Superconductivity and magnetism in the Heusler alloys $\text{MPd}_2\text{Pb}$ ($M=\text{rare earth, Th, and U}$)

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We report on an investigation of superconductivity and magnetism in the series of compounds $\text{MPd}_2\text{Pb}$ ($M=\text{rare earth, Th, U}$) through measurements of electrical resistivity, magnetic susceptibility, specific heat, and lattice parameters. Both single crystals and polycrystalline samples were studied. The compound $\text{UPd}_2\text{Pb}$ was examined for possible heavy-fermion behavior, and found to exhibit antiferromagnetic order below $T=35$ K.

INTRODUCTION

Several Heusler alloys (cubic $L_2_1$ structure) with the general chemical formula $RT_2X$ have been found to exhibit superconductivity, including $\text{YPd}_2\text{X}$ ($X=\text{Sn, Pb, In, and Sb}$), $\text{YAu}_2\text{Sn}$, and $\text{RPd}_2\text{Sn}$ ($R=\text{Sc, Y, Tm, Yb, and Lu}$), with critical temperatures as high as 4.76 K. Moreover, superconductivity and antiferromagnetism coexist in the compound $\text{YbPd}_2\text{Sn}$. Higher $T_c$ values were generally found for compounds with larger lattice parameters, with $\text{YPd}_2\text{Pb}$ yielding the highest reported value of 4.76 K. For $\text{RPd}_2\text{Pb}$ samples, we also expected the effects of magnetic pair breaking by the magnetic $R$ ions to be minimized because of the large lattice parameters, which could give rise to interesting effects due to the interaction and competition between superconductivity and magnetism. We report on an investigation of superconductivity and magnetism in the series of compounds $\text{MPd}_2\text{Pb}$ ($M=\text{rare earth, Th, and U}$), primarily through measurements of electrical resistivity and magnetic susceptibility. Both polycrystalline samples and single crystals were studied. We find that the magnetic rare-earth ions order antiferromagnetically at low temperatures with the lowest Néel temperature $T_N$ values among $\text{RPd}_2\text{X}$ compounds. Bulk superconductivity is found for $R=\text{Sc, Y, Tm, Yb, and Lu}$, but with lower $T_c$ values than expected, probably associated with sample quality. Motivated by heavy-fermion behavior previously observed in $\text{UPd}_2\text{Sn}$, the compound $\text{UPd}_2\text{Pb}$ was examined for possible heavy-fermion behavior, and found to exhibit antiferromagnetic order below $T=35$ K, inferred from a sharp cusp observed in the magnetic susceptibility. The large value of the linear coefficient of the specific heat $\gamma=100$ mJ/mol K$^2$, determined from data measured below 35 K, along with the temperature dependence of the electrical resistivity, suggest that this may be an antiferromagnetic low effective mass heavy-fermion compound.

EXPERIMENTAL DETAILS

Single crystals and polycrystalline samples of $\text{MPd}_2\text{Pb}$ were successfully grown in Pb flux for $M=\text{Sc, Y, Gd, Tb, Dy, Ho, Er, Tm, and Lu}$. Attempts to grow crystals with $M=\text{Yb and U}$ were unsuccessful, even though polycrystalline samples could be prepared by arc melting. In addition, attempts to grow crystals consisting of the lighter rare-earth ions $M=\text{Ce, Pr, Nd, Sm, and Eu}$ were unsuccessful, consistent with our inability to make polycrystalline samples, most likely due to the large size of the trivalent ions. The crystals were prepared in the following way.

 Stoichiometric amounts of 99.9% pure $M$ and 99.999% pure Pd were placed in an alumina crucible with 99.999% pure Pb, which comprised 90 mol % of the mixture. Quartz wool was then placed inside the crucible, which was then sealed in a quartz tube and backfilled with 150 torr ultrahigh-purity (UHP) Ar. The sample was heated to 1200 °C, then slowly cooled (10 °C/h), allowing single crystals to nucleate. In our case, Pb from the flux was incorporated into the crystal structure. The sample was removed from the furnace at 800 °C and centrifuged immediately so that the molten flux spun through the quartz wool, leaving the crystals in the crucible. To etch away any remaining free Pb, the crystals were placed in a 1:1 solution of $\text{H}_2\text{O}_2$ (30%): glacial acetic acid for no more than 5 min. The crystals formed as cubes or clusters of cubes which appeared to grow in the $\langle 111 \rangle$ direction. Of these, crystals with $M=\text{Gd and Sc}$ formed the largest- (~1 mm on a side) and smallest-sized cubes, respectively.

