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Authors
Nair, S
Wirth, S
Nicklas, M
et al.

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Hall effect and magnetoresistance in the heavy fermion superconductor $CeCo(In_{1-x}Cd_x)_5$

Sunil Nair[1], S Wirth[1], M Nicklas[1], A D Bianchi[2], Z Fisk[3] and F Steglich[1]

[1] Max Planck Institute for Chemical Physics of Solids, 01187 Dresden, Germany
[2] Départment de Physique, Université de Montréal, Montréal, Quebec H3C 3J7 Canada
[3] University of California, Irvine, California 92697, USA

Abstract. We present measurements of the low temperature Hall effect and magnetoresistance in the heavy fermion superconductor $CeCo(In_{0.925}Cd_{0.075})_5$ as a function of applied magnetic field. The Hall resistivity ρ_{xy} is observed to be negative indicating electron dominated transport. Features corresponding to the possible destabilization of the antiferromagnetic ground state are observed. Magnetic field sweeps show that the resistivity $\rho_{xx}(H)$ is hysteretic in this regime, indicating that these transitions could be first order in nature.

1. Introduction

The heavy fermion systems of the form $CeMIn_5$ (where M = Co, Ir or Rh) have attracted wide attention, owing to the fact that their physical properties reveal a fascinating interplay between unconventional superconductivity and magnetism [1]. $CeCoIn_5$ is an ambient pressure superconductor, with a superconducting transition temperature T_c of 2.3 K, which is the highest amongst all Ce based heavy fermion superconductors [2]. Even more striking has been the observation that the superconducting gap function has line nodes [3], and is most likely to have a d wave symmetry. This was conjectured to arise as a consequence of the coupling of the incipient antiferromagnetic fluctuations to the inherently two-dimensional Fermi surface in this class of materials. This along with a host of other experimental observations, like a linear temperature dependence of the resistivity, $\rho_{xx}(T)$, a strongly temperature dependent Hall effect, $R_H(T)$, and even the possible presence of a pseudogap [4] in the electronic density of states has brought into focus the remarkable similarities which these systems share with the high T_c cuprates [5].

A recurring theme of interest which binds some of these systems with the high T_c cuprates, is the influence which a putative quantum critical point (QCP) may have on their physical properties. In $CeCoIn_5$, this QCP is expected to be passed by the application of magnetic fields of the order of the superconducting upper critical field (H_{c2}). Whether these two fields exactly coincide [6] or are separated [7] remains to be determined unambigously. A possible means of disentangling the superconductivity from the magnetism in these systems is the use of dopants on specific sites which preferentially influence one ground state over the other. However, the substitution of La in the Ce site [8], and Rh in the Co site [9] were relatively unsuccessful in this regard, since in both these cases the superconductivity was observed to be suppressed without the emergence of long-range magnetic order. A pronounced destabilization of superconductivity was also observed when small amounts ($\approx 3.6\%$) of Sn were substituted on the In site [10]. Investigation of the local structure around the Sn dopants, using X-ray absorption spectroscopy revealed that this rapid suppression of superconductivity arises as a consequence of the perturbation of the Ce-In planes. This is because of the fact that Sn is not distributed randomly on the in-plane and out-of-plane In sites, but it preferentially substitutes within the Ce-In plane [11]. A remarkable advance was the observation that Cd substitution acts as an extremely efficient electronic tuning agent, and unequivocally shifts the ground state from a superconducting to an antiferromagnetic one [12]. Besides being a direct indication of the proximity of the parent $CeCoIn_5$ to an antiferromagnetic instability, this also opened up an exciting ambient pressure phase space for extensive investigations. For instance, at intermediate doping levels (nominal doping of 7.5% to 12.5%), a two phase region with co-existing orders was observed, with the antiferromagnetic transition temperature T_N being larger than the superconducting T_c. Though the smooth evolution of both T_c and T_N with doping was used to infer against real space inhomogeniety [12], recent nuclear magnetic resonance measurements [13] have concluded that superconductivity and magnetism coexist microscopically. It was suggested that Cd substitution does not directly influence the Fermi surface, but acts as nucleation sites where droplets with antiferromagnetic order emerge. Here we report on preliminary Hall effect and magnetoresistance measurements on $CeCoIn_5$ system with 7.5% nominal Cd substitution. This system is reported to have a T_N of 2.3 K and a superconducting T_c of 1.8 K [12]. The effects of an applied magnetic field on both these electronic ground states are investigated.

