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# Magnetoresistance of the Kondo insulator $Ce_3Bi_4Pt_3$

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The magnetoresistance (MR) of the narrow-gap Kondo insulator $Ce_3Bi_4Pt_3$ and its non-magnetic analog $La_3Bi_4Pt_3$ have been measured in magnetic fields to 10 T and in the temperature range 2–300 K. $Ce_3Bi_4Pt_3$ exhibits a large negative MR component below 7 K. At higher temperatures this negative component progressively decreases and a positive contribution becomes evident. Above 75 K the MR is positive at all fields and saturates to a value of a few percent. The non-magnetic analog $La_3Bi_4Pt_3$ exhibits the same positive magnetoresistance present in $Ce_3Bi_4Pt_3$ as well as a conventional positive $H^2$ term at low temperatures. We discuss potential mechanisms for both the common positive effect and the large negative MR present in $Ce_3Bi_4Pt_3$.

## 1. Introduction

The cubic rare-earth intermetallic compound $Ce_3Bi_4Pt_3$ [1] is an unconventional narrow-gap semiconductor with physical properties characteristic of a Kondo insulator [2]. The magnetic susceptibility [1], volume thermal expansion [3], and inelastic neutron linewidth [4] of $Ce_3Bi_4Pt_3$ are all characteristic of a mixed-valency compound with $T_K = 320$ K, while the electronic contribution to the specific heat is essentially zero [1]. In addition, transport measurements [1,5] indicate that $Ce_3Bi_4Pt_3$ is a narrow-gap compound with an energy gap of 100 K. Lanthanum substitution studies [5] indicate that the insulating state stems from a hybridization gap derived from Kondo coherence.

In this paper we present the magnetoresistance (MR) of $Ce_3Bi_4Pt_3$ and its non-magnetic analog $La_3Bi_4Pt_3$. In both compounds, an unusual positive contribution to the MR is present at all temperatures that can be described by a single field-dependent function. At low temperatures ($T < 75$ K), a negative MR component becomes evident in $Ce_3Bi_4Pt_3$ that grows with decreasing temperature, resulting in a 30% reduction in $\rho$ at 3 K that stems from a field-induced suppression of the transport gap.

## 2. Experimental results and analysis

Figure 1 shows the temperature-dependent zero-field resistivity of both $Ce_3Bi_4Pt_3$ and $La_3Bi_4Pt_3$. As with earlier studies [1,5], $Ce_3Bi_4Pt_3$ displays Arrhenius behavior down to roughly 45 K with an activation energy of 50 K (i.e., an energy gap of 100 K); below 45 K the resistivity increases less rapidly, indicating that low-mobility extrinsic carriers dominate the conduction process at low temperatures (recent theoretical work suggests that non-magnetic impurities present in Kondo insulator compounds will give rise to Kondo holes and an extrinsic impurity band [6]). The room-temperature resistivity of $Ce_3Bi_4Pt_3$ ($\rho(300\text{ K}) = 220\ \mu\Omega$ cm) is typical of a mixed-valency compound in the single-impurity Kondo regime. The resistivity of the non-magnetic analog $La_3Bi_4Pt_3$ has both a magnitude ($\rho(300\text{ K}) = 150\ \mu\Omega$ cm) and a

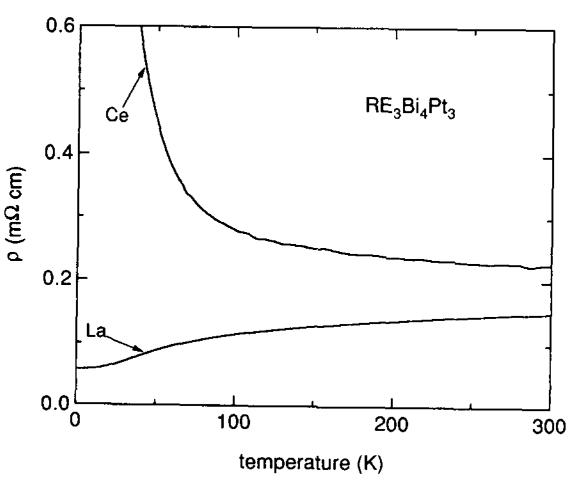


Fig. 1. Resistivity versus temperature for $Ce_3Bi_4Pt_3$ and $La_3Bi_4Pt_3$.