Subsequent x-ray powder diffraction of powdered crystals verified the single-phase $L_2_1$ cubic Heusler structure for $R=\text{Lu, Tm, Er, Ho, Dy, Tb, Gd, Y, and Sc}$. No impurity...
peaks, including those of free Pb, were evident in the x-ray patterns. The intensity of the background noise level was only ~0.1% of the most intense peak corresponding to the (220) direction. The flux growths with Gd and Eu contained long, needle-shaped crystals (~5 mm length), but they exhibited multiple x-ray peaks which did not belong to the Heusler structure. The Gd flux growths also contained the cube-shaped crystals with the Heusler structure. ThPd$_2$Pb formed, though it contained several impurity phases, one of which was identified as ThPb. Attempts to grow single crystals of R=Yb, Eu, Sm, Nd, Pr, Ce, and U were unsuccessful.

Polycrystalline samples were fabricated by melting in Ta tubes as follows. Stoichiometric amounts of each element were sealed in a 1-cm-diameter Ta tube, with 1 atm UHP Ar. The tube was then sealed in a quartz tube backfilled to 150 torr UHP Ar, heated to 1300 °C for 1 h, and subsequently quenched by placing the 1300 °C tube in water at room temperature. Samples with the Heusler structure were made for $R=$Sc, Y, Tb, Dy, Ho, Tm, Yb, and U. X-ray powder-diffraction data revealed trace amounts of elemental Pb (a superconductor with $T_c$=7.2 K) in all samples, Pb$_2$Pd (a superconductor with $T_c$=3.0 K) for $R=$Y, Dy, Ho, and Tm, and RPd$_2$ (not superconducting) for $R=$Yb. This method was not successful for $R=$Ce, Eu, Gd, Lu, or Th, although a minority Heusler phase was still discernible for Lu. The $R=$Er sample was made by arc melting with excess Pb to compensate for loss due to its high vapor pressure. None of the samples were subsequently annealed.

It is interesting to note that the related compounds RPd$_2$Sn, with $R=$Tb and Dy, exhibit structural transformations at ~250 and 50 K, respectively, which lowers the crystal symmetries. The transformations were not evident from magnetic susceptibility, and we cannot rule out similar transformations occurring in our RPd$_2$Pb samples.

RESULTS AND DISCUSSION

**RPd$_2$Pb (R=rare earth: Sc,Y,Gd,Tb,Dy, Ho,Er,Tm,Yb,Lu)**

**Electrical resistivity**

Shown in Fig. 1 is the temperature dependence of the normal-state electrical resistivity $\rho(T)$, normalized to its room-temperature value, of RPd$_2$Pb compounds in which the 4$f$ electron shell of the R ions is (a) empty or filled and (b) partially filled. Except for $R=$Gd, for which a single crystal was used, polycrystalline samples were measured because of the difficulty of attaching electrical leads to the extremely small crystals. All samples exhibit metallic behavior with positive temperature coefficient of resistance at all temperatures below 295 K. The data display downward curvature except at the lowest temperatures where phonon scattering freezes out and the data eventually saturate towards the zero-temperature value due to scattering by defects and impurities. Although the degree of curvature varies among the RPd$_2$Pb samples, it does not appear to depend in a systematic way on the R ion. In particular, temperature-dependent magnetic scattering due to splitting of the ground-state multiplet by the crystalline electric field (CEF) is not obvious. The resistance ratio $RR=\rho(295 K)/\rho(0 K)$ also varies a lot among samples, attesting to varying amounts of impurity scattering.

![FIG. 1. Normal-state electrical resistivity normalized to its room-temperature value, $\rho(T)/\rho(295 K)$, vs temperature $T$ for RPd$_2$Pb polycrystalline samples in which the 4$f$ electron shell of the $R$ ion is (a) empty or filled and (b) partially filled. Data for $R=$Gd are for a single crystal. Resistivity drops at $T$~7 K are due to Pb inclusions.](image)

Qualitatively speaking, those samples with the largest-moment $R$ ions, namely, $R=$Gd, Ho, and Dy, exhibit the smallest $RR$’s.

All of the polycrystalline samples have elemental Pb impurities, which causes $\rho(T)$ to drop below $T$~7 K owing to the superconductivity of Pb. For those samples in which $\rho(T)$ does not drop to zero by then, an additional drop is observed below $T$~3 K due to the presence of a Pb$_2$Pd impurity phase, which is superconducting with $T_c$=3.0 K. No such resistive drops are observed for the relatively impurity-free single-crystal specimen of GdPd$_2$Pb, allowing a small anomaly in $\rho(T)$, shown in the inset of Fig. 1(b), to be observed near $T=4.5$ K. This anomaly is due to antiferromagnetic ordering of the Gd moments, as inferred from the magnetic susceptibility discussed below.

