Resistivity saturation in PrFeAsO$_{1-x}$F$_y$ superconductor: evidence of strong electron–phonon coupling

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Abstract

We have measured the resistivity of PrFeAsO$_{1-x}$F$_y$ samples over a wide range of temperature in order to elucidate the role of electron–phonon interaction on normal- and superconducting-state properties. The linear $T$ dependence of $\rho$ above 170 K followed by a saturation-like behavior at higher temperature is a clear signature of strong electron–phonon coupling. From the analysis of the $T$ dependence of $\rho$, we have estimated several normal-state parameters that are useful for understanding the origin of superconductivity in this system. Our results suggest that Fe-based oxypnictides are phonon-mediated BCS superconductors like Chevrel phases and A15 compounds.

1. Introduction

The discovery of the iron-based layered oxypnictide LaFeAsO$_{1-x}$F$_x$ with high superconducting transition temperature ($T_c$) 26 K has stimulated intense experimental and theoretical activities in the field of superconductivity [1, 2]. Following the initial report, attempts have been made to enhance the $T_c$ mainly by changing the sample composition. It has been shown that the $T_c$ increases significantly when La is replaced by other rare earth elements (R) of smaller ionic size, such as Ce, Pr, Nd, and Sm [3–7]. $T_c$ as high as 55 K has been reached in this class of materials, which is the highest after cuprate superconductors. The stoichiometric compound RFeAsO is a nonsuperconducting metal; it undergoes a structural phase transition around $T_s = 150$ K and exhibits a long-range antiferromagnetic ordering of Fe moments slightly below $T_s$ [1, 8]. Partial substitution of fluorine for oxygen or creating oxygen vacancies suppresses both the structural and magnetic phase transitions, and drives the system to a superconducting ground state. Besides the high transition temperature, this system exhibits many interesting phenomena, possibly due to its layered structure, as in the case of high-$T_c$ cuprates and the presence of iron. At room temperature, the crystal structure of RFeAsO is tetragonal, with space group $P4/nmm$, and it consists of RO and FeAs layers which are stacked along the $c$ axis. In spite of the high transition temperature and layered structure, there are some important differences with respect to cuprate superconductors. For oxypnictides, the parent compound is not a Mott insulator and the superconducting-state properties are insensitive to oxygen or fluorine content over a wide range. Another important difference between high-$T_c$ cuprates and oxypnictides is the dependence of $T_c$ on the ionic size of the rare earth ion. Unlike high-$T_c$ cuprates, in RFeAsO$_{1-x}$F$_y$, $T_c$ increases with the decrease of ionic radius of the rare earth ion [7, 9]. Moreover, the symmetry and temperature dependence of the superconducting gap in these two systems are not same. The gap function of the latter is $s$-wave and its temperature dependence is consistent with the BCS theory [10, 11].

The theoretical and experimental attempts aimed at identifying the possible superconducting mechanism in oxypnictides have resulted in contradictory views [10–18]. On the one hand, the high transition temperature, structural similarities with cuprates, and the occurrence of superconductivity on the verge of a ferromagnetic instability argue in favor of a non-phononic mechanism [13–17]. Moreover, the small value of the electron–phonon ($e$–$ph$) coupling constant $\lambda_{ep} = 0.21$ obtained from the band structure calculation cannot explain the high transition temperature in oxypnictides [16]. On the other hand, Andreev reflection spectroscopy [10] and angle-resolved photomission spectroscopy [11] have shown $s$-wave symmetry of the order parameter as in the case of phonon-mediated conventional superconductors. To shed some light on the mechanism of superconductivity, we have measured the temperature
dependence of resistivity up to 560 K for PrFeAsO$_{1-x}$F$_x$ samples. From the analysis of the high-temperature resistivity, the e–ph coupling strength for the superconducting and nonsuperconducting samples has been estimated. Indeed, we observe that $\lambda_\pi$ is quite small (0.25) for the nonsuperconducting sample, in accordance with the theoretical prediction, but it is about six times larger for the superconducting samples.

