Anomalous low-temperature thermal conductivity of MgB_2

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Abstract

The *ab*-plane thermal conductivity of single-crystalline hexagonal MgB_2 has been measured as a function of magnetic field with orientations both parallel and perpendicular to the c-axis and at temperatures between 0.5 and 8 K. The observed anomalous variation of the thermal conductivity in magnetic fields at constant temperature is consistent with a field-induced suppression of two superconducting energy gaps of significantly different magnitude. An anomalous nonlinear temperature dependence of the electronic thermal conductivity, violating the Wiedemann-Franz law, is observed in the field-induced normal state.

Key words: MgB_2, superconductivity, thermal conductivity, mixed state

MgB_2 provides a unique opportunity to study multiband effects in superconductivity. Calculations of the Fermi surface of this material [1] reveal the existence of both three-dimensional (3D) sheets (π-bands) and two-dimensional (2D) tubes (σ-bands), exhibiting almost equal densities of electronic states at the Fermi level. The superconducting energy gap appears to differ substantially on these parts of the Fermi surface with different dimensionality: the value of the gap of the 2D parts at $T = 0$ K is close to $1.76k_BT_c$, as predicted by the original weak-coupling BCS theory, but the gap associated with the 3D sheets of the Fermi surface is 3 to 4 times smaller [2].

Here we present the results of measurements of the thermal conductivity κ parallel to the basal plane of the hexagonal crystal lattice of MgB_2 as a function of varying magnetic fields H between 0 and 50 kOe and temperatures between 0.5 and 40 K. The magnetic field was oriented both parallel and perpendicular to the c-axis.

In Fig. 1 we present the $\kappa(H)$ curves, measured at constant temperatures below 8 K for field directions both parallel and perpendicular to the c-axis. The typical features of these curves are the rapid initial decrease of κ with increasing field, narrow minima in $\kappa(H)$ at field values that are low with respect to H_{c2}, and a subsequent s-shape type increase of κ with further increasing field. For $H \parallel c$, the increasing slope at higher fields is caused by approaching the normal state at H_{c2}. This trend is not observed for $H \perp c$, for which H_{c2} is estimated to exceed 100 kOe at these low temperatures [3].

For the analysis of the data, contributions to the heat transport due to both electronic quasiparticles (κ_e) and phonons ($\kappa_{\rm ph}$) are considered, such that $\kappa = \kappa_e + \kappa_{\rm ph}$. Applying external magnetic fields at $T < T_c$ induces vortices in the sample. The quasiparticles associated with the vortices not only enhance the phonon scattering and hence reduce $\kappa_{\rm ph}$, but also enhance κ_e. The competition of these two processes leads to $\kappa(H)$ curves as shown in Fig. 1. An intriguing aspect of these curves is the very rapid increase of κ_e at relatively low fields, following the initial decrease of $\kappa_{\rm ph}$. For $H \perp c$, the rapid increase is followed by a region where $\kappa(H)$ varies only weakly with H. The same trend is also observed for $H||c$ but it is partly masked by yet another increase of $\kappa(H)$ close to H_{c2}. For $H \perp c$ and $T \leq 8$ K, $H_{c2}^{ab} \sim 130$ kOe (Ref. [3]), therefore the region of weak H-dependence extends to the highest fields reached in this study.

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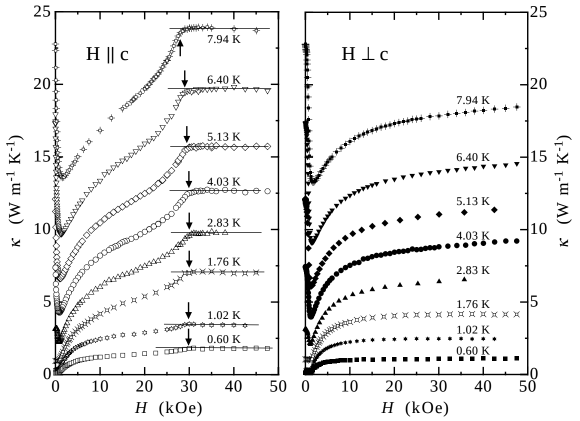

Fig. 1. Thermal conductivity in the basal plane of MgB_2 vs H at several fixed temperatures. The arrows denote the upper critical field H_{c2} for $H \parallel c$.

