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Resistance study on the itinerant ferromagnet $CrBe_{12}$ under pressure

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The electrical resistance of $CrBe_{12}$ has been measured between 1.2 and 300 K under hydrostatic pressure up to 20 kbar. The results demonstrate the existence of two kinds of phase transition from the paramagnetic state on cooling under pressure: one below ~11 kbar and the other above, in agreement with previous high-pressure magnetic study.

The body-centered tetragonal intermetallic compound $CrBe_{12}$ has been found[1] to order ferromagnetically with a Curie temperature of 50 K at ambient pressure. Detailed magnetic studies[2] suggested that $CrBe_{12}$ might be an itinerant ferromagnet. Recent ac magnetic susceptibility measurements[3] showed that in addition to the paramagnetic → ferromagnetic transition previously reported at $T_{C1} \sim 50$ K, a pressure-induced transition also exists in $CrBe_{12}$ at lower temperature T_{C2}. A *T-P* phase diagram of $CrBe_{12}$ was thus obtained. The close similarity of this $CrBe_{12}$ phase diagram to that[4] of the Cr-based alloys has led to the postulation[3] that interesting and complex magnetic structures might have occurred in $CrBe_{12}$. It is known[4] that the Cr + 0.2 at.% Ru alloy undergoes a sequence of I (paramagnetic) → II (commensurate) → III (incommensurate) antiferromagnetic transitions at low temperature and low pressure and a direct I → III transition at low temperature and high pressure. The resistance anomalies associated with the transitions in the Cr alloys are also known[4] to be characteristically different, depending on the nature of the transition, i.e., I → II or I → III. In an attempt to gain insights to the nature of the transitions in $CrBe_{12}$, we have measured the electrical resistance R of the $CrBe_{12}$ compound between 1.2 and 300 K under hydrostatic pressures up to 20 kbar. Only one R anomaly signaling a phase transition has been detected throughout our temperature and pressure ranges. However, the R anomaly below ~11 kbar is characteristically different from that above ~11 kbar. The results suggest that the phase transitions so detected in these two pressure regions are different in nature, consistent with the phase diagram previously determined magnetically.

The $CrBe_{12}$ samples examined in the present study were pieces broken off the same arc-melted ingot investigated previously.[3] A standard four-lead ac technique operating at 23 Hz was employed to measure the R. The four Pt electrodes were soldered ultrasonically with In onto the samples. The hydrostatic pressure environment was provided by a Be-Cu clamp,[5] using the 1:1 fluid mixture of *n*-pentane and isoamyl alcohol as the pressure medium. The pressure was determined with a Pb manometer situated next to the sample, and the temperature by a Chromel-Alumel thermocouple above 20 K and a Ge thermometer below.

We have measured the R of three $CrBe_{12}$ samples. The resistivity of these samples was estimated to be $\sim 10^{-4}$ Ω cm at ambient temperature and pressure, with a ~100% uncertainty due to the irregular shape of the samples, resulting from the extreme brittleness of the compound. Therefore, only R will be discussed in this investigation. Typical temperature dependence of R normalized to that at 78.5 K is shown in Fig. 1 for some of the experimental runs under various pressures. At ambient pressure, R decreases almost linearly with temperature T from 300 K down to ~50 K, but displays a drastic change in slope below ~50 K. Such a drastic change in slope occurs at a temperature where a paramagnetic → ferromagnetic transition has been detected[1,3] magnetically. We, consequently, associate this sudden slope change of the *R-T* curve with the ferromagnetic ordering at ambient pressure. The inflection point temperature[6] is taken as the phase transition temperature T_0, which is 45 ± 1.5 K at ambient pressure in contrast to 46 K, determined by the ac magnetic susceptibility anomaly. Under pressure, T_0 is shifted reversibly toward lower temperature, as summarized in Fig. 2, but no other R anomaly

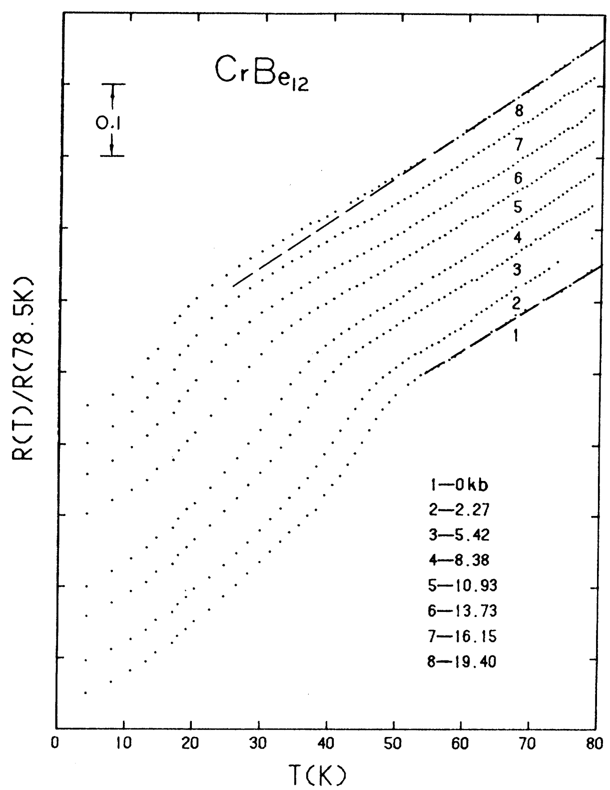

FIG. 1. The temperature dependence of resistance at different pressures. Note the difference in curvature near the transition below and above ~11 kbar.

