On the superconductivity of the ferromagnetic UGe_2

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In recent years, superconductivity (SC) under pressure has been observed in some antiferromagnets, like $CePd_2Si_2$, $CeIn_3$ and others. For such a case of unconventional SC arising in these and other heavy fermion compounds, the charge carriers are claimed to be coupled in pairs by magnetic interactions [1]. This means that spin fluctuations replace vibrations in the formation of Cooper pairs. Furthermore, it was shown that such type of pairing is most robust in quasi two-dimensional systems [2].

The recent discovery of SC in the UGe_2 ferromagnet (T_C = 53 K) under pressure [3] was quite surprising, because the inner field here is not cancelled out, like in the case of above antiferromagnets. The most important difference in respect to the latter compounds is that the SC in UGe_2 is enclosed into the ferromagnetic phase only and disappears together with the ferromagnetism at the critical pressure p_C = 16 kbar, where T_C = 0 K. The most important feature in creation of SC is connected with a broad anomaly in the temperature derivative of the resistivity having a maximum at so called characteristic temperature T^*, which taken in ambient pressure is about 30 K and reaches zero at p^*_C = 12 kbar, where T_{SC} becomes the highest (0.8 K).

UGe_2 crystallizes in the orthorhombic structure of Cmmm space group with large **b/a** an **b/c** ratios of 3.76 and 3.68, respectively. The magnetic properties were found to be highly anisotropic with the magnetic moments arranged parallel to the shortest axis **a** with a value of 1.4 μ_B [4].

The main problem arising in explanation of the appearance of SC in the ferromagnetic state of UGe_2 under pressure is attributed to the nature of the pressure dependence of the characteristic temperature $T^*(p)$. The first thing however is to explain its existence at ambient pressure. It seems that up to now there exists no definite explanation of this temperature and its pressure dependence. In our opinion the next step in trying to understand this phenomenon was undertaking the studies of the magnetoresistivity (MR). We first measured MR for a polycrystalline sample in the wide temperature range 4.2–70 K in fields up to 8 T [5]. It appeared that the MR being highly positive at 4.2 K, which is unusual for a ferromagnet, becomes gradually negative reaching a maximum with the $\Delta\rho/\rho$ value as high as –27% at 26 K. Thus this giant anomaly occurs close to T^*, while the MR at T_C was found to be almost zero. This kind of behaviour is completely strange for a normal ferromagnet. Usually below T_C, due to the uniform aligning of magnetic moments along one direction, an electron scattering on the magnetic moments gradually diminishes with decreasing temperature giving no more a contribution to the total MR at T = 0 K.

Now we present a detailed study made on a single crystal, which has allowed one to present a strong anisotropy not only in the magnetic properties, but also in the transverse MR, as well as in the thermopower S_i and thermal conductivity κ. Among a great deal of data obtained so far, the most interesting is that the MR for the current flowing along the hard magnetization direction **b** with the magnetic field **B** applied perpendicular to this axis reaches as large $\Delta\rho/\rho$ value as –40% at T^* and again almost 0% at T_C (see Fig. 1) [6]. We connect this giant effect of magnetic field on the resistivity just around T^* with freezing out of strong magnetic fluctuations at this temperature ($T^* \approx T_C/2$), coexisting deeply in the ferromagnetic order. This highly suggests that the low energy fluctuations associated with p_C^* could play a significant role in forming the SC in UGe_2.

