c2,\perp}(0) = (6.0 \pm 0.3)$ T and $(3.1 \pm 0.4)$ T for $x = 0.15$ and 0.17, respectively, by the extrapolation of equation (2) to $T = 0$, as shown by the dark solid and dashed lines in figure 5. This agrees well with the result from the field dependence of the specific heat measurements [42]. Similar results were also obtained from the electrical resistivity measurements [6] on Nd$_{2-x}$Ce$_x$CuO$_{4+y}$ with $\alpha = 1.7 - 2.0$.

The property that $\alpha \approx 2.0$ for PCCO instead of $\alpha = 1$ suggests that there exists a significant distribution of inhomogeneous vortex state and local SC regions, [43] which could serve [1, 8] as a possible mechanism leading to the vortex-glass phase as that observed in Nd$_{2-y}$Ce$_y$CuO$_{4+y}$ [6, 44].

At $H_0 \perp c$, the data of $H_{c2,\perp}$ versus $T (T/T_c > 0.5)$ shown in figure 6 can be fitted with a BCS $T$–dependence (also used by Clem [45] earlier) for $H_{c2,\perp}$. Since it is also known [6, 29] that $H_{c2,\perp}(T \to 0) = H_{c2,\perp}(0)$ as $T \to 0$ where $H_{c2,\perp}(T)$ reaches a saturation, it is appropriate to use [45]

$$H_{c2,\perp}(T) \approx H_{c2,\perp}(0) \left[1 - (T/T_c)^2\right],$$

This gives a fitted value of $H_{c2,\perp}(0) \approx 42$ T and 38 T for $x = 0.15$ and 0.17, respectively, by the extrapolation of equation (4) to $T = 0$.

According to the BCS theory, [46] the energy gap $\Delta(0)$ (SC gap) between the normal state and the SC state at $T = 0$ is related to the Pauli limit field $H_{Pauli}(0)$ as [47]

$$\Delta(0) = \sqrt{2} \mu_B H_{Pauli}(0),$$

where $\mu_B$ is the Bohr magneton. The result from the tunneling measurements [48] indicates that at $H_0 \parallel c$, the value of $2\Delta(0) \approx 4.0 k_B T_c$ and $3.4 k_B T_c$ for PCCO $x = 0.15$ and $x = 0.17$, respectively. This gives the Pauli limit $H_{Pauli}(0) \approx 45$ T and $\sim 36$ T for $x = 0.15$ and 0.17.

Thus, $H_{c2,\perp}(0)$ is far less than the Pauli limit $H_{Pauli}(0)$, while $H_{c2,\perp}(0)$ is close to it, i.e. $H_{c2,\perp}(0) \ll H_{Pauli}(0)$ and $H_{c2,\perp}(0) \approx H_{Pauli}(0)$.

To estimate the SC coherence length at $T = 0$, one can use the expression [2] $H_{c2,\perp}(0) = \phi_0/2 \pi \xi_{c,\perp}^2(0)$ and $H_{c2,\perp}(0) = \phi_0/2 \pi \xi_{c,\parallel}^2(0)\xi_{c,\perp}(0)$, where $\xi_{c,\parallel}(0)$ and $\xi_{c,\perp}(0)$ are the CuO$_2$ in-plane and out-of-plane coherence lengths at $T = 0$, respectively and $\phi_0 = 2.07 \times 10^{-7}$ G cm$^2$ which is called the flux quantum. These yield $\xi_{c,\parallel}(0) \approx 74$ Å and $\sim 103$ Å for PCCO $x = 0.15$ and 0.17, respectively. Correspondingly, their out-of-plane values are $\xi_{c,\perp}(0) \approx 10$ Å and $\sim 8$ Å, respectively, which are slightly larger than the distance between the nearest CuO$_2$ planes.

Considering the in-plane penetration depth $\lambda_{c,\parallel}(0) \approx 2500$ Å from the microwave measurement [49] for PCCO $x = 0.15$ and using the anisotropy relationship [2] $(\xi_{c,\parallel}/\xi_{c,\perp}) = \lambda_{c,\parallel}/\lambda_{c,\perp}$, we have $\lambda_{c,\perp}(0) \approx 18500$ Å for PCCO $x = 0.15$. The anisotropy field ratio $\gamma = H_{c2,\perp}(0)/H_{c2,\perp}(0) \approx 7$ for $x = 0.15$ and $\sim 12$ for PCCO $x = 0.17$.

A comparison with typical hole-doped cuprate HTSCs and Fe-based superconductors in the literature is listed in table 1. As shown in table 1, in comparison with typical hole-doped cuprate HTSCs the upper critical field $H_{c2}(0)$ values for PCCO are a few times smaller and the coherence length $\xi (0)$ and penetration depth $\lambda (0)$ are a few time larger. But their low-temperature anisotropies (as seen from the values of $\gamma$) are rather similar.

