Anisotropic magnetic and electron transport properties of a Kondo ferromagnet $UCo_{0.5}Sb_2$

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The intermetallic compounds $UTSb_2$ (T = Ru, Fe, Co, Ni, Pd, Cu, Ag and Au) for the first time were investigated by Kaczorowski *et al*. [1]. They have found an interesting evolution in the magnetic properties of the $UTSb_2$, ranging from a paramagnetic (T = Fe) through an antiferromagnetic (T = Ru, Ni and Pd) to a ferromagnetic (T = Cu, Ag and Au) behaviour [1]. Since investigations of the $UTSb_2$ compounds were performed so far only on polycrystalline samples and hence information on their anisotropy of the physical properties has been limited, we have started to prepare single crystals of all the ternaries $UTSb_2$. Single crystals of some from the $UTSb_2$ series have already been grown in our Lab. In this contribution we report on synthesises, characterization, magnetic and electron transport properties of single-crystals of $UCo_{0.5}Sb_2$. They have been grown from molten Sb by the so-called self-flux method using high quality materials: U (purity 99.98 %), Co and Sb (purity 99.99 %). The crystal structure and phase composition were determined using powder X-ray diffraction (XRD), single-crystal X-ray refinement and an energy dispersive X-ray (EDX). As a result we found a large deficit on the cobalt site, yielding chemical formula $UCo_{0.5}Sb_2$. The compound crystallizes in the tetragonal $HfCuSi_2$-type structure with the following lattice parameters a = 4.286 and c = 8.832 Å, and positional parameters $z_U = 0.2755$ and $z_{Sb} = 0.6381$.

Magnetization (M) measurements have revealed that $UCo_{0.5}Sb_2$ is a ferromagnetic compound with a Curie temperature of $T_C = 65$ K. To interpret the magnetization data in the ordered state we have assumed the existence of both the spin-wave and Stoner excitations [2], which give rise to the M as follows: $1 - M/M_s = B_0T^{3/2} + B_1T^{3/2}exp(-\Delta/T)$ (Eq. 1). The fit of this equation to the experimental data is shown as the solid line in Fig. 1 with the following parameters: $\Delta = 69(2)$ K, $B_0 = 8\text{x}10^{-5}$ K$^{-3/2}$ and $B_1 = 1.1\text{x}10^{-3}$ K$^{-3/2}$. We have evaluated the spin-wave stiffness constant $\boldsymbol{D}$ for $UCo_{0.5}Sb_2$ to be 110 meVÅ^2, corresponding to the ratio $\boldsymbol{D}/k_BT_C$ = 19.6 Å. A relatively large value of $\boldsymbol{D}/k_BT_C$ may indicate strong ferromagnetic interactions between the nearest located uranium magnetic moments.

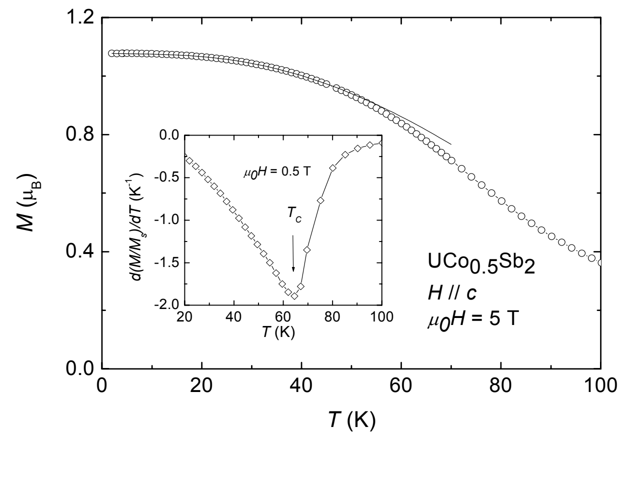

Fig. 1. Magnetization at 5 T *vs.* temperature. The solid line is a fit (see text). Inset: the derivative $d(M/M_s))/dT$ as a function of temperature

The M in magnetic field applied parallel to the c-axis saturates near 2 K and at a field of 5 T, reaching a value of ~1.1 μ_B. On the other hand, the M measured in fields perpendicular to this axis is very small and almost linear in H. At high temperatures, the effective magnetic moment μ_{eff} of approximately 3 μ_B/at.U was found for both the configurations. The difference in the paramagnetic Curie temperatures, $\Delta\Theta = \Theta_{p,//} - \Theta_{p,\perp} = 96 - (-97) = 193$ K reflects a huge magneto-crystalline anisotropy existing in this compound.