2. Sample preparation and experimental techniques

Good-quality single-phase samples are necessary for understanding the normal-state transport properties and the mechanism of superconductivity in this system. Usually, two methods have been followed for the preparation of iron-based oxypnictides. Using the high-pressure synthesis technique, one can obtain fluorine-free and oxygen-deficient RFeAsO$_{1-x}$ superconducting samples [19, 20]. However, samples prepared with this method contain appreciable amounts of impurity phases resulting from the unreacted ingredients. In the other method, oxygen is partially replaced by fluorine and the sample is prepared either in high vacuum or in the presence of inert gas. Though samples prepared with this method are superior in quality, they are not always free from impurity phases [21, 22]. We use a slightly different method for the preparation of superconducting PrFeAsO$_{1-x}$F$_x$ samples. The nominal composition for these samples is oxygen deficient, and at the same time the oxygen is partially replaced by a small amount of fluoride ($x > y \neq 0$). We observe that single-phase samples with $x \leq 0.4$ can be prepared with this method. Polycrystalline samples of nominal compositions PrFeAsO, PrFeAsO$_{0.6}$F$_{0.4}$ and PrFeAsO$_{0.7}$F$_{0.3}$ were prepared by the conventional solid-state reaction method. High-purity chemicals (Pr (99.9%), Fe (99.998%), Fe$_2$O$_3$ (99.99%), As (99.999%), PrF$_3$ (99.9%), and Pr$_6$O$_{11}$ (99.99%) from Alfa-Aesar were used for the sample preparation. Finely ground powders of Pr$_{0.96}$As, Fe, Fe$_2$O$_3$, Pr$_{0.11}$O$_{1.9}$ (pre-heated at 600°C), and PrF$_3$ were thoroughly mixed in appropriate ratios and then pressed into pellets. The pellets were wrapped with Ta foil and sealed in an evacuated quartz tube. They were then annealed at 1250–1275°C for 36 h. Pr$_{0.96}$As was obtained by slowly reacting Pr chips and As pieces first at 850°C for 24 h and then at 950°C for another 24 h in an evacuated quartz tube. The product was reground, pressed into pellets, and then sealed again in a quartz tube and heated at 1150°C for about 24 h. The phase purity and the room-temperature structural parameters were determined by the powder x-ray diffraction (XRD) method with Cu Kα radiation. The dc magnetization and electrical resistivity measurements up to 300 K were made using a Quantum Design physical property measurement system (PPMS). The resistivity was measured by the standard four-probe technique. The low-resistance electrical contacts were made using conducting silver paints. The high-temperature resistivity above 300 K was measured in a home-made set-up in which the sample temperature was increased at the rate of 1.5 K min$^{-1}$. In order to avoid oxidation, resistivity measurements at high temperatures were done in the presence of pure helium gas or in vacuum.

3. Experimental results and discussion

3.1. Powder x-ray diffraction analysis

Figure 1 shows the XRD pattern for the fluorine-doped PrFeAsO$_{0.6}$F$_{0.4}$ sample at room temperature. No impurity phase was observed for $x = 0.3$ and 0.4 samples. The diffraction pattern can be well indexed on the basis of the tetragonal ZrCuSiAs-type structure with the space group P4/nmm. The lattice parameters obtained from the Rietveld refinements are $a = 3.9711$ Å and $c = 8.5815$ Å. These values of lattice parameters are comparable with those reported for fluorine-doped and oxygen-deficient PrFeAsO samples [5, 19]. As expected, the lattice parameters of the present samples are located between those of CeFeAsO$_{1−x}$F$_x$ and NdFeAsO$_{1−x}$F$_x$ [4, 20]. We would like to mention that the nominal oxygen-site vacancy in our present sample is $(1 − x − y)$. However, we are unable to determine the exact numbers of the oxygen-site vacancies from x-ray refinements because the x-ray method is insufficient for the accurate determination of the light atom stoichiometry. Nevertheless, one can prepare good-quality and single-phase samples using this technique. The deduced bond lengths for PrFeAsO$_{0.6}$F$_{0.4}$ are $d(\text{Pr}−\text{O}/\text{F}) = 2.3405$, $d(\text{Pr}−\text{As}) = 3.3008$, $d(\text{As}−\text{Fe}) = 2.3828$, and $d(\text{Fe}−\text{Fe}) = 2.8081$ Å. The values of several of the bond angles are $\langle \text{O/F−Pr−As} \rangle = 76.57$, $\langle \text{O/F−Pr−O/F} \rangle = 73.73$, $\langle \text{Pr−As−Fe} \rangle = 77.83$, $\langle \text{Fe−As−Fe} \rangle = 72.20$, and $\langle \text{As−Fe−As} \rangle = 107.79^\circ$. It may be noted that the Fe–Fe distance in the present system is about 1.4% smaller than the Fe–Fe distance 2.8481 Å in LaFeAsO$_{1−x}$F$_x$ [21].

