Unconventional density wave in CeCoIn$_5$?

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Very recently large Nernst effect and Seebeck effect were observed above the superconducting transition temperature $2.3$ K in a heavy fermion superconductor CeCoIn$_5$. We shall interpret this large Nernst effect in terms of unconventional density wave (UDW), which appears around $T = 18$ K. Also the temperature dependence of the Seebeck coefficient below $T = 18$ K is described in terms of UDW. Another hallmark for UDW is the angular dependent magnetoresistance, which should be readily accessible experimentally.

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I. INTRODUCTION

The new heavy fermion superconductor CeCoIn$_5$ discovered recently has attracted considerable attention. For example there are many parallels between CeCoIn$_5$ and high $T_c$ cuprate superconductors: the quasi-two dimensionality, d-wave superconductivity and the appearance of superconductivity in the vicinity of antiferromagnetic state.

Very recently Bel et al. in Ref. 6 reported large thermoelectric power and Nernst effect in CeCoIn$_5$ above the superconducting transition temperature. The large thermoelectric effect is naturally understood in terms of the Kondo lattice. The schematic phase diagram of CeCoIn$_5$ is shown in Fig. 1. From the Fermi liquid to UDW region, the resistivity changes from $T^2$ to $T$. In this Letter we want to show that both the Seebeck coefficient and the Nernst effect below $T < 18$ K are described in terms of unconventional density wave (UDW).

UDW can be unconventional charge density wave or unconventional spin density wave, though further experiments are needed to select one of them. UDW is a kind of density wave with the quasiparticle energy gap $\Delta(k)$, which has usually nodes on the Fermi surface. Here $k$ is the quasiparticle wave vector. Many people think now that the pseudogap phase in high $T_c$ superconductors is UDW. Also we have shown recently that the low temperature phase of $\alpha$-(BEDT-TTF)$_2$KHg(SCN)$_4$ is UCDW. In fact high $T_c$ cuprates in the pseudogap regime and the LTP in $\alpha$-(BEDT-TTF)$_2$KHg(SCN)$_4$ exhibit large negative Nernst effect.

The quasiparticle energy in UDW in a magnetic field is quantized. Then in an electric field $E$ within the conducting plane, the quasi-particle orbits drift with the velocity $v_D = E \times B / B^2$. This gives rise to the transverse heat current $J_{\text{heat}} = TSv_D$, where $T$ and $S$ are the temperature and the entropy associated with the quasiparticles, respectively.

As to the Seebeck effect below $T < 18$ K, we have to assume that the large thermoelectric power around $T \sim 20$ K is due to the Kondo effect. We assume also that the Kondo lattice instability is disrupted by the appearance of UDW around $T = 18$ K. The present model describes the $T$ linear electric resistance observed for $T < 10$ K$\sim$ $T_c/2$. 

FIG. 1: The schematic magnetic field-temperature phase diagram of CeCoIn$_5$ after Ref. 6.
II. QUASIPARTICLE SPECTRUM

The quasiparticle spectrum in UDW in CeCoIn$_5$ is given by

$$E_{\pm}(k) = \pm \sqrt{\frac{2en}{mv^2}} |B\cos(\theta)|\Delta(T) - \mu, \quad (1)$$

where $v$, $\Delta$ and $\mu$ are the Fermi velocity, the maximum of the energy gap and the chemical potential, respectively. Here we have assumed d-wave DW as in high $T_c$ cuprates$^{9,10,11}$. In the vicinity of the nodal points it is convenient to replace $\Delta^2 \cos^2(2\phi)$ by $v^2 k_F^2$, where $v_{\perp}/v = \Delta/E_F^{12}$. Now in a magnetic field tilted by an angle $\theta$ from the c-axis, the energy spectrum becomes$^{14,18}$

$$E_{\pm} = \pm \sqrt{\frac{2en}{mv}} |B\cos(\theta)|\Delta(T) - \mu, \quad (2)$$

where $m^* = \hbar v_F/2$ and $n = 0, 1, 2, \ldots$. The energy spectrum is very similar to the one of the Dirac particle in a magnetic field$^{20}$. From the above quasiparticle spectrum, the electric conductivity and Seebeck coefficient are obtained as

$$\sigma = \sigma_0 + \sum_{n>0,\pm} \sigma_n \frac{1}{\exp(x_n^0) + 1}, \quad (3)$$

$$S_{xx} = \frac{\pi^2}{3e} T \frac{\partial}{\partial \mu} \ln(\sigma(\mu)) =$$

$$\frac{\pi^2}{3e} T \sigma^{-1} \left\{ \sum_{n>0,\pm} \frac{\partial \sigma_n}{\partial \mu} \left[ \exp(x_n^0) + 1 \right]^{-1} \right. \right.$$ \left. \left. + \frac{1}{T} \sum_{n>0,\pm} \sigma_n \exp(x_n^0) \left[ \exp(x_n^0) + 1 \right]^{-2} \right\}, \quad (4)$$