**Magnetic susceptibility**

Shown in Fig. 2 is the inverse magnetic susceptibility $\chi^{-1}$ as a function of temperature $T$ for the RPd$_2$Pb compounds with magnetic rare-earth ions $R$. The $\chi(T)$ data were acquired for many clusters of single crystals with random orientations with respect to the magnetic-field direction, except for $R=$Er for which a polycrystalline sample was measured. Over a wide temperature range (10≤$T$≤300 K), the data for all of these samples are well described by the Curie-Weiss law $\chi(T)=N\mu^2/3k_B(T−\theta_{CW})$, where $N$ is the number of rare-earth ions, $\mu_{eff}$ is the effective magnetic moment, and $\theta_{CW}$ is the Curie-Weiss temperature. The solid lines in Fig. 2 represent least-squares linear fits of the data, which yield...
values for $\mu_{\text{eff}}$ and $\theta_{\text{CW}}$ listed in Table I. The values of $\mu_{\text{eff}}$ are close to the theoretical Hund’s rules ground-state values for free trivalent rare-earth ions as illustrated in Fig. 3 and do not deviate much from the Curie-Weiss fits above the antiferromagnetic ordering temperatures, suggesting that the CEF energy level splittings $\Delta_{\text{CEF}}$ of the Hund’s rules ground-state multiplets are small ($\Delta_{\text{CEF}}<10$ K≈1 meV) in these compounds.

The Curie-Weiss temperatures $\theta_{\text{CW}}$ are all negative, indicative of antiferromagnetic (AFM) exchange interactions. These interactions give rise to AFM order at low temperatures, revealed as a peak in the magnetic susceptibility for some of these samples at the Néel temperature $T_N$, as shown in Fig. 4 and listed in Table I. Data for $R=$Gd, Tb, and Dy represent $\chi_{\text{ac}}$ from static (dc) magnetization measurements taken in a field of 10 Oe (100 Oe for $R=$Gd) after zero-field cooling (ZFC) and during field cooling (FC). Data for $R=$Ho and Er are from low-temperature ac magnetic-susceptibility $\chi_{\text{ac}}$ measurements.

Two interesting aspects of the magnetic-susceptibility data are (1) there is only a small decrease in $\chi(T)$ below $T_N$ as $T\to0$ [the ratio $\chi(0)/\chi(T_N)$ is much larger than the theoretical value of $2/3$ for an isotropic, uniaxial AFM powder specimen] and (2) irreversibility in $\chi_{\text{dc}}$ appears below an onset temperature $T_{\text{irr}}$, reminiscent of spin-glass freezing. The large $\chi(0)/\chi(T_N)$ ratio is characteristic of spin glasses, but can also occur for an antiferromagnetically ordered fcc lattice due to low anisotropy energy.8 In the latter case, the measured susceptibility below $T_N$ approaches $\chi_{\text{H}}$ (in which the antiparallel moments are perpendicular to the applied magnetic field $H$), which is more energetically favorable than $\chi_{\text{H}}$ (moments parallel to $H$). Paramagnetic impurities could also increase the measured value of $\chi(0)/\chi(T_N)$. The irreversible $\chi_{\text{dc}}(T)$ for GdPd$_2$Pb was measured with $H=1$, 10, 100, and 200 Oe, with little change in $\chi(T)$ or $T_N$. This observation, as well as the observed scaling of $T_N$ with the de Gennes factor (described below), and the electrical-resistivity results (described above) eliminate the possibility that these anomalies are due to superconductivity. The irreversibility in the magnetization might be due to structural disorder (defects) in the samples, which could give rise to

### TABLE I. Physical parameters for MPd$_2$Pb.

| $M$ | $a$ (Å) | $\mu_{\text{eff}}$ ($\mu_B$) | $\theta_{\text{CW}}$ (K) | $T_c$ (K)$^a$ | $T_N$ (K) |
|-----|--------|----------------|-----------------|-------------|-----------|
| Sc  | 6.63   | 0             | –               | 2.4        | –         |
| Y   | 6.74   | 0             | –               | 2.3        | –         |
| Gd  | 6.81   | 8.51          | –17.3           | *          | 4.5       |
| Tb  | 6.79   | 10.17         | –16.9           | *          | 2.8       |
| Dy  | 6.76   | 11.13         | –9.8            | *          | 2.4       |
| Ho  | 6.75   | 11.10         | –6.5            | *          | 0.8       |
| Er  | 6.76   | 9.77          | –5.2            | *          | 0.6       |
| Tm  | 6.72   | 7.85          | –2.7            | 2.1 $^*$   |           |
| Yb  | 6.73   | 4.15          | –3.6            | 2.8 $^*$   |           |
| Lu  | 6.73   | 0             | –               | 2.4        | –         |
| Th  | 6.88   | 0             | –               | *          | –         |
| U   | 6.85   | 2.8           | –51             | *          | 35 $^*$   |

$^a$Onset temperature of superconducting diamagnetic transition in static magnetic susceptibility.
spin-glass-like behavior, or possibly geometrical frustration of the ordered moments on the fcc lattice.

