Transport measurements on Pd_3V

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The resistivity, low-temperature magnetoresistance, and ac susceptibility of the spatially ordered intermetallic compound Pd_3V are reported. It is concluded that this is a nonmagnetic compound the resistivity of which is determined by conduction-electron scattering from phonons with a non–Debye-like spectrum. The effects of small amounts of magnetic impurities are also briefly discussed.

The properties of spatially ordered intermetallic compounds such as $ZrZn_2$, $TiBe_2$, and Sc_3In provide many interesting contrasts, and hence have been the subject of considerable experimental and theoretical interest for a number of years. The compounds listed, for example, while often being classed as weak itinerant ferromagnets, have at least one constituent which is a superconductor in its elemental form. Consequently, when recent self-consistent, spin-polarized energy-band calculations[1] predicted that Pd_3V (itself a combination of a superconductor and an incipient ferromagnetic element) should also be an itinerant ferromagnet (with a moment of about $1.4\mu_B$ per formula unit), it evoked an experimental response. Magnetization studies[2] indicated that this latter prediction was incorrect as no anomalous magnetic behavior was found above 1.45 K. As a result of this prediction we had also prepared Pd_3V and measured its resistivity, low-temperature magnetoresistance, and ac susceptibility. In this Brief Report we concentrate on the results of the transport measurements in view of the recent publication of the magnetic data.

The samples were prepared by arc melting from 99.999% Pd wire and 99.9% V metal; each component was melted separately initially, then the Pd was wrapped in cold-rolled V foil with sufficient quantities to produce a 3-g button of the required composition. This button was inverted and remelted five times to ensure homogeneity; melting losses were about 0.1%. The button was subsequently placed in a Ta boat and annealed for two days at 1100 °C in 10^{-6} Torr, at which point it was soft enough to cold roll into a foil of thickness 10^{-2} cm, from which strips (typically a few cm long and a few mm wide) suitable for various experiments could be cut. These strips were etched, washed, and dried before finally annealing them in a Ta boat at 750 ± 15 °C in 10^{-6} Torr for five weeks. The structure of the final samples was verified on a Debye-Scherrer camera which indicated spacings and intensities similar to those reported by Dwight *et al.*[3]

ac susceptibility measurements, carried out at 2.4 kHz in a driving field of 0.2 Oe rms,[4] yielded a room-temperature susceptibility of about 10^{-6} emu/g, which increased slightly with decreasing temperature in a manner similar to that reported recently.[2] This susceptibility value corresponds to a total density of states at the Fermi energy (including any exchange enhancement effects) of 3.6 states/eV atom, well below even that of Pt which exhibits only moderate exchange enhancement effects.

The electrical resistivity $\rho(T)$, measured between 4.2 and 300 K with the use of a conventional four-probe dc potentiometric technique, and between 1.5 and 10 K by use of a differential ac method,[5] is reproduced in Fig. 1. The overall change $\rho(300\text{ K})-\rho(1.5\text{ K})$ is about 27 $\mu\Omega$ cm (with shape factor uncertainties limiting the accuracy of the resistivity values of ±2%), while the high-temperature slope $d\rho/dT$ of these data is about 10^{-1} $\mu\Omega$ cm/K. Both of these parameters are larger by a factor of around 2.5 than those reported for pure Pd, but they are close to those measured[6] for related spatially ordered PtCr compounds near the stoichiometric composition Pt_3Cr. Analysis of the low-temperature data is complicated by the presence of a *small* upturn in the resistivity below about 6.9 K, as shown in Fig. 2. For data above this minimum (we will return to a discussion of the low-temperature data later) we find after several trials that a good fit over the range indicated is achieved using

$$\rho(T)=\rho_0+\alpha T^n \quad . \tag{1}$$

The fit shown uses $\rho_0=17.695(2)$ $\mu\Omega$ cm, $\alpha=4.2\times10^{-7}$ $\mu\Omega$ cm/K^n, and $n=4.0$; however, slight changes in ρ_0 and small uncertainties associated with the residual temperature dependence of the low-temperature upturn means that values for n down to 3.6 are not precluded. The larger values for n provide a better fit over the range 8 to 15 K, but tend to deviate above the experimental data at higher temperatures (around 30 K) sooner than do lower n values.

