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TLS Kondo effect in structurally disordered ThAsSe

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Abstract

Low-temperature electrical-resistivity, $\rho(T)$, measurements on single crystals of the structurally disordered ThAsSe reveal an anomalous scattering mechanism, which is apparently derived from two-level systems. For the ThAsSe specimen displaying a resistivity saturation at millikelvin temperatures, a crossover from a logarithmic to a non-Fermi-liquid behavior $\Delta\rho \propto 1 - aT^{1/2}$ is observed upon cooling below $\simeq 4$ K. A comparison of experimental results with the theoretical ones yields a characteristic energy scale of the order of a few K for ThAsSe.

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Non-magnetic interaction of a degenerate Fermi gas with structural two-level systems (TLS) may cause a logarithmic correction to $\rho(T)$, i.e., a behavior analogous to the spin Kondo effect [1]. Even more remarkable is a realization of a two-channel Kondo effect, as predicted when the Kondo temperature, T_K, exceeds the energy splitting between the localized states, Δ_{TLS}. A temperature variation of the additional resistivity due to the TLS–electron interaction, ρ_{TLS}, is shown in the inset of Fig. 1 in a schematic way: Upon cooling below T_K, the $-\log T$ dependence transforms into the non-Fermi liquid (nFL) behavior $\rho_{TLS} \propto 1 - aT^{1/2}$. At the lowest temperatures, ρ_{TLS} saturates and the Fermi-liquid state eventually develops [1].

Recently, we have reported an anomalous scattering mechanism in the structurally disordered ThAsSe [2]. At $T \lesssim 20$ K, its $\rho(T)$ displays a $-\log T$ correction that holds over one decade in temperature and is unaffected by neither magnetic fields up to 13.5 T (cf. the inset of Fig. 2) nor hydrostatic pressures as high as 1.88 GPa [3]. Additionally, for various single crystals a saturation of $\rho(T)$ between 0.2 and 2 K was observed [2]. Most probably, the low-lying excitations of the electron gas in ThAsSe are due to the TLS–electron interaction. Dynamic disorder in this diamagnet was reflected by a quasilinear-in-T term of non-electronic origin in the specific heat at $T \lesssim 1.7$ K [2].

An example of a complex $\rho(T)$ behavior in ThAsSe, presented as the $\Delta\rho(T)/\rho(0.05\text{ K})$ data on a semi-logarithmic temperature scale, is given in Fig. 1. Following observations are made below 20 K: (i) At higher temperatures, $\rho(T)$ logarithmically increases with lowering temperature down to T^*. A rough approximation for T^* yields a value somewhat larger than 2 K. (ii) Upon further cooling, $\rho(T)$ significantly deviates from the $-\log T$ dependence. (iii) An increase of $\rho(T)$ holds down to $T_S \simeq 0.2$ K, at which the saturation sets in.

In order to determine a temperature variation of the electrical resistivity at $T_S < T < T^*$, we re-plotted our data on a $T^{1/2}$ scale. The results are depicted in Fig. 2, where the value of $\rho_{ab}(300\text{ K}) = 220\ \mu\Omega$ cm was taken from Ref. [4]. As indicated by the solid line, a $T^{1/2}$ dependence holds between around ~ 0.2 and 6 K. The latter value is larger than $T^* = 2$ K, as estimated from Fig. 1. We emphasize that an unambiguous approximation of T^* cannot be expected in real, macroscopic samples where there are many TLS centers [1].