The temperature dependence of the electrical resistivity $\rho(T)$ having a $-lnT$ variation at high temperatures (Fig. 2) indicates a considerable contribution of the Kondo-type scattering. The onset of the magnetic ordering is revealed by extremum in the temperature dependence of the derivative $d\rho(T)/dT$. A clear evidence of the anisotropy is given in Fig. 2. For $J//c$ the resistivity continously increases and saturates at low temperatures. In contrast, for $J\perp c$ there is a rapid drop in the resistivity due to the loss of spin scattering below T_C. Moreover, at about 20 K $\rho(T)$ exhibits a minimum and a little upward in the resistivity measured down to 1.5 K. Therefore, the resistivity of $UCo_{0.5}Sb_2$ for $J\perp c$ has been assumed to be a sum: $\rho(T) = \rho_0 + clnT + A(T\Delta/k_B)exp(-\Delta/k_BT)(1+2k_BT/\Delta)$ (Eq. 2). For the data between 1.3 - 35 K, the fit with this equation yields the following parameters: ρ_0=360(1)μΩcm, A=6.5(3)x10^{-3}μΩcmK^{-2}, Δ = 68(1) K and c = -0.78(1) μΩcm K^{-1}. Owing to numerous vacancies in the Co atom sites, being potential centers for the elastic scattering of carries and the layer-type crystal structure of this compound, the occurrence of the $\rho(T)$~lnT dependence at low temperatures may be interpreted as an effect of two-dimensional weak localization (2DWL) [3].

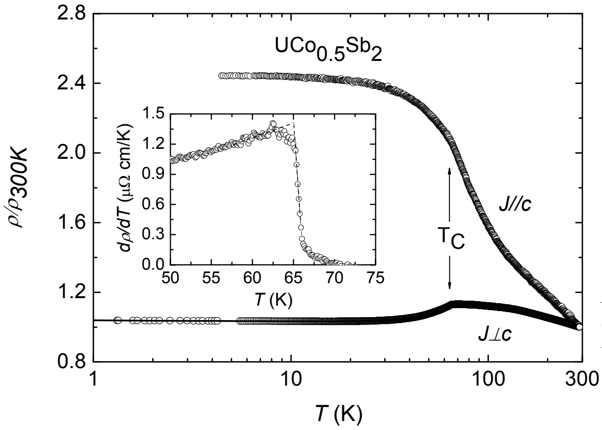

Fig. 2. Temperature dependence of the electrical resistivity. Inset shows the temperature derivative of the resistivity

The effect of an applied magnetic field on the resistivity is shown in Fig. 3. We found that the temperature dependence of the resistivity measured at 8 T can be very well fitted with Eq. 2. This fact suggests that there persists same scattering mechanism as that in the zero-field resistivity, i. e., both the zero and 8T-resistivities are governed mainly by the spin-wave scattering and 2DWL effects or eventually by a Kondo-like effect. Furthermore, we found that the magnitude of the gap is considerably altered by the applied magnetic field. Keeping A = 6.5x10^{-3}μΩ cm K^{-2} in the fit we obtain c = -1.45 μΩ cm K^{-2} and Δ(8T) = 78(3) K. The change in the magnitude of Δ may be caused by an additional Zeeman-type contribution to the gap at zero field, i.e., $\Delta(H) = \Delta(0) + g\mu_B\mu_0H$. For a field of 8 T the contribution $g\mu_B\mu_0H$ amounts to 4.3 K if we take the Lande factor g = 0.8.

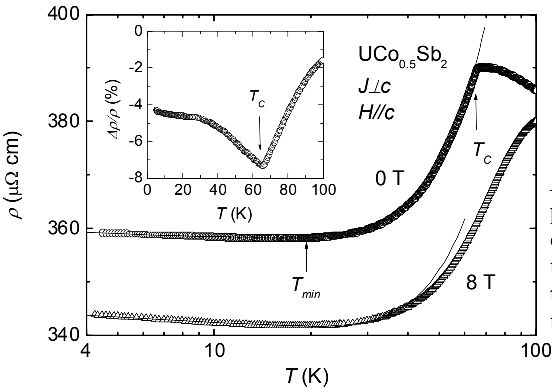

Fig. 3. The resistivity at 0 and 8 T for *J* perpendicular to the *c*-axis as a function of temperature. The solid lines are fits to the experimental data. The inset shows the magnetoresistance as a function of temperature

