Magnetotransport studies of optimally doped Sr(Fe$_{1-x}$Co$_x$)$_2$As$_2$

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Abstract

We report magnetotransport measurements and their scaling analysis for the optimally electron-doped Sr(Fe$_{0.88}$Co$_{0.12}$)$_2$As$_2$ system. We observe that both the Kohler’s and modified Kohler’s scalings are violated. Interestingly, the Hall angle displays a quadratic temperature dependence ($\cot \theta_H \propto T^2$) similar to many cuprates and heavy fermion systems. The fact that this $T^2$ dependence is seen in spite of the violation of modified Kohler’s scaling suggests that the Hall angle and magnetoresistance are not governed by the same scattering mechanism. We also observe a linear magnetoresistance in this system, which does not harbor a spin density wave ground state. Implications of our observations are discussed in the context of existing models for the magnetotransport of these strongly correlated electron systems.

Keywords: magnetotransport, unconventional superconductors, Hall effect

(Some figures may appear in colour only in the online journal)
magnetism are controlled by an intricate balance between the $h_{\text{pn}}$, lattice constants, bond angle, etc [3, 23–25]. For example, SrFe$_2$As$_2$ and EuFe$_2$As$_2$ have very similar lattice parameters and ionic radii, and consequently their magnetostructural transition temperatures are very similar [26, 27]. This is in contrast to the BaFe$_2$As$_2$ system, where larger lattice constants and higher $h_{\text{pn}}$ typically leads to lower magnetostructural transition temperatures and higher superconducting transition temperatures.

We report magnetotransport measurements and its scaling analysis in an optimally doped ($x = 0.12$) composition of the Sr(Fe$_{1-x}$Co$_x$)$_2$As$_2$ series. Scaling analysis is a powerful tool to find commonalities and differences in different classes of materials. In the past, many cuprates and heavy fermion systems were shown to have similar magnetotransport scaling behavior, indicating that underlying mechanism behind their unconventional properties might be similar [28–30]. When the transport is dominated by only one type of charge carrier, the relaxation rate is same across the entire Fermi surface, and the carrier concentration does not change with temperature, then the magnetoresistance ($\Delta \rho/\rho_0$) can be scaled as $(H/\rho_0(0))^2$, where $H$ is the applied magnetic field, $\rho_0(0)$ is the zero field resistivity and $\Delta \rho$ is the change in resistivity after the application of magnetic field. This is called Kohler’s rule [31–33]. Kohler’s rule is often violated in the strange metal phase of high-$T_C$ cuprates, heavy fermions and iron-based superconductors [7, 29, 34–38].

In many cuprates and heavy fermions, magnetoresistance was shown to scale not by $(H/\rho_0(0))^2$ but by $\tan \theta_H$ i.e. $\Delta \rho/\rho_0 \propto \tan \theta_H$, where $\tan \theta_H = \rho_{xy}/\rho_{xx}$ [35]. This modified Kohler’s scaling was shown to be valid in a number of heavy fermion systems [28–30, 39] and some FeSCs as well [7, 36, 37], indicating that the magnetotransport in these systems is governed by the same mechanism and antiferromagnetic fluctuations are thought to be at the origin of these unconventional properties [28, 30]. We observe that both the Kohler’s and modified Kohler’s scaling do not work for the Sr(Fe$_{0.88}$Co$_{0.12}$)$_2$As$_2$ system. Another interesting observation is of a quadratic temperature dependence of the cotangent of the Hall angle ($\cot \theta_H \propto T^2$) reminiscent of many cuprates and heavy fermion superconductors [28, 35, 40–42]. It is known that parent compound SrFe$_2$As$_2$ displays linear magnetoresistance in the SDW state [10, 43, 44] (along with small quadratic contribution at low fields), like many other members of FeSCs [8–16]. In the present study, we also report linear magnetoresistance in the strange metal phase of the optimally doped Sr(Fe$_{0.88}$Co$_{0.12}$)$_2$As$_2$ system.

