Scaling behavior of angular-dependent resistivity in CeCoIn$_5$: Possible evidence for $d$-wave density waves

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In-plane angular-dependent resistivity (ADR) was measured in the non-Fermi liquid regime of CeCoIn$_5$ single crystals at temperatures $T \leq 20$ K and in magnetic fields $H$ up to 14 T. Two scaling behaviors were identified in the low-field region where resistivity shows a linear $T$ dependence, separated by a critical angle $\theta_c$, which is determined by the anisotropy of CeCoIn$_5$; i.e., ADR depends only on the perpendicular (parallel) field component below (above) $\theta_c$. These scaling behaviors and other salient features of ADR are consistent with $d$-wave density waves.

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The recently discovered heavy fermion compound CeCoIn$_5$ (Ref. 1) has generated a lot of interest, partly due to the many analogies present between this compound and the high transition temperature $T_c$ superconductors. Like the cuprates, CeCoIn$_5$ has a layered crystal structure,2 a quasi-two-dimensional electronic spectrum,1,3 and a superconducting phase appearing at the border of the antiferromagnetic phase.4 NMR Knight shift5,6 and heat conductivity7 measurements revealed even parity pairing consistent with $d$-wave density waves.8,9 and electrical transport10 experiments have shown typical non-Fermi liquid behavior and have evoked the possibility of a pseudogap. In fact, infrared spectroscopy studies have revealed the development of a gap in the density of electronic states of CeCoIn$_5$ below $\sim 100$ K.11 As in the case of cuprates, all these features suggest the existence of quantum critical phenomena.12 However, the Fermi surface topology is much more complex than in cuprates, with multiple sheets, which implies the participation of several bands in the pairing process.13-15

In this complex picture, the nature of the normal state in both systems is not trivial. Until recently, the nature of the pseudogap (or the non-Fermi liquid) phase present in CeCoIn$_5$ has not been addressed. The giant Nernst effect found in this material above $T_c$,16 however, reopened the problem of the origin of the pseudogap state, not only in this compound, but also in the cuprates. It has recently been shown that the giant Nernst effect in CeCoIn$_5$ is consistent with unconventional density waves (UDW) or $d$-wave density waves ($d$-DW).17 We recall that in underdoped cuprates, the pseudogap phase has been attributed to the existence of phase fluctuations of the superconducting order parameter,18-22 as well as $d$-DW.23-25 In particular, the giant Nernst effect observed in La$_{2-x}$Sr$_x$CuO$_4$, YBa$_2$Cu$_3$O$_{7-\delta}$, and Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ has recently been interpreted satisfactorily in terms of $d$-DW.26

Here, we present information concerning the nature of the pseudogap of CeCoIn$_5$ through angular-dependent resistivity (ADR). Two different scaling behaviors are revealed in this compound in the non-Fermi liquid regime for applied magnetic fields less than 5 T. Specifically, for angles below (above) a certain critical angle $\theta_c$, the field component perpendicular (parallel) to the $ab$ planes determines the angular-dependent dissipation. The critical angle $\theta_c$ is determined by the anisotropy of the material. These results and the other salient features of ADR measured in high applied magnetic fields are consistent with $d$-wave density waves with the Landau quantization of the quasiparticle spectrum. Our findings bring further understanding of the underlying physics in the non-Fermi liquid regime of this exotic compound and could also advance the understanding of the pseudogap state of the cuprates.

High quality single crystals of CeCoIn$_5$ were grown using the flux method. Typical sizes of the crystals are $0.5 \times 0.5 \times 0.1$ mm$^3$ with the $c$ axis oriented along the smallest dimension. We determined the out-of-plane $\rho_c$ and in-plane $\rho_{ab}$ resistivities using the electrical contact configuration of the flux transformer geometry, as described in Ref. 27. The angular-dependent resistivity $\rho_{ab}(\theta)$ was measured by rotating the single crystal from the $H//c$ axis to the $H//a$ axis, with $\theta$ the angle between $H$ and the $c$ axis. Here we report only in-plane resistivity results.

The angular-dependent in-plane resistivity of CeCoIn$_5$ single crystals was measured in the non-Fermi liquid regime, for $T \approx 20$ K and in magnetic fields $H$ up to 14 T. Figure 1 is a typical contour plot of resistivity obtained from $\rho_{ab}$ vs $\theta$ data measured at different fixed applied magnetic field values and at a temperature of 6 K. A similar topologic contour is obtained over the whole $T$ range investigated. The squares, circles, and triangles correspond to $n=0.45$, 1, and $\frac{5}{2}$, respectively, where $n$ is the exponent of the power-law $T$ dependence of the resistivity; i.e., $\rho(T) = \rho_0 + AT^n$. These values match the exponent values reported previously.12 Note that the contour plot can be divided into three different regions based on the shape of the topologic plots and the values of $n$. Region I is the rectangular part, for which $n=1$. This region is the so-called low-field region ($H < 5$ T) for reasons given later on. Region II is the elliptical part, for which $n=0.45$
and which corresponds to the region around the maximum value of the $\rho_{ab}(H)$ curves for different angles. Region III is a large area with $n = \frac{2}{3}$, which is outside of regions I and II at even higher fields. Region I is more interesting since it represents the typical non-Fermi liquid behavior (for this region $n = 1$) and displays the two scaling behaviors. Therefore, we will discuss the anomalous magnetoresistivity behavior in this region in more detail.

