Unusual behavior of the Hall voltage in UBE_{13} at low temperatures

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In a superconducting system with heavy fermions UBe_{13}, the Hall voltage increases by a factor of ~ 30 with decreasing temperature, goes through a maximum at $T \sim 2$ K, and then decreases to zero and changes sign near the superconducting-transition temperature. The $U_H(H)$ curves exhibit a maximum which shifts toward lower magnetic fields as the temperature is lowered.

1. The study of heavy-fermion systems[1,2] ($CeAl_3$, $CeCu_6$, $CeCu_2Si_2$, UPt_3, UBe_{13}, etc.), which have an extremely narrow state-density peak $g_R(E)$ with an enormously large amplitude in the electronic state density near the Fermi level E_F, has recently attracted considerable interest. The characteristic energy scale, $T^* \sim 10$ K, in heavy-fermion systems is two or three orders of magnitude smaller than the width of the conduction band in normal metals. The effective mass of the "heavy fermions"—quasiparticles with energies $E \approx E_F$—is therefore $(10^2–10^3)m_0$ of the mass of the free electron. At temperatures $T \gtrsim T^*$ the magnetic f ions in the heavy-fermion systems are independent magnetic scatterers. This circumstance allows the amplitude of the peak $g_R(E)$ to be estimated as a product of the magnetic centers and the contribution of a single center to the state density[1] if the exact Wiegmann-Andrei[3] solution of the Kondo problem is used. As T is lowered, the formation of a peak is accompanied by an anomalous increase in the Hall voltage which was observed in $CeCu_2Si_2$ in Ref. 5, in $CeAl_3$ in Ref. 6, and in UBe_{13} in Ref. 7. Since the magnetic centers in the heavy-fermion systems form a periodic lattice, the scattering by f ions becomes coherent in these systems at reasonably low temperatures $T \lesssim T_{coh} \sim T^*/10$ (Ref. 1). This scattering coherence manifests itself experimentally in the decrease of the electrical resistance, of the magnetic susceptibility, and of the electron specific heat coefficient and leads to a reversal of the sign of the Hall voltage upon lowering the temperature in the region[4] $T \lesssim T_{coh}$. Accordingly, we felt it worthwhile to study the Hall voltage in the transition to a coherent regime at $T \lesssim T_{coh} < T^*$. We report here the results of a study of the Hall effect in a superconducting heavy-fermion system UBe_{13}.

2. We measured the Hall voltage U_H using $0.3 \times 2 \times 6$-mm UBe_{13} single-crystal samples with a superconducting-transition width $\Delta T_c \approx 15$ mK. The measurements were carried out in two experimental arrangements: in an ^4He cryostat with a 140-kOe superconducting solenoid at $T > 1.5$ K and in an automatically controlled apparatus with an ^3He-^4He refrigerator-liquefier at temperatures in the range $0.05 < T < 2.5$ K. A superconducting switch was used in measuring the dependences $U_H(T)$ in a constant magnetic field. The entire temperature interval was divided into sections each with a step $\Delta T \simeq 30$ mK (within which the Hall voltage was averaged) and was slowly run

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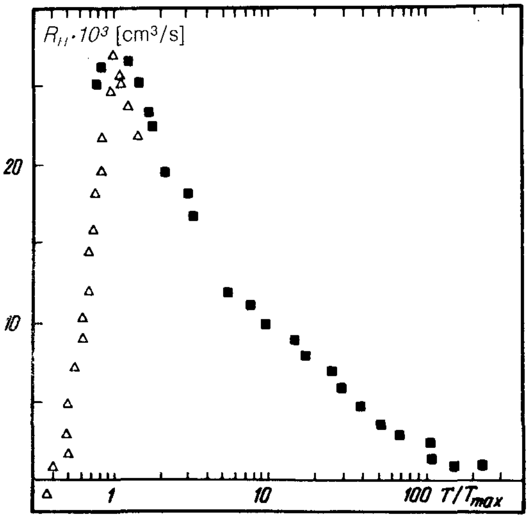

FIG. 1. Temperature dependence $R_H(T/T_{max})$ of UBe_{13} at temperatures $0.7 < T < 300$ K. Filled squares—Data of Ref. 8.

through twice for the oppositely directed magnetic fields. The value $U_H = (U_H^+ - U_H^-)/2$ was then found for each interval. The field dependences $U_H(H)$ were also measured twice in two directions of H, averaging U_H over 6 kOe within the intervals. The measurements were carried out with a direct current $i = 0.3$–1 mA.

