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Thermal conductivity of the one-dimensional $S = 1/2$ antiferromagnet $Yb_4(As_{1-x}P_x)_3$ ($x = 0$ and 0.3)

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Abstract

The thermal conductivity κ of $Yb_4(As_{1-x}P_x)_3$ ($x = 0$ and 0.3) was measured in the temperature range between 0.1 and 7 K in applied magnetic fields up to 8 T. The fact that $\kappa(T)$ follows, between 0.4 and 3 K, the relation $aT + bT^2$ confirms our earlier interpretation of the dominating role of magnons both as heat carriers and as scatterers for the phonons. Above 1 K, κ decreases with increasing magnetic field, the opening of a gap in the magnon-excitation spectrum being a possible explanation of this behavior.

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Thermal conductivity measurements can provide useful information on magnetic excitations in low-dimensional spin systems.

Yb_4As_3 behaves as an ordinary metal at room temperature, where it is cubic. The Yb ions are in an intermediate valent state with an average valence of 2.25+. At 295 K, Yb_4As_3 undergoes a first-order structural phase transition into a trigonal structure accompanied by a charge ordering transition of the smaller Yb^{+3} ions along the $\langle 1\,1\,1 \rangle$ directions. At low temperatures, heavy fermion like behavior is observed: a large specific heat coefficient (200 mJ/mol K^2), a T^2 behavior of the low-temperature electrical resistivity and an enhanced susceptibility [1]. Inelastic neutron scattering experiments revealed low-energy magnetic excitations which could be attributed to antiferromagnetic coupling within the Yb^{+3} chains. The dispersion relation and the spectral shape of the excitations are well explained by a one-dimensional spin $-\frac{1}{2}$ Heisenberg model. It was found that this model explains the value of C/T at low temperatures, as well as the enhanced susceptibility of Yb_4As_3. These results suggest that the heavy fermion like behavior in Yb_4As_3 is closely related to the formation of Yb^{+3} chains caused by the charge ordering [2].

To confirm this proposal the charge carrier concentration was further reduced by doping Yb_4As_3 with P. It was found that a reduction of the charge carrier concentration by four orders of magnitude in $Yb_4(As_{0.7}P_{0.3})_3$ had no influence on the heavy fermion like features. Here, we show that also the low-temperature thermal conductivity is almost unaffected by the dramatic reduction of the charge carrier concentration, putting our early interpretation of magnon-dominated heat transport in Yb_4As_3 [1] on a firmer ground.

In the following, we present thermal conductivity measurements of $Yb_4(As_{1-x}P_x)_3$ ($x = 0$ and 0.3) at low temperatures and in different applied magnetic fields. The equipment and the method used are standard and have been described elsewhere [3].

In Fig. 1, we replot from Ref. [1] the thermal conductivity κ as a function of temperature T in different magnetic fields B for Yb_4As_3 and compare it with new data on $Yb_4(As_{0.7}P_{0.3})_3$. As already suggested in Ref. [1], the zero-field data of Yb_4As_3 may be well

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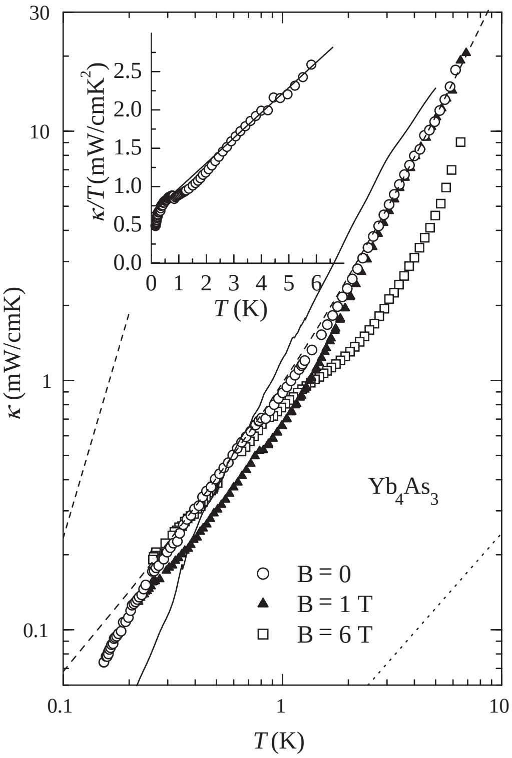

Fig 1. Thermal conductivity κ vs. temperature T for Yb_4As_3 in different applied magnetic fields B and for $Yb_4(As_{0.7}P_{0.3})_3$ (solid line) at $B = 0$. The inset shows that $\kappa = aT + bT^2$ holds between 0.4 and 6 K.