3.2. Electrical resistivity analysis

The measured temperature dependence of resistivity for samples PrFeAsO$_{0.6}$F$_{0.4}$ (S1) and PrFeAsO$_{0.7}$F$_{0.3}$ (S2) in the temperature range 45–560 K is illustrated in figure 2(a). For both samples, $\rho$ decreases initially at a very slow rate and then at a faster rate with decreasing temperature until the superconducting onset temperature ($T_{on} \sim 50$ K) is reached. Below $T_{on}$, $\rho$ drops sharply and becomes zero at around 47 K. The inset displays the enlarged view of the onset of superconductivity for sample S1. For this sample,
the transition width $\Delta T_c$ is 2.7 K, where $\Delta T_c$ is defined as the width of the transition between 10% and 90% of the normal-state resistivity. For sample S1, we have measured field-cooled (FC) and zero-field-cooled (ZFC) magnetic susceptibilities at $H = 50$ Oe. The values of shielding and Meissner volume fractions at 5 K determined from the FC and ZFC susceptibilities are 65 and 23%, respectively. The resistivity ratio $\rho(300 \text{ K})/\rho(54 \text{ K})$ for these samples is about 13. The resistivity ratio and the transition width are respectively larger and narrower as compared to those reported for other fluorine-doped and oxygen-deficient PrFeAsO samples [5, 19]. The larger resistivity ratio and narrower transition width are the indications of high sample quality. We have also determined the approximate value of residual resistivity for S1, $\rho(0) \sim 0.10 \text{ m}\Omega \text{ cm}$, by extrapolating the $\rho$ versus $T$ curve between 150 and 60 K to $T = 0$. It may be mentioned that we have prepared another sample with nominal oxygen content 0.50. The value of resistivity ratio for this sample is also large ($\sim 9$) and its $T_c$ is almost same as those for S1 and S2. However, x-ray diffraction shows the presence of impurity phases in this sample. Kito et al. [20] prepared Nd-based superconducting samples using the high-pressure synthesis technique and found that the amount of impurity phases increase rapidly when the oxygen vacancy level exceeds 0.4. This suggests that samples with oxygen deficiency more than 0.4 cannot be prepared in single phase. Though both the magnitude and $T_c$ dependence of the normal-state resistivity depend to some extent on the composition and purity of the samples, $T_c$ is more or less insensitive to oxygen content. This observation is consistent with the reported phase diagram of $T_c$ versus fluorine or oxygen content [1, 20].

The analysis of $T$ dependence of $\rho$ reveals three different temperature regimes (figure 2(b)). $\rho$ exhibits a quadratic temperature dependence, $\rho = \rho(0) + AT^2$, in the range 70 K $\leq T \leq 150$ K, while it is linear in $T$ in the intermediate region, 170 K $\leq T \leq 270$ K. The $T^2$ behavior of $\rho$ below 150 K indicates a strong electronic correlation and is consistent with the formation of a Fermi-liquid state. Above 270 K, the resistivity behavior shows marked departure from the usual temperature dependence of simple metals and high-$T_c$ superconductors. Normally, in good metals, $\rho$ is linear in $T$ at high temperature due to the $e$–$ph$ scattering. For the present samples, the slope of the $\rho(T)$ curve decreases continuously with increasing temperature above 270 K and a saturation-like behavior appears at higher temperature. For sample S1, the increase of $\rho$ is small, while $\rho$ is effectively $T$-independent for sample S2 above 500 K. The saturation-like behavior of $\rho$ at high temperature draws our attention to the $T$ dependence of $\rho$ for Nb, Chevrel phases, and several intermetallic and A15 compounds [23]. This phenomenon has been explained on the basis of the conduction-electron mean free path approaching a lower limit with the consequent breakdown of the classical Boltzmann theory [24]. The breakdown has been interpreted in terms of the Ioffe–Regel criterion [25]. The electron mean free path cannot be shorter than the interatomic distance. The resistivity of poor metals at high temperatures tends to saturate to a temperature-independent value when the mean free path $l$ approaches the wavelength $\lambda_F = 2\pi/k_F$ associated with the Fermi level, where $k_F$ is the Fermi wavevector. The Ioffe–Regel criterion for the onset of this saturation is $k_F l \leq 1$. Later, we will show that this criterion is indeed satisfied in the present case.

Figure 3 shows the temperature dependence of resistivity for the nonsuperconducting PrFeAsO sample.