2. Materials and methods

Single crystals of Sr(Fe$_{1-x}$Co$_x$)$_2$As$_2$ ($x = 0.12$) were grown using FeAs as flux. Here, $x = 0.12$ is the actual composition of the crystals determined by energy dispersive x-ray spectroscopy. The Sr(Fe$_{0.88}$Co$_{0.12}$)$_2$As$_2$ single crystal crystallize in the tetragonal ThCr$_2$Si$_2$Te type structure (I4/mmm, No. 139). The lattice parameters ($a = 3.930 \text{ Å}, c = 12.264 \text{ Å}, c/a = 3.120$) obtained from x-ray powder diffraction are in good agreement with existing literature [18]. Additional details of single crystal growth and characterization can be found elsewhere [45]. Magnetotransport measurements were carried out in a 9 T Quantum Design PPMS. Electrical contacts on the sample surface were made using a gold wire of 25 μm diameter and silver epoxy. To remove any exfoliating layers, samples were slightly polished before the measurements. The magnetic field was applied along the crystallographic c axis and electrical current in the $ab$ plane. We have used 5 mA electrical current in all measurements. Polarity of the magnetic field was reversed at each measurement and the Hall resistivity was extracted as the asymmetric component of the signal i.e. $\rho_{xy} = [\rho(+H) - \rho(-H)]/2$. Since magnetoresistance in these systems is very small at high temperatures, especially in the paramagnetic phase, averaging routines were employed to enable the scaling analysis.

3. Results and discussion

The main panel of figure 1 shows the in-plane resistivity from 2–300 K. There are no discernable anomalies associated with the magnetic/structural transitions, which are present in the underdoped systems, implying that the magnetic and structural transitions are completely suppressed. The inset shows the resistivity near the superconducting region. $T_C$ is assigned to the midpoint of the transition ($\approx 14.5$ K), which is approximately the average of onset and offset temperatures which are shown by the arrows. Similar values of optimal $T_C$ were reported previously [18, 45, 46]. Interestingly, maximum $T_C$ in the as grown crystals corresponding to the optimally doped composition ($x \sim 0.07$) in the Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$ series is $\sim 25$ K [19, 47, 48]. The maximum $T_C$ corresponding to the optimal Co doping in as grown Sr(Fe$_{1-x}$Co$_x$)$_2$As$_2$ series is smaller by approximately 10 K.
This difference between the maximum $T_C$ of Ba(Fe$_{1-x}$Co$_x$)$_2$ As$_2$ and Sr(Fe$_{1-x}$Co$_x$)$_2$As$_2$ series can be understood from the fact that maximum $T_C$ is expected to occur in systems with low effective dimensionality. This is because the strength of spin fluctuations is stronger in low dimensional systems and this can lead to higher $T_C$. For instance, it is known that the 1111 systems are most 2D in nature compared to any other member of the FeSCs [49], as a consequence of which, highest $T_C$ are observed in the 1111 systems [3]. Sr(Fe$_{1-x}$Co$_x$)$_2$As$_2$ system is less two-dimensional in nature as compared to Ba(Fe$_{1-x}$Co$_x$)$_2$ As$_2$ system. For example, the ratio of the in-plane and out of plane plasma frequencies ($\omega_p^x/\omega_p^z$), which can serve as a quantitative measure of the effective dimensionality was shown [49] to be higher in BaFe$_2$As$_2$: $\omega_p^x/\omega_p^z = 3.29$ for BaFe$_2$As$_2$ and $\omega_p^x/\omega_p^z = 2.83$ for SrFe$_2$As$_2$.