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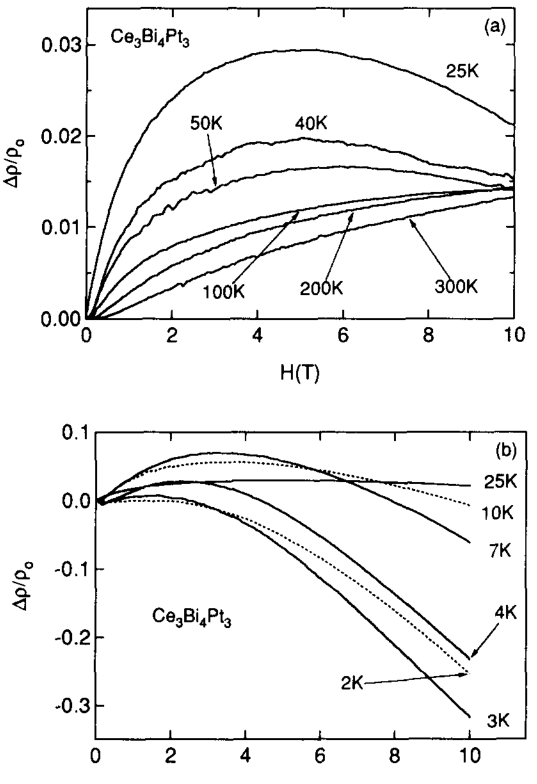

Fig. 2. Transverse magnetoresistance versus applied magnetic field $H$ for $Ce_3Bi_4Pt_3$: (a) high-temperature region, and (b) low-temperature region.

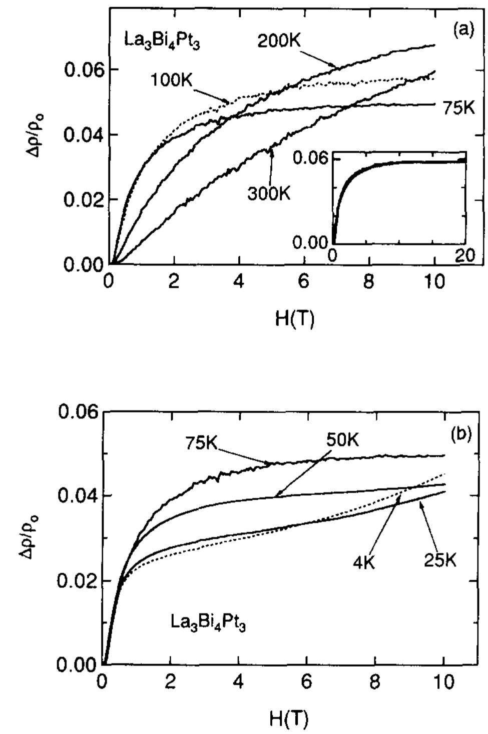

Fig. 3. Transverse magnetoresistance versus applied magnetic field $H$ for $La_3Bi_4Pt_3$: (a) high-temperature region, and (b) low-temperature region. The inset to (a) depicts the common scaled magnetoresistance for all temperatures (4–300 K) plotted versus the reduced field parameter $H^*$.

characteristic temperature dependence which saturates at high temperatures that are indicative of a poor metal with a short mean-free path [7].

The transverse MR of $Ce_3Bi_4Pt_3$ is presented in fig. 2. At 300 K, $\Delta\rho/\rho_0 = [\rho(H) - \rho(0)]/\rho(0)$ is large (~1%) and positive, and is an increasing function of field. For $T < 300$ K, the positive MR tends to saturate at a characteristic field $H_s$, which is an increasing function of temperature. Below 100 K, an additional negative contribution becomes evident that grows with decreasing temperature. While the positive component is observable at all temperatures, the negative component dominates below 25 K. At 4 K, a 10 T field decreases $\rho$ by 25%. This is qualitatively consistent with preliminary pulsed-field measurements to 50 T, which show a two order of magnitude decrease in the resistivity at 4 K [8].