where $x_n^0 = (\sqrt{2en\Delta(T)}|B\cos(\theta)|/m^* \pm \mu)/T$. Here we took the standard expression of the thermoelectric power$^{21}$. A more systematic analysis of the Kondo effect plus Landau quantization will be dealt with in a future paper. Also we have assumed $\partial \sigma_n/\partial \mu \sim \sigma_n/T_K$ with the Kondo temperature $T_K \sim 20$ K, and this is expected to be the dominant contribution to the Seebeck coefficient. The Nernst effect is given on the other hand by$^{14}$

$$\alpha_{xy} = - \frac{S}{B\sigma}, \quad (5)$$

where the entropy $S$ reads as

$$S = \frac{g(0)|B\cos(\theta)|}{m^*} \ln(2) +$$

$$\sum_{n>0,\pm} \left\{ 2 \ln \left( 2 \cosh \left( x_n^0 \right) \right) - x_n^0 \tanh \left( x_n^0 \right) \right\}, \quad (6)$$

where $g(0)$ is the density of states at the Fermi energy in the normal state.

![FIG. 2: The magnetic field dependence of the Seebeck coefficient is shown for $T = 1.3$ K, 1.65 K, 2.5 K, 3.5 K and 4.8 K from bottom to top. The circles denote the experimental data, the solid line is our fit.](image1)

![FIG. 3: The magnetic field dependence of the Seebeck coefficient is shown for $T = 7.3$ K, 10.5 K and 15 K from bottom to top. The circles denote the experimental data, the solid line is our fit.](image2)

III. COMPARISON WITH EXPERIMENTS

We first show $S_{xx}$ and $\alpha_{xy}$ versus $B$ in Figs. 2, 3 and 4 for several temperatures. The fittings to the data from Ref. 6 appear to be excellent except for very small fields. But these deviations are expected, since we used only 3 Landau levels ($n = 0, 1$ and 2) in these fittings. Also the fittings are expected to break down when the system becomes superconducting ($B < H_{c2}$ in Figs. 2 and 4). From the fittings, the temperature dependence of the conductivities ($\sigma_n$) can be extracted. Their be-
behaviour look somewhat strange, as seen in Fig. 6. First of all there is a clear break at $T \sim 5$ K, which may indicate some unknown transition. Below this temperature, $\sigma_0$ and $\sigma_2$ varies as $1/T$, while $\sigma_1$ turns out to be constant. The former is consistent with the observation $\rho = 1/\sigma \sim T$. Their ratio at 10.5 K was found to be $\sigma_0/\sigma_2 = 0.02$ and $\sigma_1/\sigma_2 = 0.5$, which suggests that the resistivity is dominated by the $n = 2$ Landau level, but $\sigma_1$ becomes also important with increasing temperature. Also the temperature dependence of $\Delta(T)/m^*$ is unusual. By assuming $\Delta(T) \sim 40$ K independent of temperature in this $T$ region, $v \sim 1/m^*$ increases with increasing temperature as $(c+T)^4$, $c > 0$ constant. Perhaps this can be the manifestation of quantum critical point in CeCoIn$_5$. Therefore, in spite of somewhat unusual temperature dependence of physical quantities like $\sigma_n(T)$ and $v(T)$, the simple theoretical expressions for the Seebeck and Nernst coefficients (Eqs. 4 and 5) work very well to describe the magnetic field dependence of $S_{xx}$ and $\alpha_{xy}$.
IV. CONCLUSION

In summary we have analysed recent magnetothermopower data from CeCoIn$_5$ for $T < 20$ K in terms of UDW, which appears around 18 K. As stressed elsewhere, the large negative Nernst effect is the hallmark of UDW. Indeed, UDW provides us with excellent description of both Seebeck coefficient and Nernst coefficient observed in CeCoIn$_5$. This situation is very similar to what we encounter in $\alpha$-(BEDT-TTF)$_2$KHS(SCN)$_2$ salt, (TMTSF)$_2$PF$_6$ and in high $T_c$ cuprates YBCO, LSCO and Bi$_2$2212.

Also we recall, that the large Nernst effect observed in NbSe$_2$ indicates, that CDW in this material should be UCDW. We expect also that the giant Nernst effect will provide definitive signature of UDW in candidate systems like the antiferromagnetic phase in URu$_2$Si$_2$, CeRhIn$_5$, CeCu$_2$Si$_2$, UBe$_{13}$ and the glassy phase in $\kappa$-(ET)$_2$ salts.

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