Evidence for a new magnetic field scale in CeCoIn$_5$

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The Nernst coefficient of CeCoIn$_5$ displays a distinct anomaly at $H_\kappa \sim 23$ T. This feature is reminiscent of what is observed at 7.8 T in CeRu$_2$Si$_2$, a well-established case of metamagnetic transition. New frequencies are observed in de Haas-van Alphen oscillations when the field exceeds 23 T, which may indicate a modification of the Fermi surface at this field.

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Heavy-Fermion (HF) compounds display a dazzling variety of physical phenomena which still lack a satisfactory general picture. The "non-Fermi-liquid" behavior emerging in the vicinity of a magnetic quantum critical point (QCP), associated with a continuous (i.e. second-order) phase transition at zero temperature, has recently attracted much attention. The case of the HF superconductor CeCoIn$_5$ is intriguing. Magnetic field alters the normal-state properties of this system in a subtle way. In zero field, the system displays neither a $T^2$ resistivity nor a $T$-linear specific heat (standard features of a Landau Fermi liquid) down to the superconducting transition. When superconductivity is destroyed by the application of pressure or magnetic field, the Fermi-liquid state is restored. In the latter case, the field-tuned QCP identified in this way is pinned to the upper critical field, $H_{c2}$ of the superconducting transition. This is unexpected, not only because quantum criticality is often associated with the destruction of a magnetic order, but also because the superconducting transition becomes first order at very low temperatures. The possible existence of a magnetic order with a field scale close to $H_{c2}$ and accidentally hidden by superconductivity, has been speculated but lacks direct experimental support.

Comparing CeCoIn$_5$ with the well-documented case of CeRu$_2$Si$_2$ is instructive. In the latter system a metamagnetic transition occurs at $H_m = 7.8$ T: the magnetization jumps from 0.6 $\mu_B$ to 1.2 $\mu_B$ in a narrow yet finite window. The passage from an antiferromagnetically (AF) correlated system below $H_m$ to a polarized state dominated by local fluctuations above is accompanied by a sharp enhancement in the quasi-particle mass in the vicinity of $H_m$. This is thus akin to a field-tuned QCP. A sudden change of the Fermi surface (FS) topology across the metamagnetic transition has been established by de Hass-van Alphen (dHvA) effect studies, where new frequencies were detected above $H_m$.

In this letter, we report on two sets of experimental studies which indicate that the effect of the magnetic field on the normal-state properties of these two systems share some common features. They point to the existence of another field scale in CeCoIn$_5$ which has not been previously identified. By measuring the Nernst coefficient and studying quantum oscillations, we find compelling evidence that close to $H_\kappa \sim 23$ T, the FS is modified. Therefore, in the $T = 0$ limit, CeCoIn$_5$ appears to display at least two distinct field scales.

Single crystals of CeCoIn$_5$ were grown using a self-flux method. Thermoelectric coefficients were measured using a one-heater-two-thermometer set-up. dHvA measurements were done using a torque cantilever magnetometer. The magnetometer was mounted in a top-loading dilution refrigerator equipped with a low-temperature rotation stage.

We begin by presenting the field-dependence of the Nernst coefficient in CeRu$_2$Si$_2$, which demonstrates the remarkable sensitivity of this probe. Fig. 1 shows the field-dependence of the Nernst signal ($N = \frac{E_x}{\partial T_x}$) in CeRu$_2$Si$_2$. As seen in the upper panel of the figure, $N$ abruptly changes sign around the metamagnetic transition field, $H_m = 7.8$ T. Besides this striking feature, the field-dependence of the Nernst signal presents additional structure. The lower panel of the same figure shows the field-dependence of the dynamic Nernst coefficient, $\nu = \frac{\partial N}{\partial H}$ at 2.2 K. It presents two anomalies just below and above $H_m$: a sharp minimum at $\sim 8.2$ T and a smaller maximum at 7 T. The inset of the figure shows the temperature-dependence of these two anomalies which closely follow the lines of the pseudo-phase diagram of CeRu$_2$Si$_2$. These are crossover lines which represent anomalies detected by specific heat and thermal expansion measurements.