![Figure 2](image1.png)  
**Figure 2.** Temperature dependence of (a) resistivity ($\rho$) for the superconducting samples PrFeAsO$_{0.5}F_{0.12}$ (S1) and PrFeAsO$_{0.5}F_{0.12}$ (S2), and (b) $d\rho/dT$ for the PrFeAsO$_{0.5}F_{0.12}$ sample. The inset of (a) shows an enlarged view of the resistivity change close to the superconducting transition temperature for PrFeAsO$_{0.5}F_{0.12}$.**

![Figure 3](image2.png)  
**Figure 3.** Temperature dependence of resistivity for the nonsuperconducting PrFeAsO sample.
However, \( \rho \) increases linearly with \( T \) from 250 up to 525 K at the rate of \( \sim 1.5 \, \mu \Omega \, \text{cm} \, \text{K}^{-1} \). No saturation-like behavior is observed for this sample in the measured temperature range. Thus, the behavior of \( \rho \) at high temperature for the nonsuperconducting sample is quite different from that of the superconducting sample. In the linear region of \( \rho \) versus \( T \) curves, the slope for the nonsuperconducting parent compound is about six times smaller than that for the superconducting sample (\( \sim 8.6 \, \mu \Omega \, \text{cm} \, \text{K}^{-1} \)).

For the quantitative understanding of the behavior of \( \rho(T) \) at high temperature, we estimate several normal-state transport parameters related to the e–ph scattering and examine its effect on superconductivity, as was done in the case of cuprate superconductors [26, 27]. At this point, it is worthwhile discussing to what extent one may rely on the data of polycrystalline samples. For instance, Otter et al [28] measured the resistivity of a Ba\(_{0.6}\)K\(_{0.4}\)Fe\(_2\)As\(_2\) sample and Ni et al [29] measured the in-plane resistivity of a Ba\(_{0.55}\)K\(_{0.45}\)Fe\(_2\)As\(_2\) single crystal. The magnitudes of \( \rho \) in both cases are large and comparable. Also, the nature of the \( T \) dependence of \( \rho \) for polycrystalline and single-crystal samples is almost the same. Kumar et al [30] studied the temperature, pressure and magnetic field dependence of resistivity of SrFe\(_2\)As\(_2\) polycrystalline and single-crystal samples to extract several physical parameters and to draw the temperature–pressure phase diagram. They concluded that polycrystalline and single-crystal samples make no difference to the extracted results. The above observations may be attributed to the formation of large crystallites (20–300 \( \mu \text{m} \)) [31, 32] and the tendency of plate-like grains to orient their \( ab \)-plane along the broad face of the polycrystalline oxypnictide samples [33]. This suggests that, unlike high-\( T \) cuprates, the charge conduction in polycrystalline oxypnictides is not significantly affected by the grain boundaries and anisotropy, and hence the resistivity data for such samples may be used for the determination of different physical parameters.

Expressing the resistivity in terms of the plasma energy \( \hbar \omega_p \), \( \rho(T) \sim \rho(0) = 4\pi/\langle a_0^2 \rangle \), where \( \omega_p \) is the Fermi velocity [26, 27]. At high temperature, where the resistivity is linear in \( T \), \( \tau \) is the e–ph scattering time \( \tau_{ep} \), and is given by \( \hbar/\tau_{ep} = 2\pi \lambda_{\nu} k T \) [27]. \( \lambda_{\nu} \) is closely related to the coupling constant \( \lambda \) that determines the superconducting transition temperature. In the case of Nb and Pd, it is found that \( \lambda_{\nu} \) differs from \( \lambda \) by about 10% [23]. From the above relations one can deduce

\[
\lambda_{\nu} = \frac{\hbar \omega_p^2}{8\pi^2 k \, d\rho / dT}, \tag{1}
\]

and

\[
\lambda = \frac{\hbar \nu_p}{2\pi \lambda_{\nu} k T}. \tag{2}
\]