Interestingly, the critical concentration ($x_c$) where optimal $T_C$ is observed, ($x_c \sim 0.12$ in the present case) is much larger in the Sr(Fe$_{1-x}$Co$_x$)$_2$As$_2$ series as compared to the Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$ series ($x_c \sim 0.07$). This might be due to the fact that the magnetostuctural transition occurs at $\approx 200$ K in Sr(Fe$_{1-x}$Co$_x$)$_2$As$_2$ series which is quite high as compared to the Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$ series. It appears that in order to obtain optimal $T_C$ in Sr(Fe$_{1-x}$Co$_x$)$_2$As$_2$ series, more carriers need to be doped. Similar results were also reported for the BaFe$_2$(As$_{1-x}$P$_x$)$_2$ [50] and (Ba$_{1-x}$K)$_2$Fe$_2$As$_2$ [51] systems, where the optimal $T_C$ is obtained only after the complete suppression of the magnetostuctural transitions.

Figure 2(a) shows the Hall resistivity ($\rho_{xy}$) as a function of the applied magnetic field. Hall resistivity is seen to be linear in the magnetic field which is similar to the optimally doped concentration of the Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$ series [5]. This allows for an unambiguous determination of the Hall coefficient, which is shown in figure 2(b). The Hall coefficient is strongly temperature dependent which is reminiscent of many other iron pnictides [5, 52, 53] and strongly correlated electron systems [28, 54].

Figures 3(a) and (b) shows Kohler’s and the modified Kohler’s plots respectively. Magnetoresistance curves do not collapse on top of each other implying that both scalings are violated in the entire temperature range. As stated previously, Kohler’s rule reads: $\Delta \rho/\rho_0 \propto (H/\rho_0(0))^2$. In the Drude picture, it can be written as: $\Delta \rho/\rho_0 \propto (\tau \hbar m^2/m)$, where $m$ is the electronic mass, $\tau$ is the relaxation time and $H$ is the applied magnetic field. Kohler’s rule is found to be valid for a number of simple metals [32, 33] and even in overdoped regime of strongly correlated electron systems like FeSCs, cuprates and heavy fermions where Fermi liquid like behaviors are typically recovered [28, 34, 37]. Violation of Kohler’s rule in strongly correlated electron systems, especially in their strange metals phase is a common occurrence [7, 30, 35]. This is because the premise on which it is based, i.e. of a single species of charge carrier dominating the transport, relaxation time being invariant over the Fermi surface and carrier concentration not changing with temperature, are often not met in these systems [55].

Unfortunately, to pin down the exact reason for the violation of Kohler’s rule is also not straightforward, especially in complex systems such as the FeSCs because any one or more of the above mentioned factors may be responsible for the violation. For example, it is well known that FeSCs are multiband systems [2, 4], a situation not favorable for Kohler’s scaling. Also, the Hall coefficient is known to be strongly temperature dependent [5, 6], which would mean that carrier concentration is not constant with temperature, which is again an unfavorable condition for the Kohler’s scaling. As stated previously, we also see strongly temperature dependent Hall coefficient, see figure 2(b). In fact, in Co doped BaFe$_2$As$_2$ systems, the carrier concentration was shown to be strongly temperature dependent in an ARPES study [56].

Another possible reason for the violation of the Kohler’s rule could be the variation of relaxation time across the Fermi surface. Such an anisotropic reconstruction of the Fermi surface is reported in FeSCs [57–59] and similar formalisms have been used to explain many non-Fermi liquid like behaviors of the high-$T_C$ copper oxide superconductors [54, 60–62]. To account for the anomalous transport properties of cuprates, the existence of two relaxation times was proposed. It was suggested that the resistivity is governed by a transport relaxation time ($\tau_H$) and $\cot \theta_H$ is governed by the so-called Hall relaxation time $\tau_H$ [35, 60]. In many cuprates, $\rho_{xy}$ is linear in temperature, at least in some region of the temperature-composition phase space whereas $\rho_{xx}$ varies as $1/T$. As mentioned earlier, the modified Kohler’s rule states that $MR \propto \tan^2 \theta_H$ or $1/\cot^2 \theta_H$. This difficulty between the maximum $T_C$ of Ba(Fe$_{1-x}$Co$_x$)$_2$ As$_2$ and Sr(Fe$_{1-x}$Co$_x$)$_2$As$_2$ series can be understood from the fact that maximum $T_C$ is expected to occur in systems with low effective dimensionality. This is because the strength of spin fluctuations is stronger in low dimensional systems and this can lead to higher $T_C$. For instance, it is known that the 1111 systems are most 2D in nature compared to any other member of the FeSCs [49], as a consequence of which, highest $T_C$ are observed in the 1111 systems [3]. Sr(Fe$_{1-x}$Co$_x$)$_2$As$_2$ system is less two-dimensional in nature as compared to Ba(Fe$_{1-x}$Co$_x$)$_2$ As$_2$ system. For example, the ratio of the in-plane and out of plane plasma frequencies ($\omega_p^x/\omega_p^z$), which can serve as a quantitative measure of the effective dimensionality was shown [49] to be higher in BaFe$_2$As$_2$: $\omega_p^x/\omega_p^z = 3.29$ for BaFe$_2$As$_2$ and $\omega_p^x/\omega_p^z = 2.83$ for SrFe$_2$As$_2$.