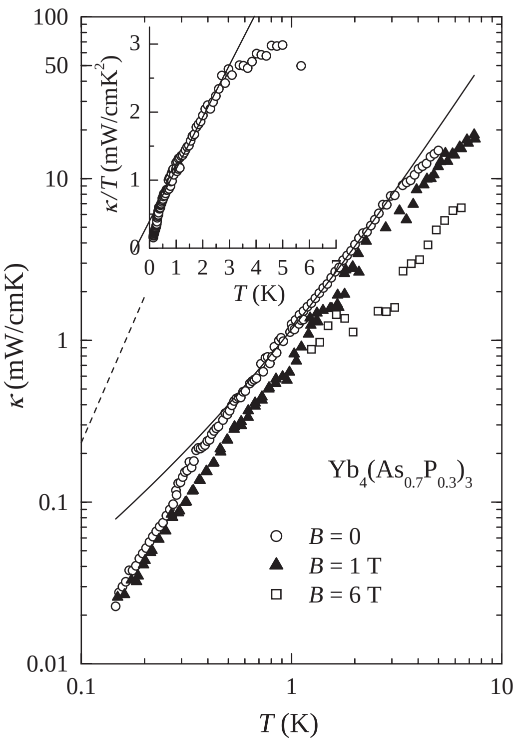

Fig 2. Thermal conductivity κ vs. temperature for $Yb_4(As_{0.7}P_{0.3})_3$ in different applied magnetic fields. The inset shows that $\kappa = aT + bT^2$ holds between 0.4 and 3 K.

approximated by $aT + bT^2$, with $a = 0.65$ and $b = 0.33\,\mathrm{mW/cmK^3}$. The electronic contribution to the thermal conductivity is more than one order of magnitude smaller than the measured total $\kappa(T)$ (cf. dotted line in Fig. 1), and the phonon contribution due to boundary scattering from the smallest sample dimensions ($\sim 800\,\mu\mathrm{m}$) is much higher than $\kappa(T)$ (cf. dashed line in Fig. 1). The $aT + bT^2$ dependence was attributed to the dominating role of magnons in the thermal conductivity of Yb_4As_3, which act as heat carriers and as scatters for the phonons [1].

Thermal conductivity as a function of temperature T for $Yb_4(As_{0.7}P_{0.3})_3$ is shown in Fig. 2 in different applied magnetic fields. Taking into account the similar temperature dependence of the thermal conductivity of both samples, we follow for the doped sample the same type of analysis as for the pure sample. The zero-field data of $Yb_4(As_{0.7}P_{0.3})_3$ can, between 0.4 and 3 K, be well approximated by $aT + bT^2$, with $a = 0.39$ and $b = 0.76\,\mathrm{mW/cmK^3}$. The electronic contribution, as estimated from the resistivity data [1] using the Wiedemann–Franz law, is four orders of magnitude smaller for the doped compound ($\kappa^{\mathrm{WF}}(7\,\mathrm{K}) = 1.7 \times 10^{-5}\,\mathrm{mW/Kcm}$) than for the pure compound ($\kappa^{\mathrm{WF}}(7\,\mathrm{K}) = 1.7 \times 10^{-1}\,\mathrm{mW/Kcm}$), ruling out that the experimentally observed linear term is due to an electronic thermal conductivity and also showing that electrons cannot be important scatterers for the phonons. The phonon contribution, estimated from the gas kinetic equation assuming that boundary scattering from the smallest sample dimensions ($\sim 400\,\mu\mathrm{m}$) determines the mean free path (cf. dashed line in Fig. 2), is much larger than the measured $\kappa(T)$. Thus, the phonons appear to be subject to an additional scattering mechanism; namely the scattering from the magnons leading to the bT^2 term. In addition, the magnons act as heat carriers (aT term). We estimate the magnon mean free path from the magnon specific heat and the gas kinetic equation, giving 80 times the Yb^{3+}–Yb^{3+} distance (130 times for the pure compound). This mean free path is most probably due to scattering from static point defects on the Yb^{3+} chains. For both compounds, below 0.4 K, the thermal conductivity drops below the $aT + bT^2$ law due to spin-glass freezing [1,4]. The magnetic field dependence of the thermal conductivity is plausible within this interpretation. For both compounds, at $B = 1\,\mathrm{T}$, the magnon thermal conductivity is reduced, but the reduction of the phonon magnon scattering rate reinforces the phonon conductivity and, thus, overcompensates this effect in higher magnetic fields such that, at $B = 6\,\mathrm{T}$, the zero field thermal conductivity is almost recovered. Above 1 K, $\kappa(B)$ decreases with increasing magnetic field, the opening of a gap in the magnon-excitation spectrum being a possible explanation of this behavior [1].

The electronic contribution to the thermal conductivity is reduced by four orders of magnitude when doping Yb_4As_3 with 30% of P due to the reduction of the number of charge carriers. The fact that the aT term is virtually unchanged rules out an electronic origin of this term. Instead, we attribute the thermal conductivity at low temperatures and in zero magnetic field of Yb_4As_3 and $Yb_4(As_{0.7}P_{0.3})_3$ to heat carried by magnons.

References

[1] B. Schmidt, et al., Physica B 300 (2001) 121.
[2] M. Kohgi, et al., Phys. Rev. B 56 (1997) R11388.
[3] B. Wand, Ph.D. Thesis, TU Darmstadt, 1998.
[4] P. Gegenwart, et al., Physica B 312–313 (2002) 315.