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Effect of randomness on anomalous Hall coefficient in antiferromagnet U_2PdGa_3

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The Hall effect has been studied in antiferromagnet U_2PdGa_3. In the paramagnetic state, the Hall data can be interpreted in terms of skew scattering theory for heavy fermion systems. We observe a large contribution of anomalous Hall coefficient, indicating a dominating contribution of incoherent skew scattering by uranium 5f moments. An interesting behaviour of the $R_H(T)$ dependence is found at low temperatures: the $R_H(T)$ curve displays a plateau between $T^* = 12$ K and $T_N = 33$ K, followed by a shoulder upon further decreasing temperature. The appearance of the anomaly around T^* suggests the existence of a new scattering mechanism, in addition to well known skew and jump-side scatterings. We compare the Hall data of U_2PdGa_3 with those observed for strongly correlated electron systems and with those of spin-glasses. Like the latter systems, non-zero spin chirality seems to play a considerable role in the anomalous Hall effect of U_2PdGa_3.

Key words: *U_2PdGa_3; Hall effect; strongly correlated electron systems; randomness; spin chirality*

1. Introduction

U_2PdGa_3 is an orthorhombic, collinear antiferromagnet with the Néel temperature $T_N \approx 33$ K [1, 2]. In this compound, there is a competition between the Kondo effect and randomness for long-range antiferromagnetism. The Kondo effect manifests itself in electrical resistivity, magnetoresistance properties at high temperatures and causes an enhancement in the electronic heat capacity at low temperatures ($\gamma_0 = 72$ mJ/(mol·K^2)). Furthermore, like in many other compounds with randomness, the specific heat of U_2PdGa_3 does not show a mean-field discontinuity at the Néel temperature but, instead, the dc magnetic susceptibility exhibits magnetic history phenomena. As a result, the antiferromagnetic state with the ordered moments of about 0.3 μ_B exists only with finite magnetic correlation lengths (below 150 Å) [2].

The measurement of the Hall effect is one of the tools of studying scattering mechanisms of conduction electrons on magnetic moments in metals. For ordinary

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magnetic materials, the Hall resistivity ρ_H measured in a field B can be approximately described by the equation:

$$\rho_{\rm H} = R_0 B + 4\pi R_s M \qquad (1)$$

where R_0 and R_s are the ordinary and anomalous Hall coefficients and M is the magnetization [3, 4]. Usually, the sign and value of R_0 determine the type and carrier concentration, respectively, while the R_s value and its temperature dependence provide information on scattering mechanisms of the charge carriers.

In the f electron Kondo attice systems, the electronic and magnetic properties are sensitive to a change in the coupling strength between f and conduction electrons. At high temperatures, weak f–spd hybridization enables f electrons to be localized ones. On the second hand, at low temperatures the strength of the f–spd hybridization becomes stronger. Thus, the ground state of more itinerant f electrons involving heavy mass quasiparticles emerges. According to the theory of Hall effect in heavy-fermion systems [5, 6], the Hall effect is mainly determined by coherent skew scattering at $T < T_{\rm coh}$ and incoherent skew scattering for $T > T_{\rm coh}$. The skew scattering contribution R_{sk} was predicted to be proportional to the product of magnetic susceptibility and magnetic resistivity, i.e., $R_{sk} = \gamma\tilde{\chi}\rho$, where γ is a parameter related to the phase shift δ by the dependence $\gamma = -(5/7)g\mu_B k_B^{-1}\sin\delta\cos\delta$, $\tilde{\chi} = \chi/C$ with C being the relevant Curie parameter deduced from the susceptibility data and ρ is the magnetic resistivity [5, 6].

In this contribution we address the question whether the carrier scattering mechanisms inferred from measuring the Hall resistivity comply with those from the magnetization and electrical resistivity measurements.

2. Experimental details

Polycrystalline samples of U_2PdGa_3 were fabricated by arc-melting in a high-quality pure argon atmosphere. The samples were annealed at 650 ºC for one week. Phase purity and composition were checked by EDX and X-ray powder diffraction. dc magnetization measurements were carried out by using a Quantum-Design SQUID magnetometer. Electrical resistivity was measured by an ac conventional four-probe method. The measurements of Hall effect were performed in the temperature range 2–300 K and in magnetic fields up to 7 T, using an ac conventional four-probe technique. Hall voltage was recorded with a low-frequency (37 Hz) excitation current of 10 mA on a 0.5 mm thick sample mounted on a horizontal rotator.

