Materials Science-Poland, Vol. 24, No. 3, 2006

Hall effect in strongly correlated electron systems

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This work provides a brief survey of the Hall effect data collected for some strongly correlated electron systems. The experimental results illustrate the behaviour of the heavy-fermion system UCu_5Al, heavy-fermion semiconductor U_2Ru_2Sn, ferromagnetic superconductor under pressure UGe_2, and the ferromagnet with a weak 2D localization effect $UCo_{0.5}Sb_2$.

Key words: Hall effect; strongly correlated electron system; heavy fermion system

1. Introduction

Over the last three decades, strongly correlated electron systems (SCES) have attracted an increased attention of many experimental and theoretical solid-state scientists around the world. The essential property of f-electron SCES is the instability of the f-electron shell and, in consequence, f-electrons in compounds with sp- and d-elements easily hybridise with conduction electrons. It is well known that the Hall resistivity of magnetic materials consists of normal R_0 (OHE) and anomalous R_s (AHE) contributions. While the normal Hall effect results from the Lorenz force, the AHE is related to an asymmetric probability of electron scattering on magnetic centres. This means that the Hall effect could be a good probe for both electronic and magnetic properties in SCES. Recently, we have reported the Hall effect measurements on some U-based SCES, such as the heavy-fermion (HF) antiferromagnet UCu_5Al [1], HF semiconductor U_2Ru_2Sn [2], ferromagnetic superconductor under pressure UGe_2 [3], and low-carrier density ferromagnet with a weak 2-dimensional localisation effect $UCo_{0.5}Sb_2$ [4]. In this contribution, some outstanding and interesting features of these investigations will be outlined and highlighted.

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2. Results

The temperature dependences of the Hall coefficient R_H for the studied compounds are shown in Fig. 1. At high temperatures R_H is proportional to the magnetic susceptibility (M/B). For UCu_5Al and U_2Ru_2Sn, the Hall effect data can be described based on skew scattering theory [5]. The R_H data for UGe_2 and $UCo_{0.5}Sb_2$ can also be decomposed into negative R_0 and positive R_s components. In all the samples, the extraordinary contribution (Table 1) was found to be dominant, indicating that the $R_H(T)$ dependence is mainly due to incoherent skew scattering by U 5f moments. Carrier concentration at room temperature, estimated in a one-band model from R_0 values, ranges from 0.4 for UGe_2, 0.8 for $UCo_{0.5}Sb_2$, 1.2 for U_2Ru_2Sn to 4.9 e/f.u. for UCu_5Al.

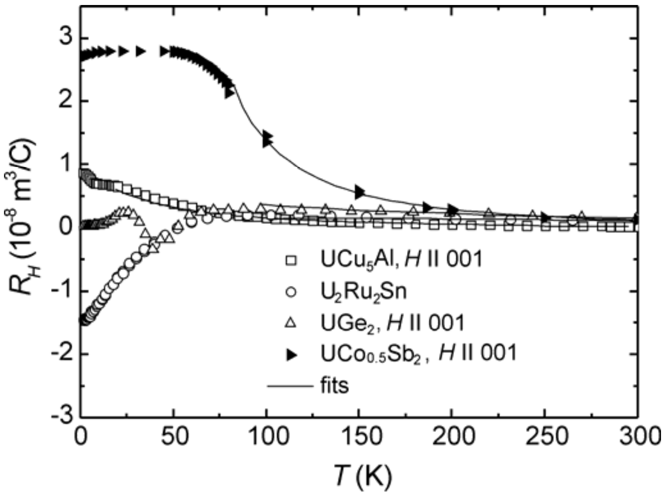

Fig. 1. Temperature dependence of the Hall coefficients of UCu_5Al, U_2Ru_2Sn, UGe_2, and $UCo_{0.5}Sb_2$. The solid lines represent fits (see text)

Table 1. Hall parameters derived from the fit of the experimental data

Compound	R_s [m^3/C]	γ_1 [K/T]	R_0 [m^3/C]	n [f.u.]	m^* [m.e.]
UCu_5Al, $H \parallel c$		0.08	-6.44×10^{-10}	0.9	105
U_2Ru_2Sn		0.38	-5×10^{-10}	0.04	48
UGe_2, $H \parallel c$	3.7×10^{-6}		-9.4×10^{-10}	3.1	15
$UCo_{0.5}Sb_2$, $H \parallel c$	1.3×10^{-5}		-1.96×10^{-10}	0.02	70

*Fit to the equations $R_H = R_0 + R_s\mu_0 M/B$ and $R_H = R_0 + \gamma_1 \rho M/B$, where γ_1 is a parameter related to the phase shift, M is magnetisation, B – magnetic induction, n – is charge carrier concentration at 2 K, and m^* – the effective mass at 2 K.

A different behaviour of the investigated compounds is observed at low temperatures. A remarkable feature is the increase in R_H for UCu_5Al below 50 K. At 2 K, R_H achieves the value of 9×10^{-9} m^3/C, corresponding to 0.9 carriers per f.u. Taking $\gamma = 210$ mJ/(K^2·mol U) [1], one can estimate the electron effective mass $m^* = 105\ m_e$.

