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Superconductivity in $LaCd_2$

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Abstract

Low temperature heat capacity and resistivity measurements indicated that $LaCd_2$ is a low temperature superconductor ($T_c = 1.44$ K). It is a conventional weak-coupling superconductor with a coupling constant $\lambda \approx 0.47$. The electronic specific heat coefficient γ (8.0 mJ mol^{-1} K^{-2}) and Debye temperature Θ_D (186 K) were determined from heat capacity data. The covalent bonding in $LaCd_2$ is probably responsible for preventing the softening of the phonon spectrum, which probably accounts for the low T_c value. $LaCd_2$ is the first superconducting intermetallic compound that has the $CeCd_2$-type structure. However, compared with the lanthanum Laves phase compound superconductors, the structural difference may be insignificant in determining the superconducting properties.

Keywords: Superconductivity; Heat capacity; Resistivity

1. Introduction

In order to further understand the physics of 4f electrons in rare earth intermetallic compounds, a study of low temperature properties of Ce–Cd intermetallics was conducted [1]. Some of the corresponding La–Cd compounds were also examined because these lanthanum compounds can often be used as reference materials. The crystal structures of La and Ce compounds and their outer electronic configurations are usually the same and thus the differences in their behaviors will be due to the 4f electron of the Ce atom. Among the La–Cd compounds studied, $LaCd_2$ is the most interesting, because a superconducting transition was found at 1.44 K.

Superconductivity has been found in several cubic Laves phase La compounds, e.g. $LaAl_2$ ($T_c = 3.2$ K [2]) and $LaPt_2$ ($T_c = 0.46$ K [3]). $LaCd_2$ crystallizes in a different structure. It has the hexagonal $CeCd_2$ structure in which La atoms occupy 1(*a*) positions (0,0,0) and Cd atoms occupy 2(*d*) positions ($\frac{1}{3},\frac{2}{3},x$), where $x \approx 0.42$ [4–8]. The lattice parameters are $a = 5.075$ Å and $c = 3.571$ Å, although Iandelli and Ferro [4] reported a significantly lower *c* lattice parameter (3.458 Å).

2. Experimental details

The starting materials, La (99.8 at.% pure) and Cd (99.999 at.% pure) metals, were obtained from the Materials Preparation Center of the Ames Laboratory and Cominco Products Inc. respectively. The $LaCd_2$ sample was prepared by melting stoichiometric amounts of the constituents in a sealed tantalum crucible under a helium atmosphere using a resistance furnace. Owing to the high vapor pressure of Cd [9], it is important to seal the starting materials in a closed crucible in order to prevent the escape of Cd vapor at high temperatures. The La–Cd phase diagram indicates that $LaCd_2$ melts congruently at 953 °C [10] and therefore no further heat treatment was carried out. Optical metallography showed that the sample was single phase.

Low temperature heat capacity measurements (1.3–20 K) were carried out using an adiabatic heat pulse calorimeter [11]. Magnetic fields of 0, 0.1 and 0.2 T were applied during the heat capacity measurements. A conventional four-probe technique was used for making resistivity measurements between 0.5 and 2.4 K in a ^{3}He refrigerator.

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3. Results

The original purpose of measuring the low temperature heat capacity of $LaCd_2$ was that it can serve as a reference material for $CeCd_2$, which showed a rather complex magnetic behavior with two magnetic transitions at 18.5 and 22 K [1]. Without the complications brought about by the 4f electrons, $LaCd_2$ should behave as an ordinary metallic material, i.e. one would expect a linear electronic specific heat (γT) and a T^3 term from the lattice contribution. This was indeed the case above 1.5 K. However, its heat capacity exhibited a discontinuous jump at 1.4 K as shown in Fig. 1. The number of points below the transition was limited by the low temperature limit of our calorimeter. Although heat capacity data for $LaCd_2$ at lower temperatures are lacking, the nature of the transition associated with this jump can be clearly seen. The C/T vs. T^2 plot (Fig. 2) showed a linear behavior down to the transition point, which indicated a non-magnetic nature of the transition. Heat capacity measurements in a magnetic field destroyed the peak observed at zero magnetic field (see Fig. 2) indicating that this is a superconducting transition. As a matter of fact, the value of $(C_s - C_n)/\gamma T_c$ at T_c obtained from the heat capacity data is 1.46, which is close to the theoretical Bardeen–Cooper–Schrieffer (BCS) value of 1.43 for a superconductor [12]. In calculating the above value, a γ of 8.0 mJ mol^{-1} K^{-2}, determined from the intercept of the straight line in Fig. 2, was used. The transition temperature T_c was found to be 1.44 K from the peak of the jump in the heat capacity.