The case of CeRu$_2$Si$_2$ shows how sensitively the Nernst signal probes metamagnetism. This is presumably due to its intimate relationship with the energy dependence of the scattering rate (the so-called Mott formula: $\nu = \frac{\pi^2 k_F^2 T}{3\hbar m} (\hat{\tau}^{-1})_{\epsilon=\mu}$). With this in mind, let us focus on the case of CeCoIn$_5$. The first study of the Nernst effect in this compound found a very large zero-field Nernst coefficient emerging below $T^* \sim 20K$. Below this temper-
FIG. 1: Upper panel: field-dependence of the Nernst signal in CeRu$_2$Si$_2$ for selected temperatures. Lower panel: the Nernst coefficient, defined as the derivative of the signal at $T = 2.2$ K. The arrows show the position of a maximum and a minimum close to the metamagnetic transition field. The inset shows the position of these anomalies (triangles) in the $H - T$ plane compared to those detected by previous studies of thermal expansion (solid and empty circles) and specific heat (solid and empty squares).

FIG. 2: Upper panel: field-dependence of the Nernst signal in CeCoIn$_5$ for two temperatures. Lower panel: the Nernst coefficient for 2.2 K obtained by taking the derivative of the data presented in the upper panel. Arrows identify three anomalies in the 2.2 K curve. A sketch of the $H - T$ phase diagram based on these anomalies is shown in the inset of the upper panel.

The field-dependence of the Nernst coefficient in the 12 – 28 T field range, reported here for the first time, reveals new features emerging at still higher magnetic fields. The $H - T$ (pseudo-)phase diagram of the system is apparently more complicated than previously suggested, and the field associated with the emergence of the Fermi-liquid close to $H_L(0)$ ($\sim 5$ T) is not the only relevant field scale for CeCoIn$_5$.

After detecting the Nernst effect anomalies, we performed high-resolution dHvA measurements at high fields. They provide another evidence for the existence of a magnetic field, the Nernst signal saturates and, therefore, $\nu$ becomes very small. This is the behavior previously detected and identified as the signature of a field-induced Fermi-liquid state. However, above 15 T, $N$ increases suddenly again, reaches rapidly a maximum and then decreases. The field-dependence of $N$ at $T = 1.1$ K repeats the same scheme with all field-scales shifted to lower values. The two anomalies of opposite signs revealed in $\nu(B)$ (marked no.2 and no.3 in the figure) are reminiscent of what was observed in the case of CeRu$_2$Si$_2$.

This indicates the presence of two distinct field scales in CeCoIn$_5$. However, contrary to the case of CeRu$_2$Si$_2$, they do not tend to merge in the zero-temperature limit. The lower-field anomaly (no.2) lies close to the line already identified by the resistivity measurements. At $T = 0$, this line ends up very close to the superconducting upper critical field ($\sim 5$ T for this field orientation). The high-field anomaly (no.3) identifies another (almost horizontal) line in the $H - T$ plane and yields a second field scale ($\sim 23$ T). A sketch of the (pseudo-)phase diagram of CeCoIn$_5$ is shown in the inset of Fig. 2.

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The field-induced emergence of new dHvA frequencies becomes evident when comparing the Fourier spectra of the dHvA oscillations below and above 23 T. Such a comparison is shown in Fig. 4 for magnetic field applied at 0.5° and 2.5° from the c-axis, the two orientations for which the effective masses were measured. The dHvA frequencies and corresponding effective masses for these two orientations are given in Table I. All the fundamental frequencies observed both below and above 23 T are marked in the figure. The frequencies \(^{16 - 23\; T}\) \(F_5\) and \(F_6\) are observed both below and above 23 T and are in good agreement with those found in the previous dHvA studies performed at lower fields \(^{22, 24, 27}\). It was shown \(^{20}\) that all these frequencies correspond to quasi-two-dimensional FS that are well accounted for by the itinerant f-electron band structure calculations.

