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Hall effect in the heavy-fermion compound CePtSi

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We present Hall-effect measurements on the heavy-fermion compound CePtSi. Above the temperature of antiferromagnetic ordering T_N, the Hall effect of CePtSi exhibits the behavior generally observed in heavy-fermion systems and ascribed to skew scattering. Below T_N the Hall effect is enhanced and its field dependence is strongly nonlinear. We show that this behavior arises from skew scattering or anomalous velocity effects rather than from a change of the ordinary Hall effect induced by a reconstruction of the Fermi surface.

The Hall effect of many Kondo lattices, $CeCu_6$ (Refs. 1-3), $CeCu_2Si_2$ (Refs. 3 and 4), $CeAl_3$ (Refs. 4 and 5), $CeRu_2Si_2$ (Ref. 5), UPt_3,[5,6] has been studied during the past few years and the following characteristic features have generally been observed. The Hall constant is large (100 times larger than in normal metals), and generally positive, it increases as temperature decreases and exhibits a pronounced maximum at the onset temperature for coherence effects. This behavior has been ascribed to strong skew-scattering effects.[7,8] More recently, it has been shown that the anomalous velocity or side-jump contribution should also be significant below the Kondo temperature.[9] In Kondo lattices that present a magnetically ordered structure at low temperatures, it has been found that the onset of magnetic ordering strongly affects the Hall effect. For example, in U_2Zn_{17} (Ref. 10) and URu_2Si_2,[11] the Hall constant increases sharply below the Néel temperature. This has been ascribed to an increase of the ordinary Hall effect induced by a reconstruction of the Fermi surface.

In this paper we report Hall effect and magnetization measurements on polycrystalline samples of the CePtSi compound. Our samples were prepared by arc melting under argon atmosphere and annealing for 14 days at 800 °C. The Hall-effect measurements were performed by a classical ac method between 1.2 and 300 K and up to 60 kG. The initial Hall constant R_H is measured in fields smaller than 1 kG. For the magnetization measurement we used a Faraday balance.

CePtSi is a heavy-fermion system presenting a temperature coefficient of the electronic specific heat of about 800 mJ/mol K^2.[12,13] Slight anomalies in the temperature dependence of the resistivity and magnetic susceptibility have suggested the existence of a magnetic order, probably antiferromagnetic, below about 2.5 K.[13] As shown below, our Hall measurements confirm the existence of a phase transition at $T_N = 2.8$ K.

Figure 1 displays the variation of the initial Hall constant R_H in the temperature range above the Néel temperature. The main features of $R_H(T)$, huge and positive values, with a pronounced maximum at low temperature, are those found in several heavy-fermion compounds ($CeAl_3$, $CeRu_2Si_2$,...; see Refs. 1-6) and generally ascribed to skew scattering. The temperature of the maximum, around 8 K, is in the range where the resistivity[12] drops (onset of coherence). Below T_N, as shown in the inset of Fig. 1, R_H increases sharply to still higher values. We discuss the data below T_N later but first consider the temperature range above T_N. Neglecting any contribution from skew scattering by defects and impurities and taking into account only the contributions from ordinary Hall effect and from intrinsic skew scattering by the ceri-