Magnetoresistance *MR*, defined as $\Delta\rho/\rho = (\rho(H,T)-\rho(0,T))/\rho(0,T)$ is negative over the investigated temperature range. The negative *MR* is going through a sharp minimum around T_C, where it reaches a value of -6.5 %. The observed effect is expected for the *MR* due to the damping of critical fluctuations by the field. The negative *MR* for $T > T_C$ may be interpreted as being due to the suppression of the Kondo-type or spin fluctuation effects. A remarkable feature has been the weak temperature dependence of *MR*; the *MR* up to 30 K retains a value of about -5%. In order to clarify any mechanism responsible for this phenomenon, we have considered a fact that the total *MR* to be consisted of partial magnetoresistances, such as the ordinary *MR* due to the orbital motion of electrons in a magnetic field, the contributions due to the anisotropic scattering, the elastic scattering on defects and impurities, the inelastic scattering on carriers and finally the magnetic scattering on local magnetic moments. We suppose that the contribution from the ordinary *MR* (Lorentz type) being always positive, can be negligible because our total *MR* is essentially negative. Furthermore, for $UCo_{0.5}Sb_2$ the *MR* data do not obey completely the scaling function: $\Delta\rho/\rho \sim f(H/H^*)$, where $H^*(T) = H^*(0) + k_BT/g\mu$ and $H^*(0) = k_B\,T_K/g\mu$, as for a typical single-ion Kondo system. Thus, the description for the *lnT* dependence of the resistivity below 20 K in terms of Kondo-type effect may be not reliable. Moreover, we do not observe any corelation between the *MR* and magnetization for temperatures measured below 40 K. This fact may suggest that the magnetic scattering process is not likely related to the magnetization process governed by the domain effect or the orientation of magnetic moments. Therefore, the elastic scattering process at low temperatures seems to be large, and this probably mainly determines the MR behaviour, resembling that of the 2DWL effect. Indeed, we may apply the theory of the 2DWL [3] to our data, where the conductance is given by:

$$\frac{\sigma(H,T)-\sigma(0)}{\sigma(0)} = \frac{e^2}{2\sigma(0)\pi\hbar}\left[-\Psi\left(\frac{1}{2}+\frac{H_1}{H}\right)+\frac{3}{2}\Psi\left(\frac{1}{2}+\frac{H_2}{H}\right)-\frac{1}{2}\Psi\left(\frac{1}{2}+\frac{H_3}{H}\right)-\ln\left(\frac{H_2^{3/2}}{H_1H_3^{1/2}}\right)\right],$$

where Ψ is a digamma function and H_k represents different scattering fields. We have obtained a good fit to experimental data if we assume that $H_2 = H_3$. In the above equation, H_1 corresponds mainly to an elastic scattering mechansim while H_2 characterizes an inelastic one. The results of the fits are shown as the solid lines in Fig. 4, indicating that the magnetoresistance data are consistent with the interpretation in terms of the 2DWL effect.

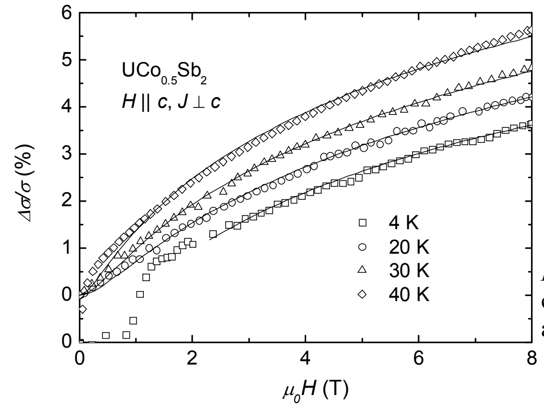

Fig. 4. Field dependence of the magneto-conductance of $UCo_{0.5}Sb_2$. The solid lines are fits