The bottom inset to Fig. 2(a) shows $\rho_{ab}(\theta)$ measured in a low magnetic field of 2 T (region I). The resistivity decreases as $\theta$ increases from $0^\circ$, reaches a minimum around $60^\circ$, and then displays a peak at $90^\circ$. The data of the top inset to Fig. 2(a) were measured in a high field of 9 T (region III). The resistivity increases with increasing angle and displays a shoulder, followed by a peak at $90^\circ$.

In the low-field region (region I), a spectacular scaling of these data is achieved by plotting the resistivity as a function of the component of the applied magnetic field perpendicular to the $ab$ planes, i.e., $H_{\perp} = H \cos \theta$, as shown in the main panel of Fig. 2(a). Note that all the curves measured in $H = 5$ T overlap for all $\theta$ values between $0^\circ$ and a critical angle $\theta_c = 60^\circ$, marked by the arrows, and deviate from this $H \cos \theta$ scaling at higher angles. This value of the critical angle is independent of temperature and applied magnetic field for the range investigated.

We employed a second protocol to measure resistivity, in which we kept the angle between the magnetic field and the $c$ axis fixed and scanned the magnetic field. Figure 2(b) shows the resistivity as a function of the field component parallel to the $ab$ axis ($H_{\parallel} = H \sin \theta$), measured at 6 K for different orientations of $H$. Note that all the resistivity curves scale this time with $H \sin \theta$ for $\theta > \theta_c = 60^\circ$. Therefore, the resistivity data follow two scaling laws:

$$\rho(H, \theta) = \begin{cases} f_1(H \cos \theta) & \text{for } \theta \leq \theta_c = 60^\circ \\ f_2(H \sin \theta) & \text{for } \theta > \theta_c = 60^\circ \end{cases}$$

Figure 1 also clearly shows the presence of the two scaling laws in region I as evidenced by the rectangular region of the $\rho_{ab}$ contours. The presence of these two scaling behaviors indicates that below (above) the critical angle, the field component perpendicular (parallel) to the $ab$ planes determines the in-plane dissipation. A similar analysis of the angular-dependent resistivity data measured in high magnetic fields (region III) has shown that the data are still dominated by the perpendicular (parallel) field component below (above) the critical angle, although the two scaling laws are no longer present.

Next we try to understand the above shape of $\rho_{ab}(\theta)$ measured in both low and high fields and the relationship between the two scaling behaviors. We plot in the inset to Fig. 3 the resistivity measured at 6 K in scanning $H$ up to 14 T at the two fixed angles ($\theta = 0^\circ$ and $\theta = 90^\circ$) corresponding to the two field orientations (perpendicular and parallel, respectively, to the $ab$ planes) which seem to determine the physics below and above $\theta_c$, respectively. For the first field orientation ($H_{\perp}ab$ planes), $\rho_{ab}(H_{\perp})$ increases with increasing $H_{\perp}$, reaches a maximum around 5 T, and decreases with further increasing $H_{\perp}$. We define the low- (high-) field region as the field region for which $H_{\perp} < 5$ T ($H_{\perp} > 5$ T), based on this behavior of $\rho_{ab}(H_{\perp})$. This $\rho_{ab}(H_{\perp})$ dependence gives a qualitative explanation of the $\rho_{ab}(\theta)$ dependence [shown in the
The scaling of the magnetoresistivity curves for the \( H \parallel c \) axis (for which the Lorentz force is maximum) and for the \( H \parallel \parallel a \) axis (for which the Lorentz force is zero) shown in Fig. 3 implies that the spin effect, rather than the orbital effect, is responsible for the magnetoresistivity in region I. The fact that in this region the resistivity is also linear in \( T \), indicates that this linear \( T \) dependence is as well a result of spin fluctuations. This conclusion that spin fluctuations dominate the charge transport in the non-Fermi liquid regime is consistent with recent In-NQR (nuclear quadrupole resonance), and Co-NMR experiments, which have revealed that the magnetic nature in CeCoIn\(_5\) is characterized by strong antiferromagnetic spin fluctuations in the vicinity of the quantum critical point.