In this temperature range many nonmagnetic transition elements exhibit resistivities with temperature dependences between T^3 and T^5; the former is often associated with a Wilson-type *s-d* phonon scattering model[7] and the latter with

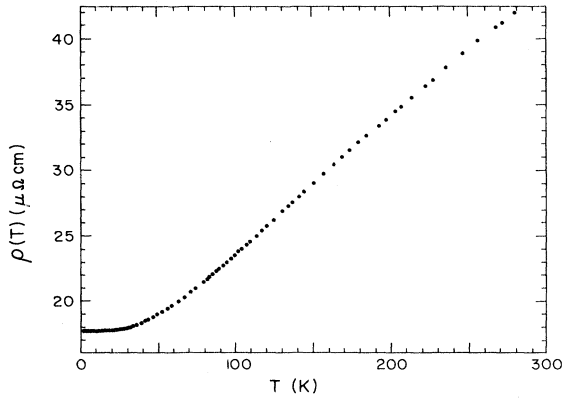

FIG. 1. Resistivity $\rho(T)$ (in $\mu\Omega$ cm) of Pd_3V plotted against temperature T (in K).

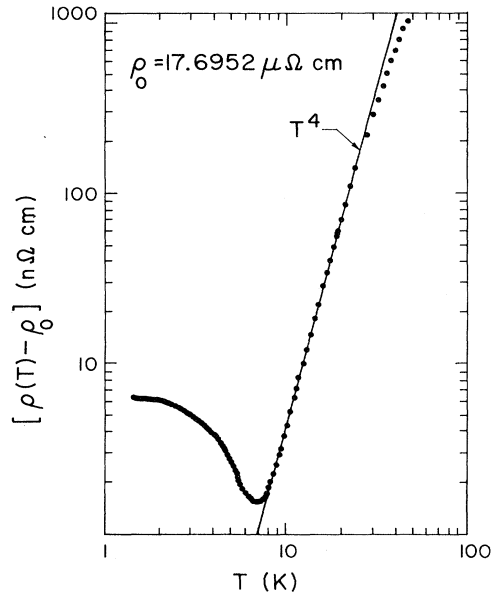

FIG. 2. Double logarithmic plot of $[\rho(T)-\rho_0]$ (in $n\Omega$ cm) against temperature T (in K) for data below 40 K.

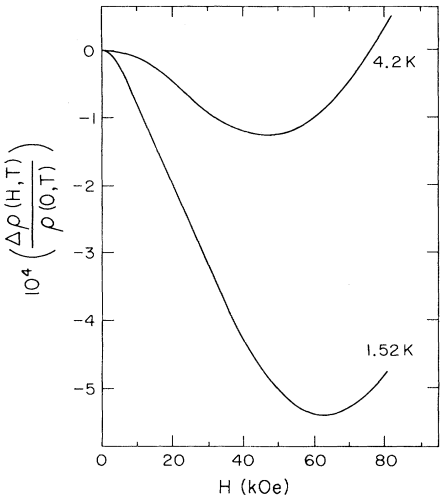

FIG. 3. Fractional magnetoresistance $\Delta\rho(H,T)/\rho(0,T)$ $[(\Delta\rho(H,T)=\rho(H,T)-\rho(0,T)]$ as a function of field H (in kOe) at $T=4.2$ and 1.52 K.