3. Results and discussion

Figure 1 shows the temperature dependence of the Hall coefficient measured at 7 T. We notice that R_H has a positive sign over the entire temperature range of investigation. In the paramagnetic state, R_H increases with decreasing temperature, resembling the temperature dependence of the magnetization and resistivity reported previously [1]. Since theory of the Hall effect for heavy fermions [5, 6] predicts the following dependence of R_H(T):

$$R_H = R_0 + \frac{\gamma\chi\rho}{C} \tag{2}$$

this form was used to fit the data. In the inset of Fig. 1 we plot the experimental R_H values against the product $\rho\chi/C$ and the solid line is the result of the fitting for the data in the temperature range 60–300 K. The agreement between the experimental and theoretical data may support the dominance of the incoherent skew scattering, being responsible for the anomalous Hall effect in the paramagnetic state. The constant $\gamma = 0.042$ K/T, derived from the fit is the same order of magnitude as those found in heavy-fermions like $CeAl_3$, $CeCu_6$ [6] and UCu_5Al [7]. From the fit R_0 has also been estimated to be $-2.28 \pm 0.05 \times 10^{-10}$ m^3/C, which corresponds to a single-band concentration of electron-like carriers $n = 6.5$ e/f.u.

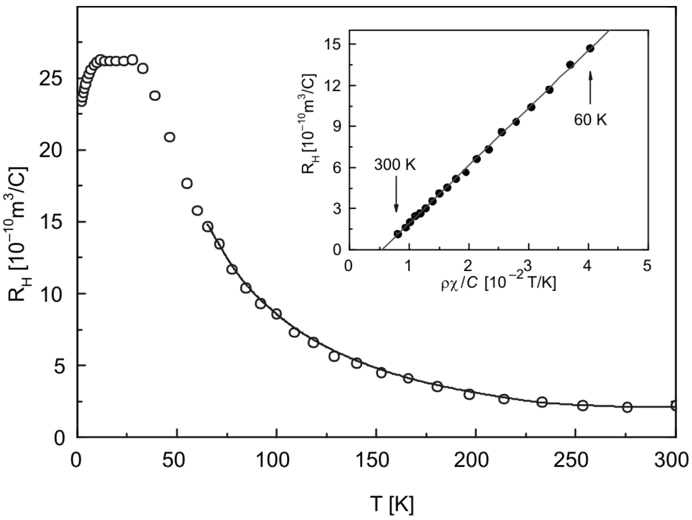

Fig. 1.Temperature dependence of the Hall coefficient of U_2PdGa_3 measured at 7 T. The inset shows the dependence of R_H on $\rho\chi/C$ with $C = 0.58$ cm$^3\cdot$mol$^{-1}\cdot$K^{-1}. The solid lines present the fits of the experimental data to Eq. (2)

In order to get access to information on scattering mechanisms at low temperatures, we compare the R_H data with the electrical resistivity ρ and volume magnetic susceptibility χ_V in Fig. 2. As shown in Fig. 2a, below the magnetic phase transition T_N the Hall coefficient levels off until it approaches T^* of about 12 K. On further decreasing temperature, R_H rapidly decreases. In the magnetically ordered state of ordinary magnets, with decreasing temperature the strength of the asymmetric scattering decreases continuously due to a continuous decrease of the spin fluctuations, and obviously no distinct anomaly would be expected at temperatures far below magnetic ordering temperature. The fact that a shoulder appears in $R_H(T)$ curve of U_2PdGa_3 at temperatures near T^* ($\sim T_N/2$), and the slope of the $R_H(T)$ curve has different values in the temperature ranges 2–12 K and 16–30 K, is remarkable. One explanation is that in these temperature ranges different mechanisms of scatterings appear. In other words, the strength of the asymmetric scattering changes dramatically when the system goes from one to another temperature range.