3. Figure 1 is a plot of the temperature dependence $R_H(T)$ of UBe_{13} measured in a constant field $H = 30$ kOe. After initially increasing significantly over the interval $(2 < T < 100)$ K (the points in Ref. 8), R_H goes through a maximum ($U_H = U_H^{max}$; $R_H = R_H^{max}$) at $T \simeq 2$ K and decreases sharply to zero near $T = T_c = 0.9$K, the superconducting-transition temperature.

The transformation of the field dependences of the Hall resistivity $\rho_H(H, T = T_0) = U_H/i$ as a result of lowering the temperature T_0 is shown in Fig. 2, a and b. At $T = T_{max}$, the first parts of the curves are linear up to $H = H_k \simeq 30$ kOe. A lowering of the temperature T_0 causes ρ_H and H_k to fall off. Near T_c and $\rho_H(H)$ curve goes through a maximum at $H \approx 30$ kOe and then decreases to nearly zero near $H = 60$ kOe. Below $T = T_c(0)$ the $\rho_H(H)$ curve has no positive slopes. At $H > H_{C2}(T)$ ($T = 0.83$ K) the values of the $\rho_H(H)$ curve lie near the abscissa, and $|R_H| < 0.05\, R_H^{max}$. At $H > H_{C2}$ the value of ($\rho_H(H)$ is negative in the region $T < 0.73$ K and the value of R_H, which is calculated by extrapolating $\rho_H(H)$ to the small-field region, is $-0.15\, R_H^{max}$.

4. The data which we obtained show that the quasiparticle spectrum in UBe_{13} changes dramatically at $T < T^*$. The temperature dependence $R_H(T)$ (Fig. 1) with a maximum at $T \sim T^*$ is similar to the dependences $R_H(T)$ obtained previously for $CeCu_6$ (Ref. 8) and $CePd_3$ (Fig. 9). By reconstructing all these data in the coordinates $R_H/R_H^{max} = f(T/T^*)$, we find that the Hall voltage behaves universally, despite the difference in T^* [$T^*(CeCu_6) \sim T^*(UBe_{13}) \sim 2$ K, $T^*(CePd_3) \sim 150$ K] and

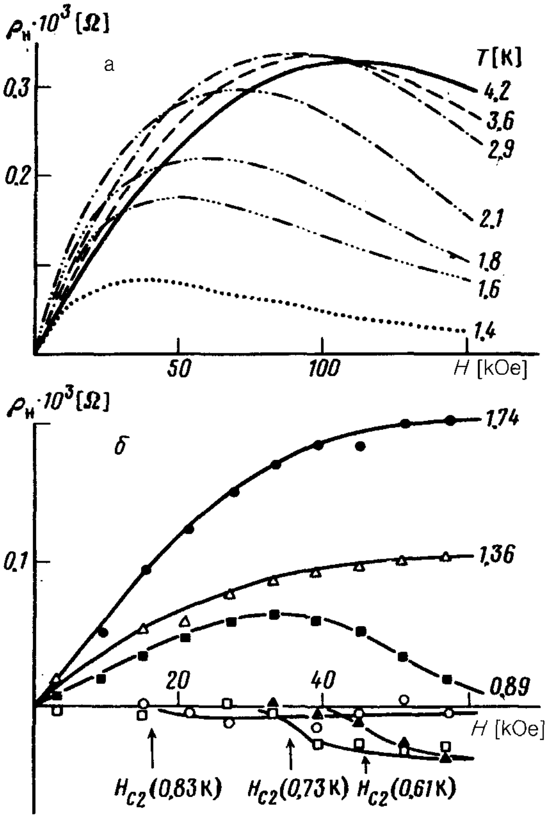

FIG. 2. (a) Field dependences of the Hall resistivity ρ_H of UBe_{13} at temperatures $1.4 < T < 4.2$ K in fields $H \lesssim 150$ kOe. The labels on the curves correspond to the temperature $T(K)$. (b) The field dependences $\rho_H(H)$ of UBe_{13} for temperatures in the range $0.61 < T < 1.74$ K. The open circles correspond to $T = 0.83$ K, the open squares correspond to 0.73 K, and the filled triangles correspond to 0.61 K.

as we change to a coherent regime, $U_H(T)$ falls off dramatically. Unfortunately, the anomalous behavior in the Hall voltage cannot yet be analyzed in greater details, since there is no theory that can describe the behavior of heavy-fermion systems in a coherent regime.

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