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The magnetic field $T^2$ in both (a) and (b) is in the range from 0–8 T in both (a) and (b).

Since both the magnetoresistance and $\cot \theta_H$ are determined by the Hall scattering time $\tau_H$ [35, 60], $T^2$ dependence of $\cot \theta_H$ and the validity of modified Kohler’s scaling are often taken as the validation of this theory. This implies that if the modified Kohler’s scaling is invalid, Hall angle should not be quadratic in temperature in this picture. This was observed in a number of cuprates and heavy fermion systems [29, 30, 35, 39]. Some isovalently doped FeSCs were also shown to obey the modified Kohler’s scaling. [7, 37]. The plot of $\cot \theta_H$ as a function of $T^2$ for our system is shown in figure 4. Evidently, a good fit is obtained in most of the temperature range; however, the fit begins to deviate from $T^2$ behavior at low temperatures around 40 K. We suspect that this deviation is due to the proximity to superconducting transition. Note that even in some high-$T_C$ cuprates, modified Kohler’s scaling was shown to be invalid even when $\cot \theta_H$ had quadratic temperature dependence [40, 41, 63, 64]. Consequently, it was suggested that the modified Kohler’s rule is not universally applicable to all high-$T_C$ cuprates either [40, 41, 64]. Our results are the first in iron-based superconductors to suggest the same.

Magnetotransport behavior of the electron-doped 122 families appears to be different from that of the isovalently doped systems. For example, it is known that the parent compound BaFe$_2$As$_2$ and the optimally doped composition ($x = 0.074$) of the Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$ series do not obey modified Kohler’s scaling [12, 65]. On the other hand isovalently doped optimal composition of the BaFe$_2$(As$_{1-x}$P$_x$) [7] and Ba(Fe$_{1-x}$Ru$_x$)$_2$As$_2$ [37] series were shown to obey the modified Kohler’s scaling. It should be noted that underdoped composition of Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$ series is an interesting exception here [12, 65]. Modified Kohler’s rule was found to be obeyed in the SDW state of two different electron underdoped compositions [12, 65]. These observations imply that the scenario of separation of scattering times may not be applicable to the electron-doped 122 families of Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$ and Sr(Fe$_{1-x}$Co$_x$)$_2$As$_2$ FeSCs but is applicable to 122 families of isovalently doped iron pnictides.

It has been argued that many unconventional transport properties of the high-$T_C$ cuprates like strongly temperature dependent Hall coefficient, modified Kohler’s rule, etc can be derived within the framework of near antiferromagnetic Fermi liquid if the current vertex corrections are taken into account [54, 66–68]. In this theory, the Hall coefficient and magnetoresistance are both normalized due to the temperature dependence of the antiferromagnetic correlation length ($\xi_{AF}$) i.e. $R_H \propto \xi_{AF}^2$ and $\Delta\rho/\rho_0 \propto \xi_{AF}^2 H^2/\rho_0^2$. Evidently, from these expressions, Kohler’s rule is violated in the presence of strongly temperature dependent $\xi_{AF}$ whereas the modified Kohler’s rule ($\Delta\rho/\rho_0 \propto R_H^2/\rho_0^2$) remains valid. However, as we can see from figure 3(b) modified Kohler’s scaling is not valid in the system under study. Very similar scaling behavior of Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$ and Sr(Fe$_{1-x}$Co$_x$)$_2$As$_2$ however require a coherent description of normal state transport properties of electron-doped FeSCs.

