Magnetic susceptibility of LaRu$_3$Si$_2$

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Abstract

The magnetization $M$ of LaRu$_3$Si$_2$ has been measured to investigate the electronic states in the normal state. The magnetization curve ($M$-$H$ curve) was analyzed with assuming that it consists of an intrinsic paramagnetic part and a ferromagnetic impurity part. The estimated intrinsic magnetic susceptibility is very dependent on temperature. This is attributable to a narrow band of conduction electrons with a high density of states, which is consistent with a considerably high superconducting transition temperature $T_c=6.5$ K.

Key words: LaRu$_3$Si$_2$; mixed valence; magnetization; magnetic susceptibility

The mixed valence phenomenon and Kondo effect in a ternary rare earth compound RRu$_3$Si$_2$ (R=rare earth element) have been a matter of interest [1–4]. CeRu$_3$Si$_2$ becomes superconducting below the superconducting transition temperature $T_c=1$ K while $T_c$ of LaRu$_3$Si$_2$ is as high as 6.5 K. To understand this depression of superconductivity by the localized 4f moment and the strength of hybridization between 4f and conduction electrons in CeRu$_3$Si$_2$, it is necessary to investigate the superconducting and magnetic properties in LaRu$_3$Si$_2$ without 4f electrons. In this paper, the magnetic field and temperature ($T$-) dependence of the magnetization $M$ in the normal state of LaRu$_3$Si$_2$ is reported and the density of states (DOS) of conduction electrons is discussed.

A polycrystalline sample of LaRu$_3$Si$_2$ was prepared in an argon arc furnace by melting pure starting elements La, Ru and Si. The powder X-ray diffraction pattern shows that the sample is of a good single phase. The magnetization $M$ was measured with a SQUID magnetometer.

$M$ measured at 300 K is plotted against the applied field $H$ ($M$-$H$ curve) by closed circles in Fig. 1. The slope of this curve becomes smaller with increasing $H$ and seems to be constant above 10 kOe. Similar behavior is observed at each measured temperature between 10 and 300 K. We consider $M=\chi H+M_{\text{ferro-imp}}(H)$, where $\chi$ is the magnetic susceptibility and $M_{\text{ferro-imp}}(H)$ is a magnetization of some ferromagnetic impurity. $M_{\text{ferro-imp}}(H)$ is considered to saturate and be constant above 10 kOe.

![Magnetization](https://via.placeholder.com/150)

Fig. 1. Magnetization $M$ (closed circles) measured at 300 K is decomposed into $H$-linear part (solid line and open circles) and impurity part $M_{\text{ferro-imp}}(H)$ (open diamonds).

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\(\chi H\) and the saturated value of \(M_{\text{ferro-imp}}(H)\) are estimated by the least-squares fitting of \( M = \chi H + \text{const.}\) to the data points above 10 kOe. The solid line and open circles give the \(\chi H\). The open diamonds show \(M_{\text{ferro-imp}}(H)\) obtained by subtracting \(\chi H\) from the raw \(M\). The saturated value of \(M_{\text{ferro-imp}}(H)\) is 0.22 emu/mol and is only about 1 \% of \(\chi H = 18.5\) emu/mol at 50 kOe. Therefore, \(M/H\) obtained at 50 kOe can be used as \(\chi\). In our previous paper, we derived \(\chi\) from the slope of the \(M-H\) curve above 10 kOe [5]. In this paper, we discuss the \(T\)-dependence of \(\chi\) obtained from \(M/H\) measured at \(H=50\) kOe.

In Fig. 2, the \(T\)-dependence of \(M/H\) measured at \(H=50\) kOe is shown by open circles. \(M/H\) is \(T\)-dependent and is considered to consist of the intrinsic \(T\)-dependent part \(\chi(T)\) reflecting the electronic correlation, the \(T\)-independent part \(\chi_0\) which contains the orbital contribution due to d electrons and spin contribution due to s and p electrons, and a paramagnetic impurity part \(\chi_{\text{imp}}(T)=C/(T+\theta)\). In the material which has a narrow band or shows Kondo effect, \(\chi(T)\) becomes a constant \(\chi(0)\) at sufficiently low \(T\). The least-squares fitting of \(\chi(T)\) is proportional to \(1/T\) as discussed above. The slope of this curve becomes smaller with increasing \(T\), and is expected to become \(\chi_0\) at sufficiently high \(T\) because \(\chi(T)\) is proportional to \(1/T\). The least-squares fitting of \(\chi(T)\) is shown by open circles.

In order to estimate \(\chi(0)\), we plot \((\chi-\chi_{\text{imp}}(T))T\) against \(T\) in Fig. 3. At sufficiently low \(T\), the data points are linear to \(T\) and the slope gives \(\chi(0)\) as discussed above. The slope of this curve becomes smaller with increasing \(T\), and is expected to become \(\chi_0\) at sufficiently high \(T\) because \(\chi(T)\) is proportional to \(1/T\). The least-squares fitting of \((\chi-\chi_{\text{imp}}(T))T\) is shown by open circles.

\[\chi_{\text{imp}}(T) = \chi_0 T + \text{const.}\] as the data points above 260 K gives \(\chi_0 = 3.20 \times 10^{-4}\) emu/mol. \(\chi(0)\) is thus estimated to be \(1.09 \times 10^{-3}\) emu/mol.

If \(\chi(T)\) originates mainly from the narrow band of Ru 4d electrons, we can estimate DOS of 4d electrons \(N_{\text{4d}}(\epsilon_F)\) at Fermi level using the formula of Pauli paramagnetism \(\chi(0)=2\mu_B^2 N_{\text{4d}}(\epsilon_F)\). \(N_{\text{4d}}(\epsilon_F)\) is obtained to be 0.56 states/eV Ru spin. This value is nearly the same as \(N_{\text{4d}}(\epsilon_F)=1.03\) states/eV Ru spin estimated in the previous paper [5]. These values are comparable to DOS of V 3d electrons \(N_{\text{3d}}(\epsilon_F)=1.60\) states/eV V spin in C15 Laves phase HFV2 [6,7], in which a strongly \(T\)-dependent \(\chi\) originates from the narrow band with high DOS. The large \(N_{\text{4d}}(\epsilon_F)\) may explain also the considerably high \(T_c\) of LaRu4Si2.

References