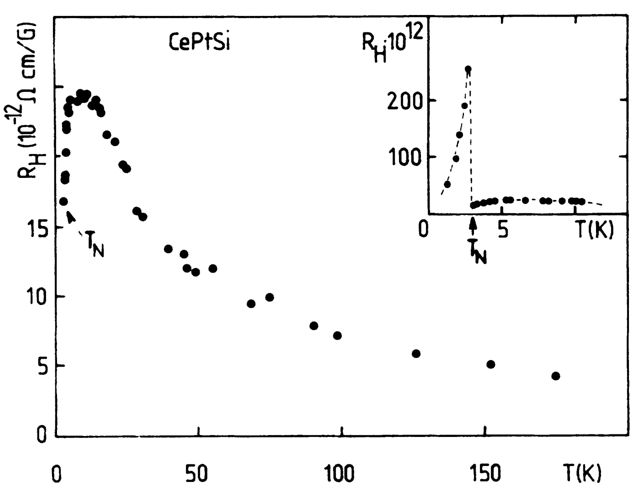

FIG. 1. Temperature dependence of the initial Hall constant of CePtSi above the Néel temperature, $T = 2.8$ K. Inset: Temperature dependence of the initial Hall constant at low temperatures above and below T_N. Notice the different scales for the main figure and the inset. To compare with typical metallic values, note that the Hall constant of Cu is about 0.5×10^{-12} Ω cm/G (1 Ω cm/G = 100/m^3/C).

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um lattice, we have tested the theoretical expression[8]

$$R_H = R_H^{ord} + \gamma \rho \tilde{\chi}\,, \qquad (1)$$

where R_H^{ord} is the ordinary Hall constant, $\tilde{\chi}$ is the reduced susceptibility ($\tilde{\chi} = \chi/C$ where C is the Curie constant), ρ is the magnetic resistivity, and γ is a constant. We have used for our analysis (i) values of the magnetic resistivity derived by Lee and Shelton[12] from the resistivities of CePtSi and LaPtSi, $\rho = \rho$(CePtSi) $-\rho$(LaPtSi), (ii) three different sets of data for χ, respectively, derived from measurements of Lee and Shelton[12] and Rebelsky *et al.*,[13] and from our own measurements on the sample used for the Hall effect (we will compare the fits obtained with these different sets of data), and (iii) the ordinary Hall constant R_H^{ord} derived by plotting the values of R_H at high temperatures as a function of $\rho\chi$ and extrapolating to $\rho\chi = 0$ (high-temperature limit), as shown in Fig. 2. We obtain $R_H^{ord} = 2.3\times10^{-12}$ Ω cm/G. In first approximation, we assume that R_H^{ord} is temperature independent.

To test Eq. (1), we have plotted $(R_H - R_H^{ord})/\rho\chi$ as a function of T in Fig. 3. In agreement with Eq. (1), the ratio $(R_H - R_H^{ord})/\rho\chi$ is approximately constant in the major part of the temperature range above T_N. At low temperatures, however, between T_N and about 25 K, the ratio $(R_H - R_H^{ord})/\rho\chi$ departs from its value at high temperature. This departure is either positive or negative, depending on the set of experimental values of χ used for the plot, and is relatively small when one uses the values of χ measured on the same sample. The difference between the three sets of data used for χ are likely due to contributions from impurities, and it may be that the departures from Eq. (1) at low temperature also arise from these contributions. We thus conclude (i) Eq. (1) is well obeyed above about 25 K and (ii) it is not possible to establish whether the departure from Eq. (1) between T_N and 25 K arises from impurity effects, or is due to an intrinsic change of the Hall effect (extraordinary or ordinary contributions) at low temperatures (below the Kondo temperature or below the onset temperature for coherence).

Below T_N, it is not sufficient to consider only the initial Hall constant R_H. This appears in Fig. 4 where the Hall resistivity ρ_{xy} (Ref. 14) is plotted as a function of the applied field at several temperatures. Whereas ρ_{xy} is a quasilinear function of H above T_N (see curve at 2.8 K) its behavior is strikingly different below T_N. ρ_{xy} first increases steeply and, at a well-defined threshold field, becomes almost field independent. The very sharp change of the slope at the threshold field is characteristic of a field-induced phase transition. When the threshold field is plotted as a function of the temperature, as shown in the inset of Fig. 4, one obtains a well-defined transition line limiting the antiferromagnetic phase. By extrapolating the transition line to zero field, we derive $T_N = 2.8$ K.

CePtSi presents a good example of the extreme sensitivity of the Hall effect to small changes of the electronic structure in heavy-fermion systems: The initial Hall constant increases by a factor of about 15 between 2.8 K just above T_N, and 2.7 K just below T_N; as a function of the field, at 2.7 K for example, the slope of ρ_{xy} (H) decreases by two orders of magnitude at the field-induced transition.