the Bloch-Grüneisen form.[8] However, in view of the small density of states inferred from the susceptibility data, the former mechanism appears unlikely and hence a behavior close to T^5 might be expected. With this point in mind, the possibility that these data include a small T^2 which might combine with a phonon scattering contribution (BT^5) to yield a behavior close to T^4 over the region being discussed has been investigated. Writing

$$\rho(T)=\rho_0+AT^2+BT^5 \tag{2}$$

means that plots of $[\rho(T)-\rho_0]T^{-2}$ against T^3 should yield straight lines; such a form produces a barely tolerable fit to the experimental data and then over a rather limited temperature range from 8.5 to 15–16 K, requiring $A=(14\text{–}17)\times10^{-6}$ $\mu\Omega$ cm/K^2 and $B=(24\text{–}26)\times10^{-9}$ $\mu\Omega$ cm/K^5. Above 16 K the assumed T^5 contribution causes $\rho(T)$ calculated from Eq. (2) to rapidly climb above its experimental value. Thus, at best, the data reported above are consistent with Eq. (2) over only a restricted temperature range. Further, the magnitude of the coefficient A is comparable with that observed in pure Pt, where it is attributed to s electron scattering from spin-density fluctuations in the exchange-enhanced d band. A comparison of the density of states[9] in Pt with that calculated above for Pd_3V makes the presence of such a T^2 term seem unlikely in this latter host.

The consensus emerging from this analysis thus suggests that a single T^n ($n=3.6$ to 4.0) form provides the most appropriate fit to such data, arising probably from Bloch-Grüneisen–like processes, but with a *non*-Debye phonon spectrum so that a phonon scattering component weaker than T^5 can be realized.

Surprisingly, the *low*-temperature resistivity minimum data, while not being directly related to the problem being discussed, provide indirect support for the conclusions drawn in the preceding paragraph. We suspect that both this resistivity anomaly and the increase in susceptibility with decreasing temperature arise from a *small* concentration of moment bearing impurities. Magnetoresistance data (shown in Fig. 3) taken at 1.5 and 4.2 K have a form (i.e., are negative), temperature dependence, and overall magnitude which are consistent with this suggestion. Indeed, analysis provided with the starting materials suggest that the Pd_3V samples could contain about 50 ppm Fe, which has been shown to carry a magnetic moment in this host by Burmester and Sellmyer.[2] The latter authors also concluded that this moment is close to the spin-only moment of Fe^{2+} ($4.9\mu_B$), and, in addition, the interactions between such moments at about 1 at.% Fe (presumably mediated by the conduction electrons) lead to a spin-glass state below 2 K. Both of these results imply that there is little or no exchange enhancement in Pd_3V, which should therefore be regarded as a nonmagnetic intermetallic compound.

The properties of Fe in this host thus resemble those of Fe in Cu rather than Fe in exchange-enhanced hosts like Pd, and this is further supported by the low-temperature resistivity data, shown in Fig. 4. From this figure it is clear that the resistivity exhibits a Kondo-like *increase* with *decreasing* temperature, although these data are not convincingly fitted by any of the conventional expressions used in analyses of the Kondo effect. However, uncertainties relat-

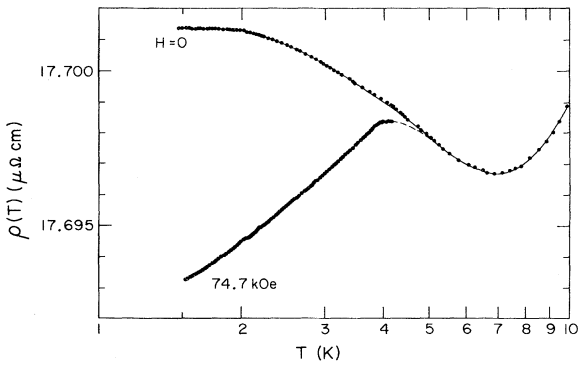

FIG. 4. Low-temperature resistivity $\rho(H,T)$ (in $\mu\Omega$ cm) in zero field and 74.7 kOe, plotted against $\log(T)$.

ing to the lattice resistivity to be subtracted, and the possibility that even at 50 ppm weak interaction effects could be present, compound the difficulties of such an analysis. This Kondo-like increase can clearly be quenched by large applied fields, as it can for magnetic impurities in nonmagnetic hosts[10,11] like Cu. This again reinforces previous conclusions regarding Pd_3V.

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