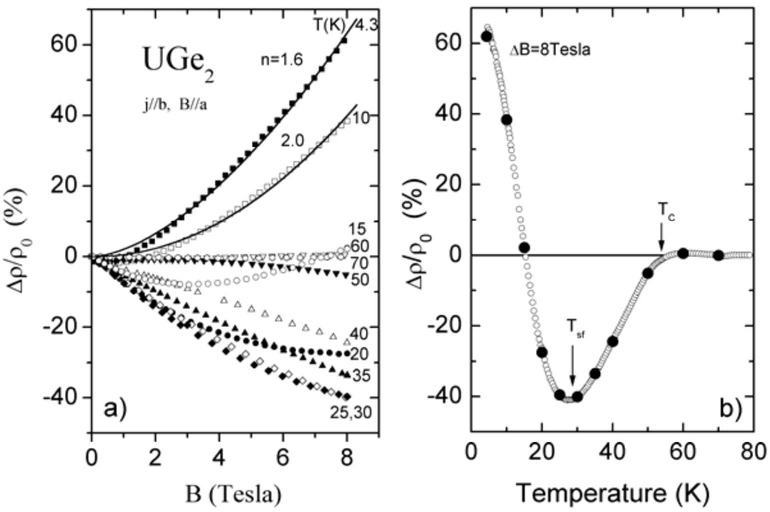

Fig.1. The MR measured for the current j//b and B//a **a**) taken at various temperatures in fields up to 8 T and **b**) taken at an isofield of 8 T between 4.2 and 80 K (small open circles). Large filled circles are data taken at 8 T for various temperatures as shown in panel **a)**.

The temperature dependences of the transverse MR measured for **j//a** and **c** are similar to each other. At low temperature MR is positive, while at temperatures above 20 K it becomes negative going first by a shallow minimum around T^* and then, in contrast to the **j//b, B//a** configuration, through a somewhat sharper negative minimum at T_C. The ratios of the $\Delta\rho/\rho$ values taken at 4.2 K and B = 8 T for **j//a, b** and **c** amount approximately to 1:4:2 [6].

Considering the phonon contribution to $C_p(T)$ in UGe_2, Watanabe and Miyake [7] have proposed that the nature of superconductivity of UGe_2 is being associated with the coupled CDW and SDW fluctuations, which in their opinion just form the $T^*(p)$ new boundary. In order to response to this theory, we will present below the recent results of our heat capacity measurements and discuss the anomalies occurred in the temperature dependences of separated from the total C_p the C_{5f} heat capacity, as well as the thermopower S and thermal conductivity κ, all these quantities were determined for the UGe_2 single crystals at temperatures around T^*[8].

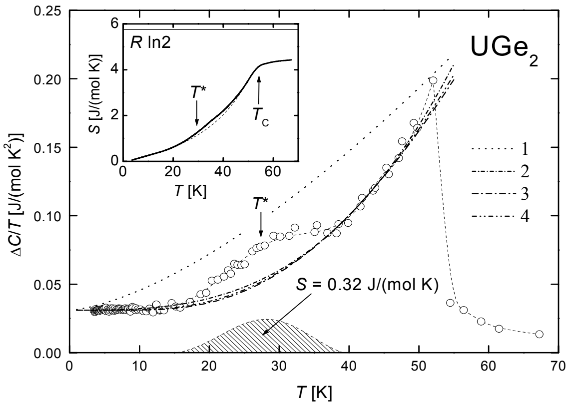

Fig. 2. Magnetic and electronic heat capacity in the form of the ΔC/T versus T plot. The curves marked from 1 to 4 are a fitting to the magnon excitations formulae. The inset shows the magnetic entropy S_m *vs.* T.

A. Heat capacity. Fig.ure 2 presents the $\Delta C_p/T$ versus T plot. ΔC_p which has been extracted by subtracting from measured C_p its phonon part, taken as $C_p(T)$ of $ThGe_2$. The numbers represent the fitting curves to different magnon excitation expressions. The large difference exists only between fitting to $aT^{3/2}$ behaviour (no.1) and those to the remaining three fittings (nos. 2, 3 and 4). The latter curves have enabled us to determine the magnetic entropy associated with a transition at T^* (see a C_{5f} hump) which is only ~ 8 % of that at T_N. This is in rough agreement with the muon spin relaxation results [9], which report the existence of itinerant long-range magnetic correlations with 0.02 μ_B, involving long wavelength fluctuations modes, except for modes connected with the ferromagnetic state.