However, in comparison with the typical Fe-based superconductors, the anisotropies (at low temperatures) in the Fe-based superconductors are apparently smaller. The mechanism for their difference in anisotropies is not understood currently in the literature.

Here we would like to point out that with the same analysis method that we used here, the difference between the obtained value of $H_{c2,\perp}(0)$ in this experiment (UCLA sample) and that reported by the electrical resistivity measurements on a different sample (UM sample) [50] for PCCO $x = 0.17$ is negligible, while for PCCO $x = 0.15$ there is a rather significant difference for the corresponding values between the two samples. For clarity, we plotted the data together for both samples, which are shown in figure 7. The corresponding data of $H_{c2}(T)$ for the UM sample are the ones that labeled as $H_{c2,\perp}$ in [8] and [50] for $H_0 \parallel c$ and $H_0 \perp c$, respectively. The values of $H_{c2,\perp}(0)$ and $H_{c2,\perp}(0)$ of PCCO $x = 0.15$ analyzed here for the UM sample are $\sim 55$ T and $\sim 5.5$ T, respectively, while the
Table 1. A comparison of fit parameters of PCCO ($x = 0.15$ and $0.17$) with those of hole-doped cuprate HTSCs and typical Fe-based superconductors.

| Compound | $T_c$ (K) | $H_{c2}^{\perp}(0)$/$H_{c2}^{\parallel}(0)$ | $\xi_{ab}(0)$/$\xi_c(0)$ | $\lambda_{ab}(0)$/$\lambda_c(0)$ |
|----------|----------|----------------------------------------|--------------------------|-------------------------------|
| $^{1}$La$_{2-x}$Sr$_x$CuO$_{4-y}$ | 38      | 80/15                                  | 35/7                     | 800/4000                     |
| $^{1}$YBa$_2$Cu$_3$O$_7$ | 92      | 150/40                                 | 15/4                     | 1500/6000                    |
| $^{2}$Bi$_2$Sr$_2$CaCu$_2$O$_8$ | 110     | 250/30                                 | 13/2                     | 2000/1000                    |
| PCCO ($x = 0.15$) | 22$^{2, 3}$ | 42/5$^2$, 55/5.5$^2$, 74/10$^2$ | 103/8$^2$ | 2500/18 500$^2$ |
| PCCO ($x = 0.17$) | 20$^{2, 3}$ | 38/3$^2$, 40/3$^2$, 74/10$^2$ | 103/8$^2$ | 2500/18 500$^2$ |
| $^{4}$LiFeAs | 18      | 24/15                                  | 48/17                     | —                             |
| $^{5}$Fe$_{1.1}$Se$_{0.6}$Te$_{0.4}$ | 14      | 47/47                                  | 26.5/26.5                | —                             |
| $^{6}$ (Ba,K)Fe$_2$As$_2$ | 28      | 57/55$^a$                              | 21.7/21.7                | —                             |
| $^{7}$SmFeAsO$_{5}\delta$ | 50      | 51$^b$/56$^c$                         | 170/36                    | —                             |

* values at $\sim 10$ K.
*$^a$ 43 K.
*$^b$ 27 K.

Note: 1– [2], 2–result of these measurements, 3–result of resistivity measurements [8, 50] from our analysis, 4–[51–54], 5– [55, 56], 6– [57, 58] and 7– [59].

Figure 7. Comparison of obtained values of $H_{c2}$ versus $T$ data between the sample used in this experiment (blue curve) and a different one reported previously (red curve) from the electrical resistivity measurements [8, 50] for PCCO $x = 0.15$, with the same analysis method used here. The solid and dashed lines are the fit and the extrapolations (see text).

results for the UCLA sample from this experiment described above are $\sim 42$ T and $\sim 6.0$ T, respectively, i.e. the difference is $\sim 20\%$. One possible cause for the difference could be due to the difference in the measurement method and/or in sample thickness.

5. Conclusions

In summary, we reported the superconducting anisotropy measurements on the electron-doped high-$T_c$ superconductors PCCO ($x = 0.15$ and $0.17$) with the applied magnetic field $H_0$ up to 28 T, using the resonant frequency $f_R$ of a NMR probe circuit. The frequency data showed very sharp features at the superconducting phase transition temperature $T_c$ and almost a linear relation between $f_R$ and $T$ below $T_c$ (a sharp increase of $f_R$), thus indicating a significant advantage over the method using the electrical resistivity for the determination of $T_c$ and $H_{c2}$ values.

The measured values of upper critical field $H_{c2}$ are highly anisotropic and our analysis indicates that $H_{c2,\perp}(0)$ is far less than the Pauli limit $H_{Pauli}(0)$, while $H_{c2,\parallel}(0)$ is close to it. These $H_{c2}(0)$ values of PCCO are a few times smaller than those of the hole-doped cuprates, but their low temperature anisotropies are rather similar, while the typical Fe-based
superconductors apparently have smaller low temperature anisotropy than PCCO.

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