A measurement of the field dependence of T_c was attempted by measuring the heat capacity under applied magnetic fields. As seen in Fig. 2, a field of 0.1 T is strong enough to shift T_c below 1.4 K, which is the lower limit of our calorimeter at that field.

In order to confirm this superconducting transition in $LaCd_2$, electrical resistivity measurements were made from about 0.5 to 2.4 K (see Fig. 3). As seen, the superconducting transition is evident. The T_c value determined from the resistivity data (1.31 K) was somewhat lower than that noted above. The discrepancy between this value and the one obtained from heat capacity data is probably due to the fact that the resistivity of $LaCd_2$ in the normal state is small; thus a measuring current of 0.1 A was used in order to have a large enough voltage reading to overcome the background noise. Such a large current could cause Joule heating at the junctions between the sample and electrical leads. Another source of contact heating could be due to the fact that $LaCd_2$ is air sensitive, and during the time when the sample was taken out of the argon-filled glove-box to connect the electrical leads, a thin layer of oxide may have formed on the surface of the sample. As a result, the actual temperature of the sample was probably higher than the reading on the thermometer. We believe that the T_c value derived from the heat capacity measurements reflects the true transition temperature.

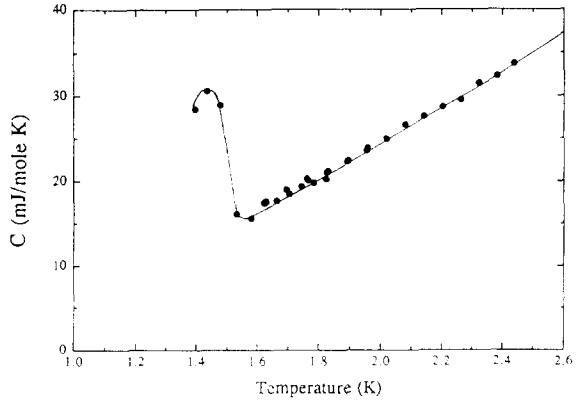

Fig. 1. Low temperature heat capacity of $LaCd_2$ from 1.3 to 2.5 K.

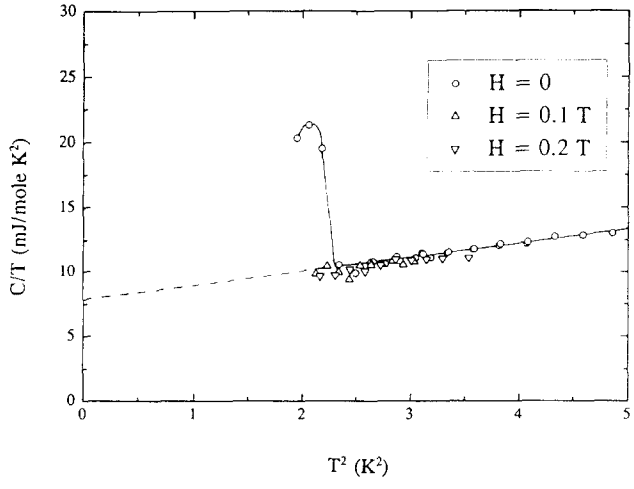

Fig. 2. Low temperature heat capacity of $LaCd_2$ plotted as C/T vs. T^2. Magnetic fields of 0, 0.1 and 0.2 T were applied during the measurements.

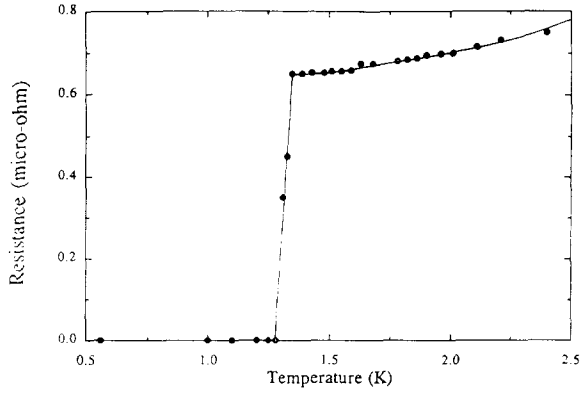

Fig. 3. Electrical resistivity as a function of temperature from 0.5 to 2.4 K.