This enhancement of the electron mass points out that a development of the heavy-fermion state occurs in this compound at low temperatures.

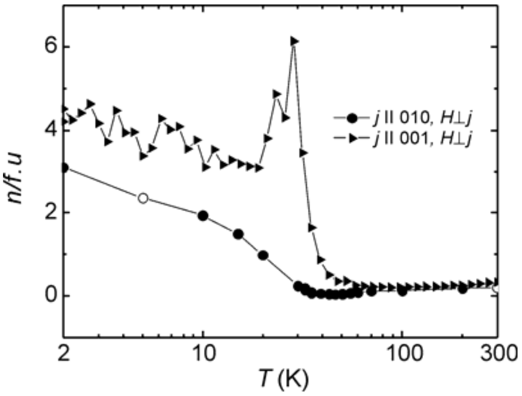

Fig. 2. Temperature dependence of the charge carrier concentration n of UGe_2, measured with a field applied perpendicular to the 010 and 001 directions

For U_2Ru_2Sn, the R_H (T) dependence shows a broad positive maximum at about 80 K and changes its sign below 50 K. At 2 K, R_H reaches the value of -1.5×10^{-8} m^3/C, which corresponds to a single-band concentration of n = 0.04 e/f.u. In the temperature range 15–80 K, the $n(T)$ dependence can be described with the help of an exponential law with the energy gap of about 60 K. The latter value is comparable with those derived from the specific heat and NMR studies at 70 and 80 K, respectively [2]. All these features point to a gap opening in U_2Ru_2Sn.

Physical properties of UGe_2 are very unusual. Under the pressure of ~12 kbar, superconductivity with T_{SC} = 0.8 K coexists with ferromagnetism [6]. It has also been pointed out that there exists a close relation between T_{SC} and T^*. The latter temperature is a characteristic temperature, visible in the temperature dependence of resistivity and tending to T_{SC} on increasing pressure. In the ordered state, the coefficients R_0 and R_s of UGe_2 have been separated using $R_H(B)$ and $M(B)$ data simultaneously. Interestingly, the R_0 coefficient displays a distinct anomaly at T^*. In consequence, the charge carrier concentration calculated within the single-band model has an upturn with decreasing temperature below T^* (Fig. 2). This phenomenon can be understood in terms of the so-called "dual nature" of 5f-electrons. Assuming that a hybridisation between the 5f and conduction electrons takes place below T^*, one can explain not only the carrier concentration, but also the enhancement of the density of states, and the itinerant behaviour of 5f electrons at low temperatures.

The Hall coefficient of $UCo_{0.5}Sb_2$ increases rapidly with decreasing temperature below 100 K. This behaviour is associated with a decrease in the carrier concentration. At 2 K, n falls to 0.024 e/f.u (Fig. 3), making $UCo_{0.5}Sb_2$ a low carrier system. It should be emphasised that the Hall mobility in $UCo_{0.5}Sb_2$ changes sharply with temperature. It passes through a maximum of 450 $cm^2/(V\cdot s)$ at 20 K and decreases by as

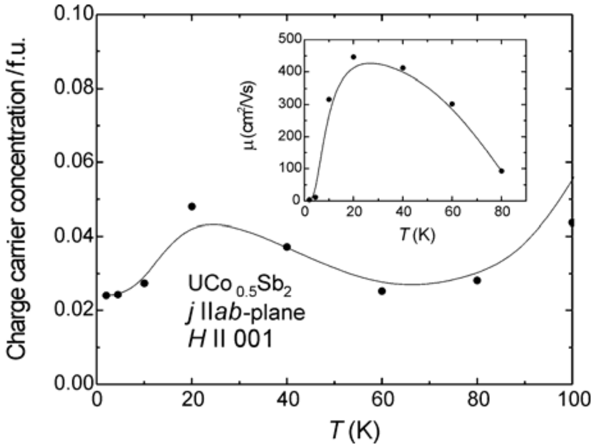

Fig. 3. Temperature dependence of the charge carrier concentration of $UCo_{0.5}Sb_2$.
The inset shows mobility as a function of temperature

many as two orders of magnitude, i.e. to 3.7 $cm^2/(V\cdot s)$ at $T = 2$ K (see the inset in Fig. 3). This change is probably related to a decrease in the carrier collision time. The Hall mean free path λ, estimated from $R_H(T)$ and resistivity, also shows a dramatic drop, falling from about 350 Å at 20 K to 12 Å at 2 K. The temperature dependences of μ and λ may support the weak localization effect suggested previously [4].

3. Summary

This work is an attempt to show some important results obtained by the measurements of the Hall coefficient on four 5f electron-based compounds (UCu_5Al, U_2Ru_2Sn, UGe_2, $UCo_{0.5}Sb_2$). Though these materials have different ground states, they belong to the so-called SCES family. The Hall effect data provided evidence of the enhancement of electron effective masses in all the studied compounds and shed new light on the behaviour associated with electron correlations.

Acknowledgements

The author is indebted to M. Baenitz, E. Bauer, Z. Bukowski, T. Komatsubara, S. Paschen, F. Steglich, and R. Troć for their collaboration and discussion on this subject. This work was supported by the KBN Grant No. 2 PO3B 109 24.

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Received 1 June 2005