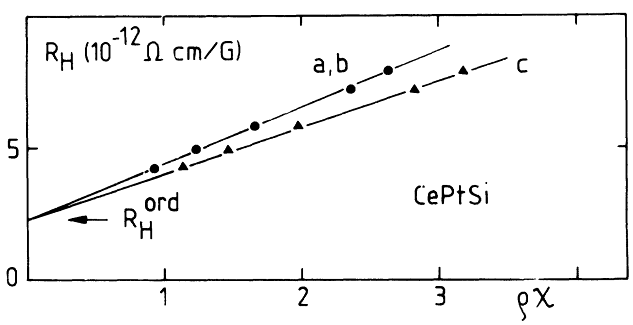

FIG. 2. R_H (high-temperature data) vs $\rho\chi$. The ordinary Hall constant is found by extrapolating to $\rho\chi = 0$. The magnetic resistivity is derived from Ref. 12, $\rho = \rho$(CePtSi) $-\rho$(LaPtSi). (a,b) χ from Refs. 12 and 13, (c) χ from our own measurements on the sample used for the Hall effect. All three sets of data yield $R_H^{ord} = 2.3\times10^{-12}$ Ω cm/G.

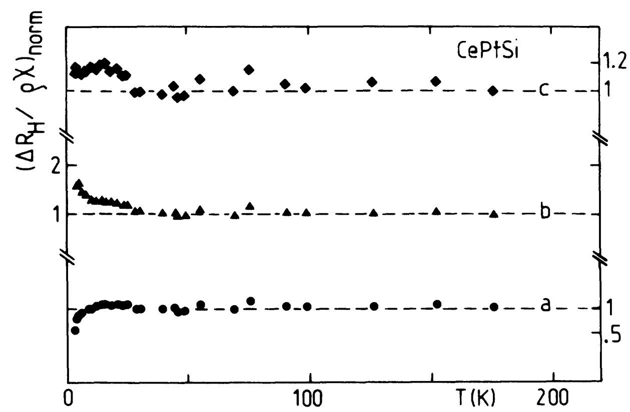

FIG. 3. $\Delta R_H/\rho\chi = (R_H - R_H^{ord})/\rho\chi$ vs T in the range $T > T_N$. $\rho = \rho$(CePtSi) $-\rho$(LaPtSi) from Ref. 12; (a) χ from Ref. 13, (b) χ from Ref. 12, (c) χ from our measurements on the sample used for the Hall effect. The values for $(R_H - R_H^{ord})/\rho\chi$ are normalized with respect to the value at 175 K.

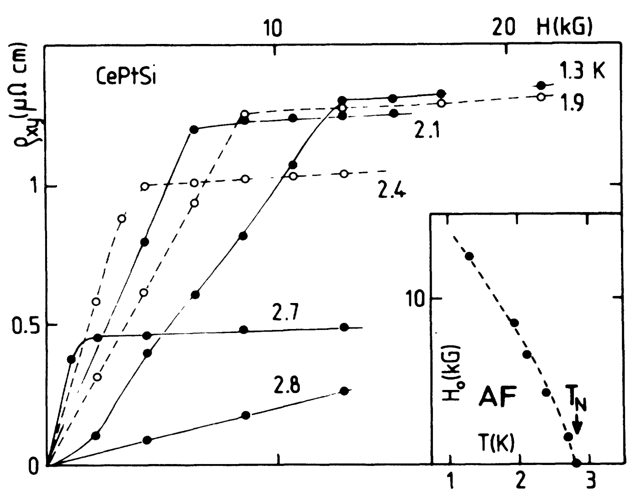

FIG. 4. Hall resistivity vs applied field at several temperatures (indicated on the curves). Inset: phase diagram of CePtSi derived from the sharp turn of the ρ_{xy} (H) curves.