Table 1
Properties of some LaM_2 superconductors (T_c, superconducting transition temperature; Θ_D, Debye temperature; γ, electronic specific heat constant; λ, electron–phonon coupling constant)

Compound	Structure type	T_c (K)	Θ_D (K)	γ (mJ mol^{-1} K^{-2})	λ
$LaCd_2$	Hexagonal, $CeCd_2$	1.44 [a]	186 [a]	8.0 [a]	0.47
$LaAl_2$	Cubic, C15	3.2 [2]	352 [16]	10.95 [16]	0.49
$LaPt_2$	Cubic, C15	0.46 [3]	236 [17]	3.51 [17]	0.36

[a] This study.

4. Discussion

The agreement between the measured value of $(C_s - C_n)/\gamma T_c$ (1.46) and that from the BCS theory (1.43) implies that $LaCd_2$ is a conventional weak-coupling superconductor [13]. The magnitude of the electronic specific heat coefficient ($\gamma = 8.0$ mJ mol^{-1} K^{-2}), which is about average for a low temperature superconductor, is consistent with this conclusion.

The phonon spectrum of $LaCd_2$ is moderately soft. The Debye temperature Θ_D determined from the slope of the C/T vs. T^2 plot is 186 K. The study by Mulokozi [8] indicated the formation of strong covalent bonds in RCd_2 (R ≡ rare earth) compounds. This covalent bonding might be responsible for preventing the softening of the phonon spectrum and therefore limiting the value of T_c to rather low temperature [14].

We now examine the superconducting behaviors of $LaCd_2$ and the two cubic Laves phase superconductors $LaAl_2$ and $LaPt_2$ to determine what factor(s) may play an important role in determining their T_cs. The important properties (T_c, Θ_D and γ) are given in Table 1. It appears that the structure is not the predominant factor, nor do the T_cs scale with Θ_D. There does appear to be a relation between the γ value and T_c. Since the electronic specific heat constant is dependent in part upon the electron–phonon enhancement factor $(1+\lambda$, where λ is the electron–phonon coupling constant), it would appear that the strength of the electron–phonon interaction is the most important parameter. We have calculated λ using the McMillan equation [15]

$$T_c = \frac{\Theta_D}{1.45} \exp\left(- \frac{1.04(1+\lambda)}{\lambda - \mu^*(1+0.62\lambda)} \right)$$

where μ^* is the electron–electron (Coulomb) coupling constant and generally has a value of about 0.10. Assuming that $\mu^* = 0.10$ for the three LaM_2 compounds, one can calculate λ using the T_c and Θ_D values listed in Table 1. The calculated λ values are also presented in Table 1. One notes that the T_cs follow the general trend in λ values, which parallel quite closely the γ values of the three LaM_2 phases. Since the scaling between T_c and λ (or γ) is not perfect, Θ_D also exerts some influence on the observed T_c. This is especially evident when one compares the T_c and Θ_D values of $LaCd_2$ with those of $LaAl_2$; those of the latter are about twice as large as those of the former.

5. Conclusions

$LaCd_2$ was found to be a superconductor with $T_c = 1.44$ K. Both heat capacity and electrical resistivity experiments confirmed this result. The value of $(C_s - C_n)/\gamma T_c$ at T_c (1.46) and the relatively small electronic specific heat coefficient γ (8.0 mJ mol^{-1} K^{-2}) suggested that $LaCd_2$ is a conventional weak-coupling superconductor. The electron–phonon coupling constant was estimated to be about 0.47, which indeed falls into the weak-coupling category. The Debye temperature was also determined from heat capacity data. $\Theta_D = 186$ K indicated a rather soft phonon spectrum; however, the covalent bonding in $LaCd_2$ probably prevented further softening of the phonon mode and thus resulted in the observed low T_c. $LaCd_2$ is a new member of the rare earth superconductor family. It is the first superconducting intermetallic compound with the $CeCd_2$-type structure.

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