2. Experimental details

All the magnetotransport measurements are done in the form of isothermal field sweeps on a flux-grown high quality single crystal. The standard six contact geometry was used, with the magnetic field being applied along the crystallographic c axis and the current along the ab plane. The setup is based on a modified Kelvinox 25 dilution refrigerator, with low temperature transformers, low noise voltage pre-ampliers and lock-in amplifiers used in conjunction to achieve a sensitivity of the order of $\pm$ 0.01 nV. Measurements were done at temperatures down to 60 mK and in magnetic fields up to 15 T. The Hall contribution was obtained as the asymmetric component under magnetic field reversal.

3. Results and Discussions

The Hall effect has proven to be of great utility in the investigation of heavy fermion systems in the vicinity of a QCP. In these systems, the Hall response at low temperatures is predominantly from the normal part of the Hall effect and thus, is an indirect measure of the Fermi surface volume. For instance, in the system $YbRh_2Si_2$ it was shown that the Fermi surface volume changes abruptly across the QCP [14]. Besides implying that complete Kondo screening of local moments abruptly vanishes at the QCP, this was also used to preclude the spin density wave scenario, where one would expect a continous change in the Fermi surface volume. Measurements of the Hall effect (in conjunction with the resistivity) have also been used in $CeCoIn_5$ and $CeIrIn_5$ to infer on the presence of antiferromagnetic fluctuations [7] and the possible presence of a precursor state to superconductivity [15] respectively.

Fig. 1a depicts the Hall resistivity $\rho_{xy}(H)$ as measured in $CeCo(In_{0.925}Cd_{0.075})_5$ at 200 mK. The measured ρ_{xy} is negative indicating electron-like transport. Moreover, it is observed to be strongly nonlinear as a function of applied magnetic field down to the lowest measured temperatures. This is in sharp contrast to observations made in the parent compound $CeCoIn_5$ [7]. H_{c2} is manifested as a sharp drop in ρ_{xy} at around 4 T. In the high field region a nearly quadratic dependence on H is observed, as is shown by the dotted line. It is interesting to note that a similar behavior ($\rho_{xy} \sim H^2$) was earlier seen in the system $CeIrIn_5$ [15], presumably related to the fact that it is a compensated metal. In the absence of more direct evidence like de Haas-van Alphen measurements on Cd substituted $CeCoIn_5$, it is not possible to claim