In the following, we show that all the observed features of ADR of CeCoIn\(_5\) in the non-Fermi liquid regime, when a magnetic field is rotated from the \( H \parallel c \) axis to the \( H \parallel \parallel a \) axis with \( \theta \) the angle between the \( H \) and the \( c \) axis, can be consistently described in terms of \( d \) wave-density waves in a magnetic field. The UDW or \( d \)-DW is a kind of density wave in which the gap function \( \Delta(\vec{k}) \) vanishes on the line nodes. Therefore, the transition from the normal state to the UDW is a metal to metal transition. The UDW exhibits two characteristics: angular-dependent resistivity and the giant Nernst effect. A UDW in the low temperature phase of \( \alpha-(ET)_2KHg(SCN)_4 \) and the metallic phase of (TMTSF)\(_2\)X with \( X=PF_6 \) and ReO\(_3\) has been identified through ADR.

We assume that the electrical conductivity in the non-Fermi liquid regime is given by

\[
\rho(H, \theta)^{-1} = \sum_n \sigma_n \text{Sech}^2(E_n/2k_B T),
\]

where \( E_n \) is the energy of all fermionic excitations (holes and particles). As shown below, this new formula appears to be more appropriate than the one used earlier. In the absence of a magnetic field, we assume that the quasiparticle energy spectrum is given by

\[
E(\vec{k}) = \sqrt{\xi^2 + \Delta(\vec{k})^2},
\]

where \( \xi = \epsilon(k_0 - k_F) - (\nu'/\nu) \cos(c k_z) \) and \( \Delta(\vec{k}) = \Delta(\vec{\phi}) \); here \( \nu \) and \( \nu' \) are Fermi velocities in the \( ab \) plane and along the \( c \) axis, respectively, \( k_0 \) is the radial wave vector within the \( ab \) plane, \( \Delta \) is the maximum value of the \( d \)-DW energy gap \( \Delta(\vec{\phi}) \), and \( \tan \phi = k_z/k_z \). Here we assume that \( \Delta(\vec{\phi}) \) has \( d_{xy} \)-wave symmetry. In the vicinity of the nodal points, it is convenient to replace \( \Delta^2 \sin^2(2\phi) \) by \( \nu^2 k_z^2 \), where \( k_z \) is perpendicular to \( k_0 \) within the \( ab \) plane and \( k_z = \Delta/E_F \). Then in a magnetic field which makes an angle \( \theta \) with the \( c \) axis, the energy spectrum becomes

\[
E_{1n}^+ = \pm \sqrt{2env_F H(\nu \cos \theta + \nu' \sin \theta)} - \mu,
\]

\[
E_{2n}^+ = \pm \sqrt{2env_F H(\nu' \cos \theta + \nu \sin \theta)} - \mu.
\]

Here \( E_{1n}^+ \) and \( E_{2n}^+ \) are the two branches of the Landau levels, \( n=0,1,2,... \), and \( \mu \) is the chemical potential. We note that in Ref. 26 only \( E_{1n}^+ \) is considered. The electrical conductivity is then given by

\[
\rho_{ab}(H) = \sigma_{ab}^{-1} = \sum_n \sigma_n \text{Sech}^2(E_n/2k_B T).
\]
the model used to analyze the experimental data.

Moreover, the $d$-DW model given by Eq. (6) also gives the scaling observed experimentally at $H < 5$ T. Figure 5 is a plot of the $\rho(\theta)$ data (open symbols), the fitting with Eq. (6) (solid line), and the two scalings (dashed lines) calculated from Eq. (6) in which $E_{1n}^a$ and $E_{2n}^a$, Eqs. (4) and (5), respectively, include only the $H \cos \theta$ or $H \sin \theta$ terms, for $\theta < 60^\circ$ and $\theta > 60^\circ$, respectively. Note the excellent agreement between the fitting line and the two scaling lines. Therefore, even though the model proposed here is quite complex, it gives the two experimentally observed scaling laws at low magnetic field values.

In summary, comprehensive ADR measurements in the non-Fermi liquid region of CeCoIn$_5$ at $T \approx 20$ K have shown the presence of two different scaling behaviors in the low-field region (region I) which involve the $H$ and $\theta$ dependence and are due to spin fluctuations. The two scaling regions are separated by a critical angle $\theta_c$, which is determined by the intrinsic anisotropy. In the scaling region, the resistivity is linear in $T$. At higher fields, the ADR data are governed by the same physics, even though the two scalings fail. A possible explanation for this anomalous ADR in terms of $d$-wave density waves with Landau quantization of the quasiparticle spectrum was presented. This approach describes very well the salient features of ADR data: (i) the distinctive angular dependences observed in the low- ($dp/dH_x > 0$) and high-$\theta$ ($dp/dH_x < 0$) field regimes follow naturally from Eq. (7); (ii) the low-field scaling behaviors follow from the quasiparticle spectrum given by Eqs. (4) and (5). In addition, the quasi-two-dimensional aspect of $d$-wave density waves is explored here.

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SCALING BEHAVIOR OF ANGULAR-DEPENDENT...