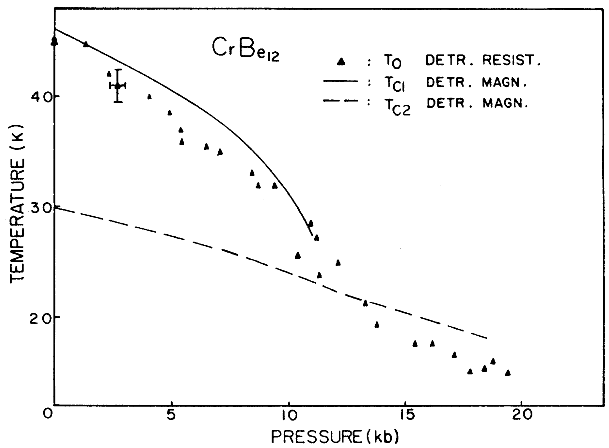

FIG. 2. The temperature-dependence diagram for $CrBe_{12}$ determined resistively in the present study and magnetically previously (Ref. 3).

indicative of the second phase transition, observed magnetically at low temperature and pressure, has been detected unambiguously. However, a close examination of the R-T curves, e.g., those in Fig. 1, revealed that R exhibits a subtle different T behavior near the phase transition depending on the pressure applied. For instance, R always shows a negative curvature on cooling following the initial linear T dependence of R and before entering the phase transition when the pressure is below ~11 kbar, whereas a positive curvature when above ~11 kbar (see the dashed lines as a guide in Fig. 1). This observation suggests that the phase transitions below and above ~11 kbar may be of different nature, in agreement with the phase diagram previously proposed.[3] The clear break in slope of the T_0-P plot shown in Fig. 2 lends further support to such a suggestion. Results from the earlier magnetic study of $CrBe_{12}$ were also included as curves in Fig. 2 for comparison. The solid curve represents the I-II phase boundary with a transition temperature T_{C1}, and the dashed curve denotes the II-III or I-III phase boundary with a transition temperature T_{C2}. The slight disagreement between T_0 and T_{C1} or T_{C2} is common for a transition temperature when determined by different methods.

The T_{C1}-P curve, separating the paramagnetic I phase from the itinerant ferromagnetic II phase in Fig. 2, has been shown[3] to fit well the expression $T_{C1}(P)=T_{C1}(0)\times(1-P/P_c)^{\tau}$ with $T_{C1}(0)=46.2$ K, $P_c=22.3$ kbar, and $\tau=0.244$. The above expression was originally proposed[7] to account for the pressure effect on the Curie temperature of an itinerant ferromagnet but with $\tau=0.5$ (or 0.75 when spin fluctuation dominates). The nature of phase III remains enigmatic. By comparing this phase diagram with that of the Cr + 0.2 at.% Ru, it was therefore postulated[3] that the I, II, and III phases in $CrBe_{12}$ might be associated with the paramagnetic, commensurate (or incommensurate) ferromagnetic, and incommensurate (or commensurate) ferromagnetic states, respectively.

In the present study, the characteristic of the R anomaly accompanying the phase transition and the P dependence of T_0 demonstrates that two different types of phase transition are observed, one below ~11 kbar and the other above. They correspond to the I → II and I → III transitions in Fig. 2, respectively. The failure to detect resistively the II → III transition at low temperature below ~11 kbar may be attributed to our inability to separate the weak R anomaly associated with the II → III transition from that with the I → II transition. It should be noted that the II → III phase transition also failed to be detected[4] resistively in the Cr + 0.2 at.% Ru alloy.

In spite of the gross similarity between the T-P phase diagrams of the $CrBe_{12}$ compound and Cr-based alloys, difference does exist between the two systems. The R anomaly in the Cr-based alloys displays a rapid rise (first order for the I → II transition and second order for the I → III transition) following the formation of spin-density waves associated with the removal of conduction electrons from the Fermi surface resulting from the nesting of the electrons and holes. On the contrary, the R anomaly for $CrBe_{12}$ always exhibits a drop. The difference may be ascribed to the different magnetic long-range orders involved in the two systems: ferromagnetic in $CrBe_{12}$ and antiferromagnetic in the Cr-based alloys. An R drop is typical of a ferromagnetic ordering as a result of the removal of the spin-disorder scattering.

In conclusion, the present resistance study under pressure on the $CrBe_{12}$ compound shows that there are two types of phase transition: one below ~11 kbar and the other above, in agreement with the earlier magnetic investigation under pressure. While difference exists between the $CrBe_{12}$ compound and the Cr-based alloys, the similarity between the T-P phase diagram cannot be ignored. The different electron-scattering processes near the I → II and I → III transition in $CrBe_{12}$, evident from the different R anomalies detected, should be taken into consideration in future model calculations. More careful transport and magnetic experiments under pressure are in progress. However, a neutron-diffraction study under pressure to determine the magnetic structure of this compound is most worthwhile.

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[1]N. M. Wolcott and R. L. Falge, Jr., Phys. Rev. 171, 591 (1968).

[2]N. M. Wolcott, R. L. Falge, Jr., and L. H. Bennett, Phys. Rev. Lett. 21, 546 (1968); A. Hen and R. Kuentzler, Phys. Status Solidi (b) 45, K1 (1971).

[3]B. J. Jin, T. H. Lin, C. W. Chu, Y. S. Shen, and P. H. Schmidt, Phys. Rev. B 26, 3878 (1982).

[4]A. Jayaraman, T. M. Rice, and E. Bucher, J. Appl. Phys. 41, 969 (1971).

[5]C. W. Chu, T. F. Smith, and W. E. Gardner, Phys. Rev. Lett. 20, 198 (1968).

[6]We are indebted to Professor M. Croft for suggesting such a method of defining a transition temperature which yields a better agreement with the magnetically determined results.

[7]E. P. Wohlfarth, *Physics and Application of Invar Alloy,* Honda Memorial Series, Vol. 3 (Maruzen, Tokyo, 1978), p. 327.