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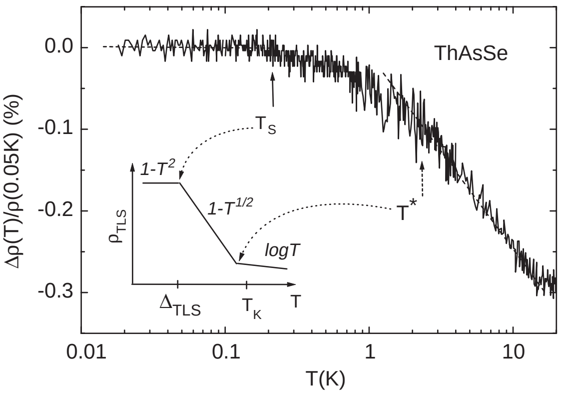

Fig. 1. The *ab*-plane resistivity normalized to the corresponding value at 0.05 K, $\Delta\rho(T)/\rho(0.05\text{ K})$, for the ThAsSe single crystal. The solid arrow at T_S marks the temperature of saturation. The dashed arrow indicates the temperature, T^*, below which $\rho(T)$ deviates from a $-\log T$ dependence. Dashed lines are a guide to the eye only. Inset: Expected temperature dependence of ρ_{TLS} shown in a schematic way for the case of $\Delta_{TLS} \ll T_K$.

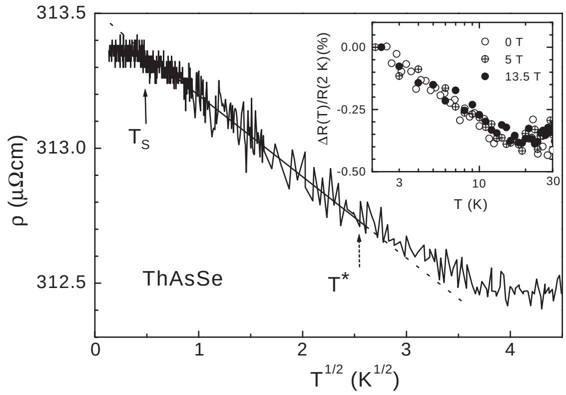

Fig. 2. The *ab*-plane resistivity of the structurally disordered ThAsSe showing a $T^{1/2}$ behavior in a temperature window $T_S < T < T^*$, as indicated by the solid line. Inset: The low-T upturn for another single crystal of ThAsSe shown on a semi-logarithmic temperature scale. The results, plotted as $\Delta\rho(T)/\rho(2\text{ K})$, were obtained along the *ab*-plane in varying magnetic fields applied along the *c*-axis.

As mentioned above, the anomalous low-T properties of ThAsSe are apparently caused by the TLS–electron interaction. Furthermore, the ThAsSe sample with $T_S \simeq 0.2$ K displays a far-reaching similarity of the experimental $\rho(T)$ results to the theoretical ones. Therefore, for this particular specimen, we roughly estimate a characteristic energy scale in terms of the TLS Kondo model: Firstly, we consider $T_S \simeq 0.2$ K as the temperature of the breakdown of the nFL scaling $\Delta\rho \propto T^{1/2}$. Further, we take $T_K = 5$ K, i.e, slightly more than an average value of $T^* \simeq 4$ K inferred from Figs. 1 and 2. Note that T^* represents a low-temperature limit of the $-\log T$ dependence that is expected to hold at $T_K < T$. Finally, we get a crude estimate of the energy splitting $\Delta_{TLS} \approx (T_K T_S)^{1/2} \approx 1$ K. Thus, the $\Delta_{TLS} \ll T_K$ requirement for the two-channel Kondo effect seems to be fulfilled in the ThAsSe sample discussed. Nevertheless, the large value of the Kondo temperature remains unclear, although the recent theoretical studies have shown that T_K of the order of 0.5 K can be achieved outside the tunneling regime, i.e., when the first exited state is above the barrier [5].

To conclude, a complex low-T behavior of $\rho(T)$ in the structurally disordered ThAsSe was observed. Though the enhanced energy scale, our $\rho(T)$ results appear to be consistently interpreted in terms of the TLS Kondo model. In particular, indications towards a two-channel Kondo effect and the resultant nFL properties $\Delta\rho \propto 1 - aT^{1/2}$ derived from structural two-level systems were found for the ThAsSe single crystal with the very small value of $T_S \simeq 0.2$ K.

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