High pressure insulator–metal transition in SmB$_6$

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Abstract

We report the temperature and pressure dependence of the electrical resistivity and Hall constant of single crystal SmB$_6$ for temperatures ranging from 1.2 K to room temperature, and pressures from 1 bar to 80 kbar. Our results indicate that at low pressures SmB$_6$ is an insulator, but undergoes a sudden transition to metallic behavior at a pressure of 50 kbar.

1. Introduction

Recently, there has been extensive theoretical discussion regarding the stability of Kondo insulators under variations in temperature and magnetic field of order the insulating gap [1]. Experimentally, it is a challenge to test these theories by identifying systems in which the insulating gap is both comparable to accessible temperatures and magnetic fields, and also continuosly variable. SmB$_6$ is an ideal candidate for such a study. Previous high pressure resistivity measurements on Smb$_6$ [2, 3] found that the application of pressure continuously reduces the observed activation gap, which vanishes in the vicinity of 50 kbar. Our experimental strategy is to continuously tune the gap using pressures which approach the critical pressure, and search for signatures in the transport properties suggestive of transitions to new phases. We have simultaneously measured the temperature and pressure dependent Hall voltage of SmB$_6$ allowing the separation of variations in scattering rates and carrier density.

2. Experimental details

The samples used in this study are high quality single crystals grown from an aluminum flux. Hall effect and resistivity measurements were carried out using a Bridgman anvil cell, with the applied pressure estimated from force–pressure relations. The Hall voltage and longitudinal magnetoresistance were measured in swept positive and negative fields to correct for contact misalignment voltages.

3. Experimental results

The temperature dependences of the electrical resistivity for pressures ranging from 1 bar to 80 kbar are plotted in Fig. 1. Below 48 kbar, the electrical resistivity initially decreases with reduced temperature, before sharply increasing and ultimately saturating at the lowest temperatures. The temperature dependence of the resistivity in this pressure range is activated for temperatures
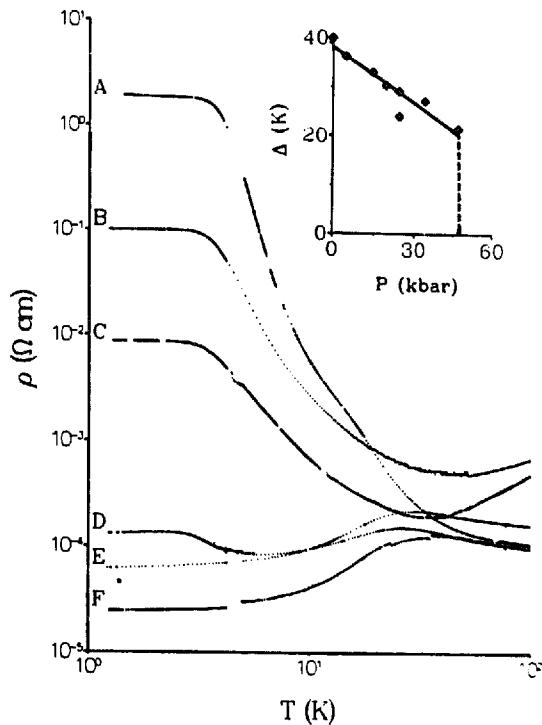
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Fig. 1. The temperature dependence of the electrical resistivity of single crystal SmB_6 for pressures A = 1 bar, B = 35 kbar, C = 48 kbar, D = 60 kbar, E = 70 kbar, and F = 80 kbar. Note the qualitative differences in the temperature dependences above and below 48 kbar. The inset shows the pressure dependence of the resistivity activation gap. As described in the text, no gap is found above 48 kbar.

Fig. 2. The temperature dependence of the Hall constant for pressures from 1 bar to 80 kbar. $\bigcirc$ = 1 bar, $\oplus$ = 20 kbar, $\bullet$ = 25 kbar, $\square$ = 35 kbar, $\boxminus$ = 48 kbar, $\blacksquare$ = 60 kbar, $\triangle$ = 70 kbar, $\blacktriangle$ 80 kbar. Solid lines are guides for the eye.

between 3 and 30 K, if a parallel resistor formulation is used to remove the almost constant saturation resistance observed at the lowest temperatures. The pressure dependence of the activation gap extracted from such fits is plotted in the inset to Fig. 1. The ambient pressure magnitude of the activation gap is 40 K, similar to that found in a variety of previous transport and spectroscopic studies of SmB_6 [4–7] but much smaller than that reported in a recent infrared transmission experiment [8].