In contrast, the existence of an antiferromagnetic phase and of field-induced transitions do not appear clearly in the magnetization curves shown in Fig. 5. In fact the onset of antiferromagnetic ordering can be detected only by a careful analysis of the temperature dependence of the susceptibility.[13] In the same way the onset of antiferromagnetic ordering weakly affects the temperature dependence of the resistivity.[13] The existence of a field-induced transition appears in the magnetoresistance[15] but much less clearly than in the Hall resistivity curves of Fig. 4.

Strong changes in the Hall effect below the temperature of magnetic ordering have already been observed in other heavy-fermion systems, U_2Zn_{17} (Ref. 10) and URu_2Si_2,[11] for example. The sharp increase of the Hall constant below T_N in URu_2Si_2 has been interpreted by Schoenes, Schonenberger, Franse, and Menovsky[11] in terms of the ordinary Hall effect and ascribed to a reconstruction of the Fermi surface induced by the formation of an antiferromagnetic modulation. Our data on CePtSi do not support this type of interpretation. Our arguments are the following.

(i) Strong changes in the Fermi surface should be reflected in the resistivity. In CePtSi, when the temperature decreases below T_N, the initial Hall constant increases by a factor of 15 and becomes 100 times as high as the ordinary Hall constant derived at high temperatures. It is hard to assume that the effective number of carriers decreases suddenly by a factor of 100, while the resistivity remains almost constant around T_N.[13]

(ii) An antiferromagneticlike gap in the Fermi surface would appear progressively below T_N and would reach its maximum value at the lowest temperatures. This is in contrast with our data in which the initial Hall constant is high just below T_N and decreases rapidly at low temperatures (by a factor of 5 at $T_N/2$).

Our results for CePtSi rather support an interpretation in terms of extraordinary Hall effect (skew scattering[7,8] or anomalous velocity[9] contribution). As the extraordinary Hall effect is expected to be a very sensitive function of the $l=3$ phase shifts of the resonant scattering at the Fermi level,[7-9] it should be strongly affected by any fine structure of the f levels arising from cooperative effects. The existence of such effects in CePtSi is supported by the field dependence of the Hall resistivity (Fig. 4) which appears to be closely related to the effects of the applied field on the antiferromagnetic phase.

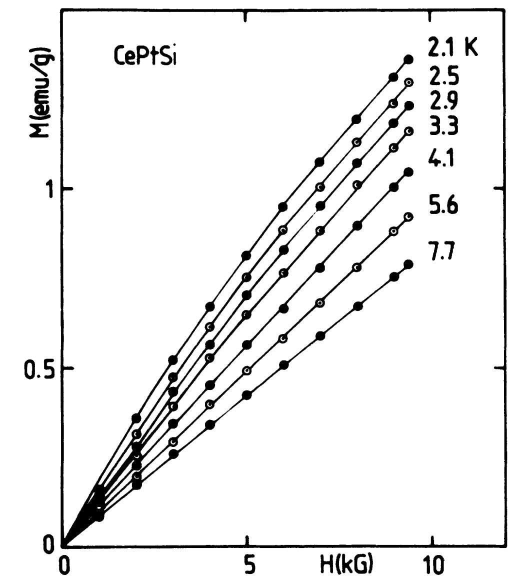

FIG. 5. Magnetization vs applied field at several temperatures (indicated on the curves).

In conclusion our Hall-effect data on the heavy-fermion compound CePtSi show interesting aspects above and below the Néel temperature. Above T_N the Hall constant exhibits the typical behavior of many heavy-fermion systems with a pronounced maximum at about the onset temperature for coherence effects. Above about 25 K, its temperature dependence fits well with the predictions of skew scattering models. It is hard to establish whether the departures observed below 25 K are due to intrinsic effects or to impurity contributions. Below T_N, the Hall effect changes definitely and its field dependence shows evidence for the existence of a field-induced phase transition. In contrast with what has been proposed for URu_2Si_2, the behavior of the Hall effect below T_N in CePtSi cannot be accounted by a reconstruction of the Fermi surface but rather to strong changes of the extraordinary contributions.

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[14] We define ρ_{xy} by $E_y = +\rho_{xy} j_x$ so that $R_H = +(\rho_{xy}/H)_{H\to 0}$.

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