We now turn our attention to the phenomena of linear magnetoresistance (LMR). As is evident from figure 5, magnetoresistance is linear in magnetic field similar to what was seen in the paramagnetic phase of electron-doped Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$ systems [65]. As mentioned previously, linear magnetoresistance has been observed in SDW state of many families of FeSCs [8–16]. It is often assumed to originate due to the presence of Dirac cone states which arises due to the reconstruction of the Fermi surface that occurs at the
onset of a SDW instability \cite{8,11,15}. Dirac cone states are indeed observed in the photoemission \cite{69} and quantum oscillation experiments \cite{22,70} and are now an established fact in FeSCs.

This LMR is often explained using the quantum LMR (QLM) model of Abrikosov \cite{71-73}. In this model, linear magnetoresistance was predicted in the quantum limit where all carriers occupy the lowest Landau band. Thus, $\rho_{\alpha} \propto NH/n^2$ provided $n \ll (eH/\hbar c)^{3/2}$ and $T \ll eH/\hbar m^*$, where $N$ and $n$ are the density of scattering centers and charge carriers respectively and $H$ is the applied magnetic field. Clearly, low carrier concentration, low temperature and high magnetic field are the favorable conditions to obtain this quantum limit. It is believed that the quantum limit can be reached even at relatively high temperatures and typical laboratory magnetic fields in small Dirac pockets which are formed in the SDW reconstructed Fermi surfaces. Dirac pockets have linear dispersion, as a consequence of which, it is possible to fulfill QLM condition because energy level splitting for linear band (Dirac states) is proportional to the square root of magnetic field ($\Delta_{LL} = \pm \sqrt{2eH/\hbar}$), whereas, for parabolic bands, it is proportional to the magnetic field ($\Delta_{LL} = eH/m^*$ \cite{16}).

Doubts have been raised on the applicability of QLM model to FeSCs \cite{12,65}. For instance, in Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$ the coefficient of LMR determined from experiments was not compatible with the QLM model \cite{12}. QLM model also cannot explain LMR recently discovered in the high temperature paramagnetic phase of several electron-doped compositions of the Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$ series \cite{65}, and the same can be said for the composition in the present study. This is because it is highly unlikely that quantum limit conditions can be reached at such high temperatures and typical laboratory fields \cite{9 T} in the absence of small Dirac pockets.

Another relevant model is due to Koshelev \cite{74} which can in principle explain LMR in the SDW state of FeSCs. It is known that the SDW ordering leads to the reconstruction of the Fermi surface. They argue that the scattering is strongest at the points on the Fermi surface which are connected by the nesting wave vector $Q_{AF}$. The area of regions close to these points grows linearly with the magnetic field, as a consequence of which, linear magnetoresistance is observed. This model also predicts a crossover between the linear and quadratic regimes of magnetoresistance at approximately 2 T, which is in agreement with the experiments in the SDW state. This model, however, has its own limitations in that, it has no mechanism which can explain the LMR in the paramagnetic regime of the optimally doped composition in the present study, which has no SDW order.

4. Conclusions

In summary, we have carried out magnetotransport measurements and the scaling analysis in the optimally electron-doped Sr(Fe$_{1-x}$Co$_x$)$_2$As$_2$ ($x = 0.12$) system. We observed that both the Kohler’s and modified Kohler’s scalings do not work for this system. Interestingly, Hall angle displays a quadratic temperature dependence. These observations imply that the Hall angle and magnetoresistance are not governed by the same scattering process. We also observed linear magnetoresistance (LMR) in this system. This suggests that LMR is possibly a generic feature of the paramagnetic phase of the electron doped 122 systems.

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