The thermopower is positive over the investigated temperature range and is indicative of a *p*-type conductivity of the material. The *S(T)*-curves show also a highly anisotropic behaviour (Fig. 5). An appreciable thermoelectric power with a value of 25 μV/K occurs in the case of the heat flow $Q \perp c$. In the ferromagnetic order, we have not observed any signal due to a phonon-drag scattering , the latter as the lattice specific heat, should follow the T^3 power law. In fact, we found only the difussion and magnon-drag contributions, which are dependent on temperature as follows: $S(T) = \alpha T + \beta T^{3/2}$. The results of a fit to the experimental data in the temperature range 4 - 20 K are shown as the dashed lines in Fig. 5. Interestingly, we have not detect any anomaly near T_C in the $S_{\perp c}$(T) curves, which could imply that the contribution from the magnon drag to *S* is minor in comparison with other contributions, namely those originating from the magnon-magnon and magnon-phonon scattering, discussed by Morkowski many years ago [4]. Consequently, the observed changes in both $S_{//c}(T)$ and $S_{\perp c}(T)$ in the vicinity of T_C may be interpreted in terms of a significant change in the structure of the density of states at the Fermi level, E_F. Moreover, the relaxation time τ of conduction electrons seems to play an important role. Within the *ab*-plane, where the magnetic uranium moments tend to align parallel, the carriers become scattered on the localized moments much more effectively than by those along the *c*-axis. In addition, τ alters very much due to the presence of vacancies in the Co layers. This is equivalent to a larger value of *S* measured in the configuration *Q // ab*-plane. At high temperatures, we may also interpret the *S(T)* behaviour with the help of a phenomenological model for a Kondo lattice [5]. According to

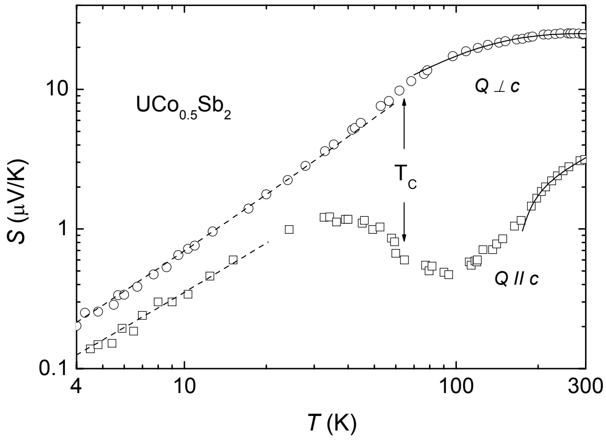

Fig. 5. Temperature dependence of the thermoelectric power. The solid and dashed lines are the fits

the Freimuth's model [5], a high temperature thermopower of a *f*-electron system due to the scattering between the conduction electrons in the broad *s-d* bands and the *f*-electrons in the narrow Lorentzian shaped bands, one can describe it by using the following phenomenological formula:

$$S(T) = \alpha T + \frac{CTT_0}{T_0^{\,2} + (T_f \exp(-T_f / T))^2},$$

where T_f sets the width of *f*-band, while T_0 represents the position of the *f*-band, and C is a chararacteristic constant. The resutls of the fits are shown as solid lines in Fig. 5.

In summary, we have measured the magnetization, electrical resistivity, magnetoresistance and thermoelectric power of $UCo_{0.5}Sb_2$ single crystals. This compound exhibiting a large magnetocrystalline anisotropy, undergoes a transition on a ferromagnetic order at T_C = 65 K. Below about $T_C/2$, two types of magnetic excitations are observed; the spin-wave and Stoner-type excitations. The most unusual finding in our work is the observation of the 2DWL effect in $UCo_{0.5}Sb_2$. This effect together with the electron–magnon scattering are being the main mechanism governing the resistivity in the ordered state. The latter mechanism can be described by a gap in the magnon spectrum Δ, which is altered by the applied magnetic field. The change in the magnitude of the gap may be interpreted as an additional contribution of Zeeman term to the gap determined at zero field. Negative magnetoresistance is observed over a wide range of temperatures below 150 K. The behaviour of the magnetoresistance taken at temperatures far below T_C is consistent with the interpretation in terms of the elastic scattering in a 2D system with the weak localization effect. We have ascribed the effect of magnetic field on the magnetoresistance around T_C to the suppression of the critical scattering and/or spin-fluctuations. In the paramagnetic state, the resistivity of $UCo_{0.5}Sb_2$ is branded by a $-lnT$ dependence which is indicative of the Kondo behaviour. Based on the spin-wave theory, the $T^{3/2}$ dependence of the thermoelectric power of $UCo_{0.5}Sb_2$ followed at temperatures below $T_C/2$ could be accounted for, while the applied here a phenomenological Kondo-lattice model could give an adequate description for the temperature dependencies of the *S(T)* at high temperatures.

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