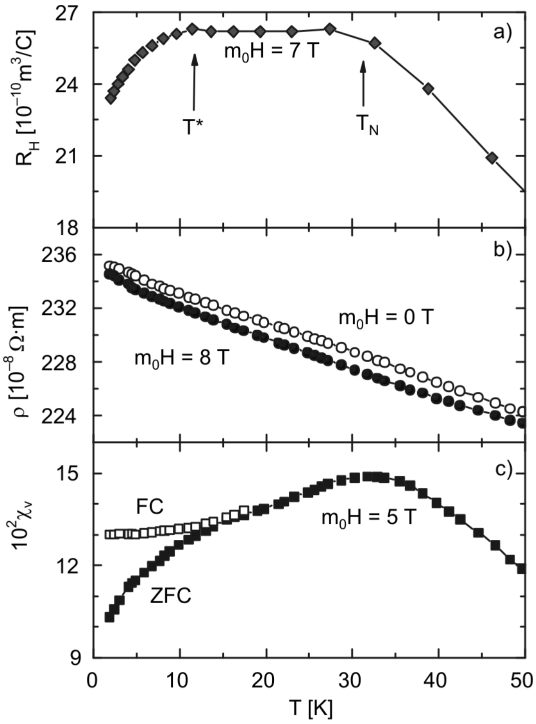

Fig. 2. Temperature dependence of a) the Hall coefficient, b) electrical resistivity at 0 and 8 T, and c) volume susceptibility at 5 T after zero-field cooling and field-cooling in U_2PdGa_3

In contrast to the R_H behaviour, the resistivity measured at 0 and 8 T (Fig. 2b) does exhibit weak temperature dependence. This fact, together with the lack of a clear singularity at the magnetic ordering temperature, may point to a significant influence of the short-range interactions and/or to the Kondo effect, though the magnetoresistance, $[\rho(8\text{ T}, T) - \rho(0\text{ T}, T)]/\rho(0\text{ T}, T)$ displays a negative minimum at T_N [2]. Moreover, since the resistivity has no anomaly at T^*, it is difficult to ascribe the behaviour of R_H to the same scattering mechanism as for the resistivity solely. In fact, the magnetic susceptibility taken at 5 T after zero-field cooling and field cooling exhibits an irreversibility point around 15 K and a broad maximum at $T_N \approx 33$ K (Fig. 2c). These features point to closely correlated behaviour between $R_H(T)$ and $\chi_V(T)$. Previously, the irreversibility effect observed in the susceptibility curves was interpreted in terms of short-range magnetic interactions dictated by disorder effects [2]. It is accepted that the atomic disorder is favourable for the system to develop magnetic clusters. In terms of the electronic transport properties, magnetic moments belonging to clusters may stand for new scattering centres, in addition to magnetic moments not belonging to any cluster yet. Therefore, the randomness not only breaks the coherent scattering but may also modify the magnitude of the anomalous Hall component which in natural manner depends on centres scattering electrons.

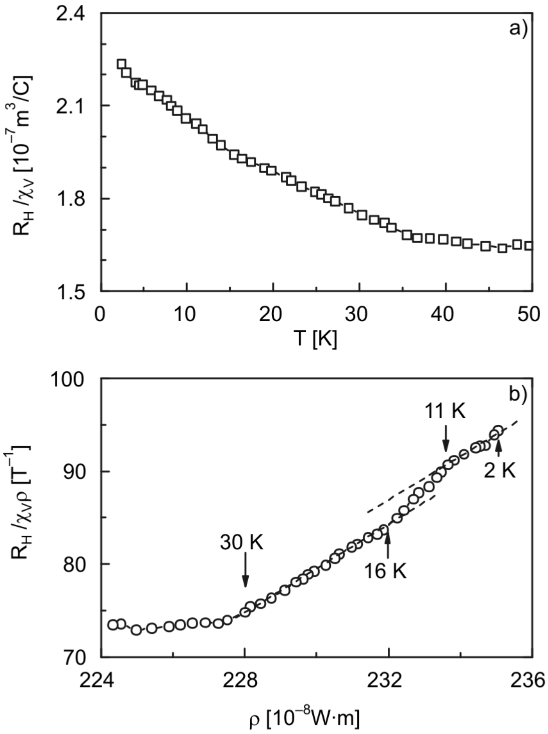

Fig. 3. Temperature dependence of the ratio R_H/χ_V (a) and the ratio $R_H/\chi_V\rho$ vs. ρ in U_2PdGa_3