A dramatic change in the temperature dependence of the resistivity is observed at pressures higher than 48 kbar. Here, the resistivity initially increases with reduced temperature, attaining a maximum at ~ 25 K, and dropping again at the lowest temperatures. This temperature dependence is reminiscent of metallic mixed valence compounds. There is no appreciable range of temperatures for pressures above 48 kbar where the electrical resistivity exhibits an activated temperature dependence, indicating that there is no gap present in SmB_6 above 48 kbar. We conclude that while the insulating gap initially decreases linearly with applied pressure, diminished to 22 K at 48 kbar, the gap vanishes suddenly in
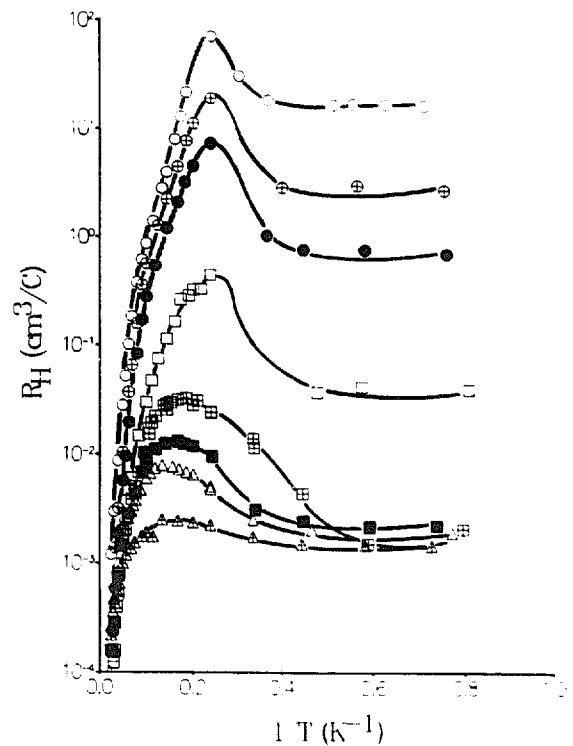
a narrow range of pressures near 50 kbar. In this respect, our data differ qualitatively from those of previous reports [2, 3], which on the basis of more limited data reported a continuous reduction and vanishing of the activation gap near 50 kbar.

Further evidence for an abrupt transition from insulating to metallic behavior in the vicinity of 50 kbar is also found in the pressure and temperature dependences of the Hall constant, plotted in Fig. 2. The Hall constant is negative at all temperatures and field independent up to 7 T, initially increasing sharply with reduced temperature, attaining a maximum value near 4 K, before decreasing and becoming constant at the lowest temperatures. The magnitude of the temperature induced changes in the Hall constant is dramatically reduced with the application of pressure. Interestingly, there is no appreciable range of temperatures or pressures on which the Hall constant exhibits activated behavior with the same gap as the resistivity, suggesting that the observed temperature dependence not only depends on the semiconducting background and impurity bands but possibly also reflects the presence of anomalous skew scattering.

4. Discussion

In view of the potentially complex nature of the temperature dependent Hall constant, we focus here on its low temperature properties. We can gain insight into the nature of the low temperature electronic structure by comparing the low temperature, constant values of the residual resistivity ρ_0 and the carrier population n_0 derived from the inverse Hall constant. At ambient pressure these quantities are $1.9 \, \Omega \, cm$ and $3.6 \times 10^{17} \, cm^{-3}$, respectively. It is important to note that the maximum resistivity resulting from a single unitarity scatterer per unit cell in SmB_6 is only $540 \, \mu\Omega \, cm$ [5] more than three orders of magnitude smaller than the observed ambient pressure ρ_0. The simultaneous observations of enormous ρ_0 and small n_0 at low pressures can be reconciled by postulating that the low temperature transport is dominated by an extended impurity band. With increased pressure, the number of carriers in the impurity band grows and the bandwidth increases, decreasing the associated residual resistivity. Above 50 kbar, the carrier number becomes essentially pressure independent, signalling that the impurity band has been absorbed into the conduction band, presumably as a result of the sudden gap closure revealed by the resistivity measurements.

In summary, the pressure dependence of the electrical resistivity and the Hall constant reported here suggest that SmB_6 is an insulator at low pressure, but that a sudden transition to metallic behavior similar to that found in metallic Kondo lattice materials is observed when the pressure is increased past 50 kbar.

Acknowledgements

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