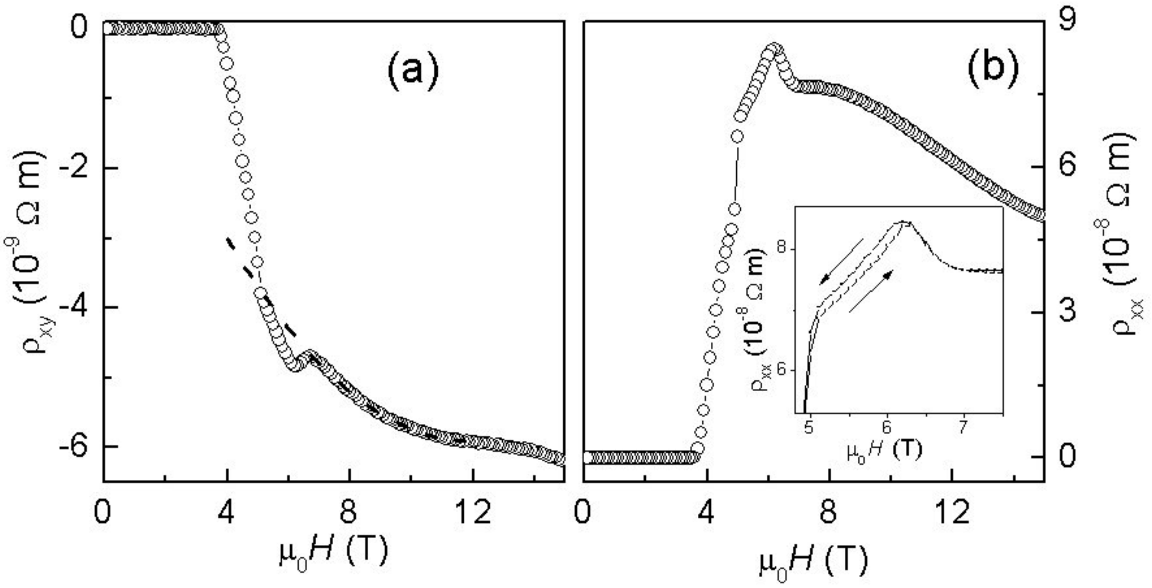

Figure 1. (a) The isothermal Hall resistivity $\rho_{xy}(H)$ as measured in $CeCo(In_{0.925}Cd_{0.075})_5$ at 200 mK. The sharp drop corresponds to the onset of superconductivity. The resistivity $\rho_{xx}(H)$ as measured at the same temperature is shown in (b). A step in $\rho_{xx}(H)$ is observed at around 5 T, followed by a change in the sign of the magnetoresistance at 6 T. These features probably correspond to the destabilization of antiferromagnetic order, the hysteretic nature of which is depicted in the inset.

unequivocally that the doped systems are also compensated metals like the parent systems. However, the quadratic regime observed in our Hall measurements do indicate that this is most probably the case. An additional feature is seen at about 6 T (between H_{c2} and the region with a quadratic H dependence), which is unlike that reported earlier in the undoped parent systems. Considering the fact that the Cd doped $CeCoIn_5$ has a magnetically ordered state preceeding superconductivity, this feature could correspond to a magnetic field destabilization of the antiferromagnetic ground state in this system.

This destabilization of the antiferromagnetic state is more clearly seen in the field dependence of the magnetoresistance. Fig 1b depicts the resistivity ρ_{xx} measured as a function of the applied field H at 200 mK. Careful inspection shows that two distinct features are now visible above H_{c2}: a sharp step-like rise in $\rho_{xx}(H)$ at about 5 T and a more gradual crossover in the sign of the magnetoresistance at 6 T. Beyond this field, $\rho_{xx}(H)$ is seen to reduce with the applied field, probably indicating that the quasiparticle scattering processes arising as a consequence of magnetic fluctuations are suppressed. If these features truly correspond to a magnetic field induced transition of the antiferromagnetic lattice, then they in all probablity must also be first order in nature. That this is indeed the case here is evidenced by the presence of a hysteresis in the increasing and decreasing field cycles, as is shown in the inset.

In the absence of prior reports on the high field magnetization of the Cd doped $CeCoIn_5$ systems, one can only speculate on the nature of these anomalies observed in our magnetotransport measurements. In the closely related antiferromagnetic $CeRhIn_5$ for instance, no field induced metamagnetic transition was observed up to 52 T when the field was applied along the crystallographic c axis [16]. However, it is pertinent to note that recent neutron diffraction measurements on Cd substituted $CeCoIn_5$ of similar doping have revealed that the antiferromagnetic ordering in these doped systems is commensurate with the crystal lattice [17]. This is in sharp contrast to observations in $CeRhIn_5$, where the magnetic structure is clearly seen to be incommensurate [18]. In spite of the subtle differences in the magnetic structure, it would be reasonable to expect that anisotropy in the doped systems is also XY like. Thus the applied field along the c axis could result in a spin-flop-like transition, with the spins being forced to align perpendicular to their preferred basal orientation. The sharp step-like feature observed in $\rho_{xx}(H)$ is even more intruiging, and could be related to a rather abrupt change in the scattering mechanism at the interface of the antiferromagnetic droplets which are speculated to form in this system as a consequence of Cd substitution. Similar experimental signatures has been observed earlier, for instance, in the mixed valent manganites [19] and some dilute layered antiferromagnets [20]. Low temperature magnetization measurements are currently being conducted to throw more light on this aspect.

In summary, preliminary Hall effect and magnetoresistance measurements on single crystalline $CeCo(In_{0.925}Cd_{0.075})_5$ are reported. Experimental signatures corresponding to a possible destabilization of the antiferromagnetic ground state is observed in the isothermal field sweeps. The presence of a hysteresis in the increasing and decreasing field cycles suggests that this transition may be first order in nature.

4. Acknowledgements

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