The field dependence of κ_e can qualitatively be explained in terms of a two-band model. The pairing interaction leads to a gap Δ_L in one of bands (L-band) whereas Cooper-pair tunneling leads to merely induced superconductivity and a significantly smaller gap Δ_S in the second band (S-band) [4]. Quasiparticle states in the vortex cores are expected to be highly confined in the L-band but only loosely bound in the S-band. Therefore the quasiparticle states of neighboring vortices in the S-band overlap already in weak fields $H \ll H_{c2}$ [4]. In terms of the two-gap model, the saturation of $\kappa_e(H)$ much below H_{c2} may be regarded as evidence for the closing of Δ_S. The heat transport via quasiparticles of the band associated with the larger gap is significant only in the vicinity of and above H_{c2}.

As shown in Fig. 2, the thermal conductivity in the field-induced normal state ($H \parallel c > 30$ kOe) is considerably higher than $\kappa(T)$ in the Meissner state ($H = 0$), naturally because of the much enhanced κ_e in the normal state. In order to establish $\kappa_e(T)$ in the normal state, an estimate of $\kappa_{\rm ph}$ in the normal state is required. Taking into account that the minima of $\kappa(H)$ shown in Fig. 1 are the result of a competition between the decreasing $\kappa_{\rm ph}$ and an increasing κ_e, it is clear that the values of $\kappa_{\rm min}(H)$ are at most equal to the maximum value of the lattice contribution, $\kappa_{\rm ph}^{\rm max}$. The minimum possible value of the phonon contribution $\kappa_{\rm ph}^{\rm min}$ is zero, and therefore, κ_e must lie somewhere between $\kappa - \kappa_{\rm ph}^{\rm max}$ and κ. The range of possible values of κ_e in the normal state below 8 K, shown in Fig. 2 by the shaded area, exceeds, at all temperatures, the values calculated using the Wiedemann-Franz law (WFL) $\kappa_e^{\rm WFL}(T) = L_0 T/\rho(T)$. Here $L_0 = 2.45 \times 10^{-8}$ W Ω K^{-2} and $\rho(T)$ is the experimental value of the practically constant *bulk* electrical resistivity $\rho_0 \approx 2.1$ $\mu\Omega$cm at $H = 33$ kOe. It may be seen in the inset of Fig. 2, where $\kappa_e(T)$ is displayed in the form of $L(T)/L_0$, with $L(T) \equiv \kappa_e(T)\rho_0/T$, that $\kappa_e(T)$ does not exhibit the expected linear-in-T behavior.

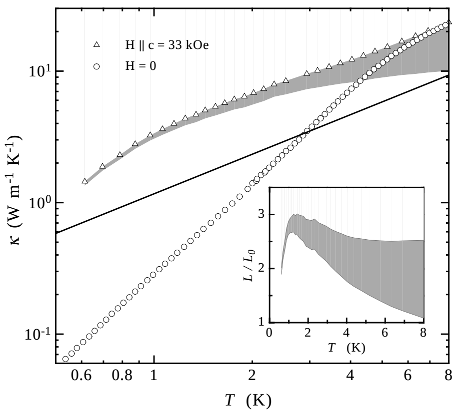

Fig. 2. Thermal conductivity in the superconducting state (circles) and the normal state in $H = 33$ kOe (triangles). The shaded area corresponds to possible values of electronic contribution calculated as described in the text. The solid line represents the electronic contribution $\kappa_e^{\rm WFL}$ calculated using the Wiedemann-Franz law. In the inset, the possible values of the electronic contribution are plotted in form of the Lorenz ratio $L(T)/L_0$.

This violation of the WFL at low temperatures is quite unexpected because the validity of this law normally holds for the Fermi-liquid ground state of common metals where $\rho(T) = \rho_0$, the residual resistance. A deviation from the WFL in the form of a peak-type structure of $L(T)$ (see the inset of Fig. 2) might be the consequence of some kind of an anomalous gap formation in the electronic excitation spectrum in the normal state [5].

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