We can calculate \( \lambda_{\nu} \) using the values of resistivity slope (8.6 \( \mu \Omega \, \text{cm} \, \text{K}^{-1} \)) in the linear region and plasma energy (\( \sim 0.9 \, \text{eV} \)) determined from the optical conductivity data [12]. Equation (1) reveals \( \lambda_{\nu} = 1.53 \). Such a large value of \( \lambda_{\nu} \) suggests that the e–ph coupling strength in this system is quite strong. Using this value of \( \lambda_{\nu} \) and the Fermi velocity \( \nu_p = 1.3 \times 10^7 \, \text{cm} \, \text{s}^{-1} \) calculated from band theory [13], we find \( l \sim 3.4 \, \text{Å} \) at 300 K. This value of \( l \) is comparable to the Fe–Fe separation. We observe that the Ioffe–Regel criterion for the onset of resistivity saturation \( k_p l \leq 1 \) is satisfied in this case. \( k_p \) was deduced using the values of Fermi energy \( (E_F = 0.4 \, \text{eV}) \) and Fermi velocity, as well as from the experimental value of the carrier density \( (n = 10^{21} \, \text{cm}^{-3}) \) reported for LaFeAsO\(_{1-x}\)F\(_x\) with the free electron approximation [13, 21].

In the case of a layered system, one can also check the Ioffe–Regel criterion solely from the resistivity data using the relation \( k_p l \sim \left( \hbar c / 4e^2 \right) / \rho \), where \( c \) is the interlayer distance. If we use the value of \( \rho \) at 300 K and \( c = 8.6 \, \text{Å} \), then also \( k_p l < 1 \). Thus, the e–ph scattering is dominating the high-temperature resistivity, and the large value of \( \lambda_{\nu} \) is consistent with the resistivity saturation.

Having acquired qualitative and quantitative knowledge on normal-state transport properties, we now discuss the role of e–ph coupling on superconductivity. In the limit of strong e–ph coupling, one can use the McMillan equation [34] to estimate the superconducting transition temperature

\[
T_c = \frac{\Theta_D}{1.45} \exp \left[ -\frac{1.04(1 + \lambda)}{\lambda - \mu(1 + 0.62\lambda)} \right], \tag{3}
\]

where \( \mu \) is the Coulomb pseudopotential and \( \Theta_D \) is the Debye temperature. Assuming \( \mu \sim 0 \) and \( \lambda = \lambda_{\nu} = 1.53 \), and using the reported value of \( \Theta_D = 355 \, \text{K} \) for PrFeAsO [35], we find that \( T_c = 44 \, \text{K} \). This value of \( T_c \) is only a few kelvin lower than the observed \( T_c \) for PrFeAsO\(_{0.6}F_{0.4} \). Thus the estimated and observed values of \( T_c \) are comparable for this class of materials. A more accurate estimation of \( T_c \) can be made using the Allen–Dynes equation [36], in which the prefactor \( \Theta_D/1.45 \) in equation (3) is replaced by \( \omega_p \mu_{1/2} \), where \( \omega_p \mu_{1/2} \) is a logarithmic-averaged phonon frequency. As we do not have any knowledge of \( \omega_p \mu_{1/2} \) for PrFeAsO\(_{0.6}F_{0.4} \), \( T_c \) could not be deduced using this equation. If we assume that the e–ph interaction does not change significantly from system to system, then using the same value 1.53 for \( \lambda_{\nu} \) along with the theoretically derived \( \omega_p \mu_{1/2} = 205 \, \text{K} \) for LaFeAsO [16], the observed value of \( T_c \) for LaFeAsO\(_{0.8}F_{0.1} \) can be reproduced. Now, we would like to comment on the dependence of \( T_c \) on the rare earth ionic size in RFeAsO\(_{1-x}\)F\(_x\). In oxypnictide superconductors, it has been reported that the lattice parameter \( a \) decreases while \( T_c \) increases when La is replaced by smaller rare earth ions [19]. The decrease of \( a \) means the decrease of the Fe–Fe distance. Thus, one expects an increase in the characteristic phonon frequency and hence \( T_c \) with the decrease of ionic radius of R. This observation is consistent with phonon-mediated superconductivity but quite different from that of cuprate superconductors where \( T_c \) is not sensitive to the rare earth ionic size.

It may be interesting to compare \( \lambda_{\nu} \) deduced from the resistivity data with the theoretically predicted values for understanding the role of e–ph interaction in Fe-based oxypnictides and similar materials. In most of the reports, these Fe-based materials are commonly viewed
as unconventional superconductors because of their high transition temperature in spite of the predicted weak e–ph coupling and the occurrence of superconductivity in close proximity to magnetism [13–17]. For the undoped compound, the value of the e–ph coupling strength calculated from band theory [16] is comparable with that (0.25) obtained from the resistivity data. However, there is a large disagreement in the values of \( \lambda_{tr} \) determined from the resistivity data and band theory for the superconducting sample. According to the band structure calculation, the value of \( \lambda_{tr} \) does not change significantly as one goes from the undoped to the doped sample, though a 5–6 times larger coupling constant is needed to reproduce the experimental value of \( T_c \) in this system [16].