To determine the non-magnetic background MR in $Ce_3Bi_4Pt_3$, we next consider the transverse MR of $La_3Bi_4Pt_3$, as presented in fig. 3. The MR is positive at all temperatures and is similar to the positive component present in the $Ce_3Bi_4Pt_3$ data. The positive effect is characterized by a rapid increase at low fields (a simple $H^2$ dependence is observable only below ~200 G), and a high-field saturation to a constant value above $H_s$. The characteristic saturation field drops to only a few Tesla at 4 K. Below 50 K an additional conventional positive $H^2$ contribution is evident. This additional component is a decreasing function of temperature with an amplitude which scales as $1/\rho_0(T)$. By first removing this conventional $H^2$ term from the $\Delta\rho/\rho_0$ data and then applying temperature-dependent scaling factors to both the MR amplitude and $H$-field values, the positive MR can be scaled throughout the temperature range of 4–300 K to a single, common field dependence as indicated in the inset to fig. 3(a). The $La_3Bi_4Pt_3$ MR can therefore be parametrized as

$$\frac{\Delta\rho}{\rho_0}(H, T) = \alpha \frac{H^2}{\rho_0(T)} + \beta\rho_0(T)f(H^*) , \qquad (1)$$

where $f(H^*)$ is the scaled positive MR function depicted in the inset to fig. 3(a), $\alpha$ and $\beta$ are temperature- and field-independent constants, and $H^*$ is the reduced field parameter ($H^* = Hg(T)$) scaled by $g(T)$; $g(T)$ scales roughly as $1/T$. The function $f(H^*)$ also fits the positive MR component present in the $Ce_3Bi_4Pt_3$ MR data for $T > 10$ K; below 10 K the positive MR contribution is small compared to the negative contribution, making a scaling analysis problematic.

## 3. Discussion

The MR data indicate that a positive magnetoresistance component is present in both $Ce_3Bi_4Pt_3$ and $La_3Bi_4Pt_3$. Further, this component can be described by a single field-dependent function $f(H^*)$. The positive MR of both compounds must stem from the same underlying physical mechanism. Similar MR data with $H_s \sim 1$ kG have been reported in elemental semimetals; in the case of bismuth the highly field-dependent MR stems from the interplay between three small ellipsoidal carrier pockets [9]. For a generic multiband model, the onset to saturation of the MR occurs when the product of the cyclotron frequency $\omega_c$ and the relaxation time $\tau$ is unity. Indeed, the MR function $f(H^*)$ can be qualitatively reproduced with a simple two-band model involving a poorly conducting band, wherein $\omega_c\tau = 1$ at $H = 1$ T, and a second band with $\rho_0 \sim 100\ \mu\Omega$ cm. This simple two-band model suggests that the positive MR could stem from the presence of a subordinate band lying very close to the Fermi energy. This possibility is supported by the fact that the substitution of just 1% Ce by La entirely destroys the positive MR and gives rise to a conventional single-impurity Kondo-like MR [10]. Regardless of its cause, the common positive MR indicates that $Ce_3Bi_4Pt_3$ and $La_3Bi_4Pt_3$ share a similar electronic structure above 100 K.

We next consider the large negative MR exhibited by $Ce_3Bi_4Pt_3$ below 50 K. Qualitatively similar results have been reported in other Kondo insulator systems, notably $YbB_{12}$ [11] and CeNiSn [12]. The substantial reduction of the resistivity is presumably due to a suppression of the gap by the applied field $H$, since an applied field with a characteristic energy comparable to the gap energy will excite carriers between the valence and conduction bands. Although a simple reduction of the gap in $Ce_3Bi_4Pt_3$ involving the Zeeman effect cannot be entirely ruled out, the applied field could act instead to suppress the interactions responsible for the hybridization gap. This is borne out by the fact that attempts to fit the negative MR component of $Ce_3Bi_4Pt_3$ with a Zeeman gap-reduction mechanism (i.e., $E_g(H) = E_g(H = 0) - gJ\mu_B H$) were unsuccessful (poor fits were also reported in [11] for $YbB_{12}$). Hence, the applied field may reduce the gap by suppressing the physical interactions which are the underlying cause of the Kondo insulator state. No theoretical model currently exists to test this conjecture and the development of such a model would assist in determining the cause of the large negative magnetoresistance exhibited by Kondo insulator systems.

In conclusion, $Ce_3Bi_4Pt_3$ exhibits a large, negative magnetoresistance in its low-temperature gapped state that may stem from a field-induced suppression of the interactions responsible for the hybridization gap present in this compound. In addition, both $Ce_3Bi_4Pt_3$ and $La_3Bi_4Pt_3$ exhibit an unusual positive magnetoresistance, indicating that the electronic structure is similar above 100 K in these two materials.

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