For the magnetic field orientation at 0.5° from the c-axis, two new frequencies \(F_5\) and \(F_6\) appear in the oscillatory spectrum above 23 T (Fig. 4 b). Neither of them was observed in the previous lower field dHvA studies. The corresponding effective masses of the new frequencies are quite high, being of the order of 35 \(m_0\) and 65 \(m_0\). The frequency \(F_a\) might correspond to one of the closed orbits of the 15-electron band of the band structure calculations \(^{20}\). In this case, however, there is no reason for this frequency not being observed at lower field. Even taking into account its high effective mass and its presumable field dependence it should have been observed at lower fields since its effective mass is considerably smaller than that of \(F_b\), while the amplitude is much stronger. The other frequency, \(F_b\), can not be reconciled with any orbit from the theoretical calculations.

For the magnetic field at 2.5° to the c-axis (Fig. 4 c and d), \(F_a\) and \(F_b\) with high effective masses are also present.

**TABLE I: dHvA frequencies and corresponding effective masses observed below and above \(H_k \sim 23\; T\).**

| \(\theta = 0.5^\circ\) | \(\theta = 2.5^\circ\) |
|----------------------|----------------------|
| \(F_1\)               | \(F_1\)               |
| \(F_5\)               | \(F_5\)               |
| \(F_6\)               | \(F_6\)               |
| \(F_7\)               | \(F_7\)               |
| \(F_8\)               | \(F_8\)               |
| \(F_9\)               | \(F_9\)               |

Another field scale at \(H \sim 23\; T\) in CeCoIn\(_5\). Fig. 3 shows the torque signal at \(T = 40\; mK\) as a function of magnetic field applied close to the c-axis. Clear anomalies observed at around 5 T correspond to the suppression of superconductivity. There are no other remarkable anomalies at higher field, in particular similar to that observed at 9 T in CePd\(_2\)Si\(_2\), where a metamagnetic transition was established by torque measurements \(^{24}\). However, a sudden emergence of a new dHvA frequency is clearly detected above \(23\; T\) and becomes evident after subtracting the background (insets of Fig. 3). Remarkably, the amplitude of the new frequency is so strong that it dominates all the other dHvA oscillations above \(23\; T\) at very small inclinations from the c-axis.

The field dependence of the magnetic torque in CeCoIn\(_5\) observed at 40 mK for two orientations of the magnetic field close to the c-axis. The insets show the high field oscillatory torque signal after subtracting the background.
above 23 T. Furthermore, two more higher frequencies, $F_2$ and $F_3$ emerge above 23 T for this orientation (Fig. 4 d). Like $F_a$, these two frequencies were not observed either below 23 T or in the previous studies. The effective masses corresponding to these frequencies are also quite enhanced being about 18 $m_0$ and 24 $m_0$ respectively.

The frequencies $F_a$ and $F_b$ exist only over a small angular range close to the c-axis. Therefore, they might be due to a magnetic breakdown. This is not the case of the frequencies $F_c$ and $F_d$ which survive over a wide angular range between the [001] and [100] directions. Their emergence above 23 T seems to imply an important modification of the FS topology. Since these new frequencies are associated with large effective masses, the drastic change observed in the Nernst signal at 23 T would be a natural consequence of such a modification.

Thus, two independent sets of evidence points to the existence of a new field scale in CeCoIn$_5$ at 23 T: A drastic change in the magnitude and sign of the Nernst signal and the appearance of the new frequencies in dHvA spectrum. Both these features have been observed in CeRu$_2$Si$_2$ as experimental signatures of the metamagnetic transition. Let us also note that a temperature enhancement being about 18 $T_a$ seems to imply an important modification of the FS topology. Since these new frequencies are comparable with one of the characteristic energy scales, $E_K$, it is possible that the modification of the FS topology observed here may be closely related to the drastic change of the FS recently detected in CeRhIn$_5$ at $P = 2.4$ GPa, just above its critical pressure $P_c = 2.35$ GPa [33]. The opposite effects on the FS produced by pressure and magnetic field are in good agreement with the opposite actions on the volume (contraction and expansion respectively).

In conclusion, we have demonstrated the existence of another field scale in CeCoIn$_5$ besides $H_c$. The new characteristic field $H_K \sim 23$ T is marked by an anomaly in the Nernst signal reminiscent of that observed at the metamagnetic field of CeRu$_2$Si$_2$. The characteristic field is also associated with the appearance of new frequencies in dHvA oscillations, like in CeRu$_2$Si$_2$. However, contrary to the latter system, there appear to be two distinct field scales widely separated in the $T = 0$ limit.

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