If the ordinary component of R_H is small compared to the anomalous one, the ratio R_H/χ_V should approximately represent the anomalous contribution R_s. When inspecting Fig. 3a, where the plot of the ratio R_H/χ_V vs. T is shown, we see that the ratio R_H/χ_V, i.e., $\sim R_s$, increases with decreasing temperatures. A comparison of $R_H/\chi_V(T)$ with $\rho(T)$ suggests a contribution of the electrical resistivity to the anomalous Hall coefficient. Usually, the anomalous Hall coefficient in a magnetically ordered state consists of two contributions: the skew scattering proportional to ρ, and the side-jump scattering proportional to ρ^2 [4]. We have considered the relationship between R_H/χ_V and ρ given by

$$\frac{R_H}{\chi_V} \sim R_s = a\rho + b\rho^2 \quad (3)$$

Parameters *a* and *b* are the coefficients of the skew and jump-side scattering contributions, respectively. According to Eq. (3), a plot R_s/ρ versus ρ should be a straight line, and the coefficients *a* and *b* can be deduced. In Figure 3b, the ratio $R_H/\chi_V\rho$ is plotted in function of ρ. The data indeed approximately lie on a straight line. Interestingly, the slopes of the curve $R_H/\chi_V\rho$ vs. ρ (i.e., parameter *b*) in the temperature ranges 2–11 K and 16–30 K are the same, suggesting that there is no change in strength of the side-jump scattering across T^*, whilst for the skew scattering, the coefficient *a* (i.e., the intercept of the plot) is different above and below T^*. As we have considered above, the formation of magnetic clusters below T^* should bring in new scattering centres, yielding additional contribution to skew scattering.

Recently, the chirality mechanism [8] has been proposed as an important mechanism for the anomalous Hall effect in spin glass systems [9–12]. Tatara and Kawamura [8] have shown that the uniform chirality χ_0 contributes to anomalous Hall effect as follows: $R_s = (a\rho + b\rho^2) + c\chi_0$. Here, *c* is a constant relevant to the detailed band structure of the conduction electrons and a uniform chirality χ_0 is the sum of the local chirality defined as $\chi_{ijk} = S_i(S_jS_k)$ for three spins S_i, S_j and S_k. Clearly, the chirality contribution to R_s is remarkable when the net uniform chirality is finite, i.e., $\chi_0 \neq 0$. In fact, the contribution from χ_{ijk} to χ_0 decays rapidly as $\exp(-3r/2l)/(k_Fr)^3$, where *r* is the distance between the spins, k_F is the Fermi wave number, and *l* is the mean free path. Thus, one expects a large contribution from χ_{ijk} to χ_0 when the distance between spins *r* is shorter than *l*. Using the value of R_H and ρ at 2 K, one estimates the mean free path to be 28.6×10^{-10} m, being larger than the average distance between the spins of the order of 3.5×10^{-10} m. This means that a number of triangles of three spins may give their contribution to χ_0 in the studied compound.

4. Conclusions

We have studied the Hall effect in the short-range antiferromagnet U_2PdGa_3. The experimental Hall coefficient was compared to the magnetic susceptibility and electrical resistivity. From the relationship between R_H, χ_V and ρ, we infer that the incoherent skew scattering dominates in the paramagnetic state. Anomalies found in the $R_H(T)$ dependence at both the Néel temperature $T_N \approx 33$ K and $T^* = 12$ K provide a new evidence in support that U_2PdGa_3 is not a classical long-range antiferromagnet. The development of magnetic clusters below T^*, and the resulting randomness have been suggested to cause an anomaly in the $R_H(T)$ curve at T^*. We considered the observed behaviour to connect with the chiral mechanism of the anomalous Hall effect. We conclude that the low-temperature R_H data of U_2PdGa_3 may be qualitatively understood in the framework of contributions from the skew, jump-side scatterings and from the spin chirality.

Acknowledgements

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