In contrast, if \( \lambda_{tr} \) does not change significantly, it is not clear why the behavior of resistivity changes so dramatically with a small amount of fluorine doping. Eschrig [18] pointed out several shortcomings of the standard band structure calculations and argued that the e–ph coupling in this system is quite strong due to the Fe in-plane breathing mode. Drechsler et al [12] also cast doubt on the calculated weak value of e–ph coupling. The gap function is the single most important quantity that can be used to reveal the pairing mechanism of a superconductor. Chen et al [10] studied Andreev spectroscopy on SmFeAsO\(_{0.85}\)F\(_{0.15}\) and observed a single nodeless gap which was nearly isotropic in size across different sections of the Fermi surface. The value of the normalized gap parameter (2\( \Delta \)/\( kBT_c \)) determined by them was 3.68, which is slightly larger than the BCS prediction of 3.52 in the weak coupling regime but close to that observed in many conventional superconductors with strong e–ph coupling such as Nb, V\(_3\)Si, etc [10, 37]. Also, the \( T \) dependence of the gap is consistent with the BCS prediction, but dramatically different from that of the pseudogap in the cuprate superconductors. From these observations, they concluded that the structure of the gap is not compatible with theoretical models involving antiferromagnetic fluctuations, strong electronic correlations, the \( t–J \) model, and that proposed for the cuprate superconductors. Isotropic s-wave symmetry of the gap has also been established from the angle-resolved photoemission spectroscopy [11]. It has been argued that the isotropic nature of the gap and the appearance of superconductivity in close proximity to a suppressed structural phase transition bring the role of the phonon in these Fe-based samples to the forefront [11].

The strong deviation of resistivity from linearity to saturation-like in superconducting oxypnictides immediately draws our attention to conventional superconductors where e–ph coupling is strong, such as in A15 compounds and Chevrel phases [23, 26]. In these cases, \( \rho \) shows a saturation-like behavior at high temperatures, and the values of \( \lambda_{tr} \), in general, are quite large and comparable with that of the present system [37]. However, in the A15 superconductors, the saturation occurs at a much lower value of resistivity in comparison with that for PrFeAsO\(_{1−x}\)F\(_x\) [23]. This is explainable from the fact that in the A15 superconductors the carrier density is an order of magnitude larger than those for oxypnictides [23]. Also, the short electron mean free path and low carrier density are responsible for the poor conductivity in these materials. The large in-plane resistivity of oxypnictide single crystals is consistent with this picture. It may be important to mention that, apart from \( \lambda_{tr} \), other parameters related to superconductivity such as the density of states at the Fermi level, the magnitude and \( T \) dependence of \( 2\Delta/kBT_c \), and the symmetry of the gap parameter of these systems are comparable to those of oxypnictides [37]. The \( T \) dependence of the gap parameter is compatible with the BCS prediction in both the cases. So by comparing these systems with the present one it is apparent that oxypnictides belong to a class of strongly coupled BCS superconductors.

4. Conclusions

In conclusion, we have analyzed the temperature dependence of resistivity of PrFeAsO\(_{1−x}\)F\(_x\) samples. For nonsuperconducting PrFeAsO, \( \rho \) below 155 K shows a power-law behavior, whereas in the high-temperature region (250–525 K), \( \rho \) is linear in \( T \). For the superconducting samples, \( \rho \) above \( T_c \) crosses over from \( T^2 \) dependence due to the electron–electron interaction to being linear in \( T \) and then to a saturation-like behavior at higher temperature due to the e–ph interaction. The resistivity saturation indicates that the e–ph interaction is strong and that the conduction-electron mean free path is approaching a lower limit with the consequent breakdown of the classical Boltzmann theory. We have estimated the e–ph coupling parameter \( \lambda_{tr} \) from the linear \( T \) dependence of \( \rho \) to be approximately 0.25 and 1.53, respectively, for nonsuperconducting and superconducting samples. The small value of \( \lambda_{tr} \) for the former is consistent with band structure calculations, while for the latter it is about six times larger than the theoretical value. The present resistivity results, along with the structure, value, and temperature dependence of the gap parameter \( 2\Delta/kBT_c \), and other important parameters related to superconductivity, suggest that Fe-based oxypnictides are a class of BCS superconductors with strong e–ph coupling similar to A15 compounds and Chevrel phases.

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