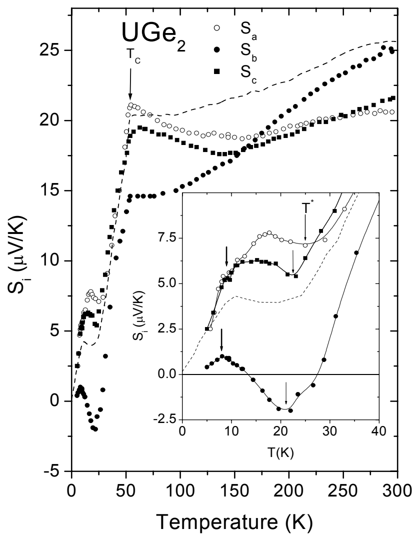

Fig. 3. Thermopower S versus T along three crystallographic directions. The dashed line illustrates the results of polycrystalline studies [10].

B. Thermopower. Figure 3 displays the three S_i curves versus T measured along the three axes **a, b** and **c**. All these curves are similar in shape, showing only small anisotropy. Except the anomaly at T_C, there are distinct anomalies seen around T^*, where S_i goes through a local minimum. In addition in these three curves: S_a, S_b and S_c versus T as well as for that reported for the polycrystalline sample [10], there are apparent, undetermined anomalies at about 10 K.

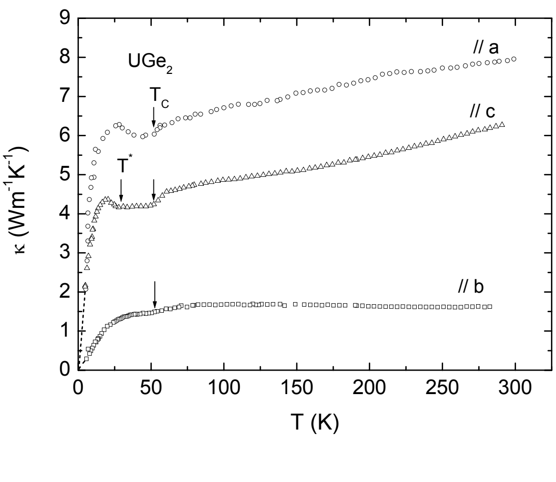

Fig. 4. Thermal conductivity κ_i along the three crystallographic directions.

C. Thermal conductivity. Fig. 4 illustrates the κ_i versus T behaviour also measured along the three axes. Unexpectedly, there is a large anisotropy in this quantity apparent. Again except for the anomalies in κ(T) at T_C, one observes for all these curves that this dependence slightly increases below T^* and goes through a distinct maximum at slightly lower temperatures. However, no sign of any anomaly is seen around 10 K.

Assuming a relation between the electronic part of the thermal conductivity $\kappa_e(T)$ and electrical resistivity ρ(T), given by Wiedemann-Franz law: $\kappa_e\ \rho/T = L_0$ ($L_0 = 2.45 \times 10^{-8}\ W\Omega K^{-2}$ is the Lorenz constant) we have derived the expected temperature variation of the electronic contribution to the total thermal conductivity. In this procedure the electrical resistivity data were taken from Ref. 6. For all three cases the electron component κ_e starts rapidly to dominate the phonon one κ_{ph} just below about 27 K, i.e. around T^*, except its domination also at higher temperatures above about 200 K. At the same time the $\kappa_{ph}(T)$ curve reaches its maximum around T_C, falling down below this temperature towards zero. The rapid increase in $\kappa_e(T)$ near T^* is in excellent agreement with the rapid rise of the carrier concentration at this temperature observed in our measurements of the Hall effect in UGe_2 [11].

Since there are three f electrons on the atomic shell of uranium in UGe_2, one has to consider the possibility that only some of the f-electrons are delocalized due to a strong hybridization with Ge p-electrons, which in consequence drive the SC in a suitable temperature and pressure condition, while the remaining f-electrons are well localized and are responsible for highly anisotropic ferromagnetism in this compound. Thus such a scenario evolves from the electron annihilation study of the Fermi surface on a UGe_2 single crystal, supported by the corresponding electronic band calculations [12].

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