The existence of bulk superconductivity was confirmed for some of the \( \text{RPd}_2\text{Pb} \) samples from dc magnetic-susceptibility measurements, taken upon both ZFC and FC in a magnetic field \( H = 10 \) Oe. ZFC data are shown in Fig. 5. The \( \chi(T) \) data were irreversible with the FC data being typically 50% of the ZFC values for each sample, which we attribute to flux pinning. A significant diamagnetic response, indicative of bulk superconductivity, is observed for \( \text{RPd}_2\text{Pb} \) compounds in which \( R \) is a nonmagnetic trivalent ion, including \( R = \text{Sc}, \, \text{Y}, \) and \( \text{Lu} \). Evidently, superconductivity is the ground state of this system in the absence of magnetic pair breaking by magnetic \( R \) ions. The \( d \) electrons of the \( \text{Pd} \) ions are believed to be mainly responsible for superconductivity in these compounds.\(^1\)

Curiously, superconductivity was not observed down to 1.8 K for \( \text{ThPd}_2\text{Pb} \), \( \text{Th} \) being a nonmagnetic tetravalent ion. Superconductivity was also observed for \( R = \text{Tm} \) and \( \text{Yb} \), which are trivalent magnetic ions with the smallest values of the de Gennes factor \( (g_j - 1)^2J(J+1) \) among the heavy magnetic rare earths. The \( \Delta \chi \) data shown in Fig. 5 for \( R = \text{Tm} \) and \( \text{Yb} \) were obtained by subtracting the magnetic contribution of the \( \text{Tm} \) and \( \text{Yb} \) ions, respectively. As shown in Fig. 5, the diamagnetic shielding fractions, estimated from the ZFC measurements, vary from –10% to –60% for single-crystal specimens, and are as high as 140% for polycrystalline \( \text{YPd}_2\text{Pb} \). These values should be multiplied by a factor of –2/3 to account for the demagnetization correction if one approximates the cube-shaped crystals as spheres.

The superconducting transitions are rather broad, with onset temperatures ranging from 2.1 to 2.8 K (see Table I). Previous measurements of \( T_c \) for arc-melted polycrystalline samples of \( \text{YPd}_2\text{Pb} \) yielded higher values of \( T_c = 4.76 \) (Ref. 1) and 4.05 K.\(^9\) The precise value of \( T_c \) is known to be highly sensitive to the stoichiometry in these Heusler systems, with a possible correlation with lattice parameter, which could be due to a sharp feature in the electronic density of states.\(^1\) It is not clear what value of \( T_c \) represents that of the stoichiometric compound \( \text{YPd}_2\text{Pb} \). We note, however, that one must be very careful to account for the effects of any superconducting impurities including \( \text{Pb} (T_c = 7.2 \) K) and \( \text{Pb}_{0.7}\text{Pd}_{0.3} (T_c = 3.0 \) K).

Magnetic interactions in a metal with rare-earth ions are governed by the \( sf \) exchange interaction between the conduction electron spins \( s \) and the total angular momentum \( J \) of the local \( 4f \) states, given by the Hamiltonian \( \mathcal{H}_{sf} = -2 \mathcal{J}_{sf}(g_j - 1)J \cdot s \), where \( \mathcal{J}_{sf} \) is the exchange coupling parameter and \( g_j \) is the Landé \( g \) factor of the rare-earth ion. The factor \( (g_j - 1) \) results from replacing the total spin \( S \) with its projection onto the total \( J \) for rare earths with finite orbital angular momentum \( L \). For superconducting metals, this interaction leads to magnetic pair breaking as described, for example, by the Abrikosov-Gorkov theory. For a lattice of rare-earth ions, this interaction leads to the RKKY indirect exchange interaction between rare-earth ions, with Hamiltonian \( \mathcal{H}_{RKKY} = -2 \mathcal{J}_{RKKY}^J \cdot J \cdot J \), where \( \mathcal{J}_{RKKY} \) is the exchange cou-

![FIG. 5. Superconducting contribution to the magnetic susceptibility \( \Delta \chi \), after zero-field cooling (ZFC) and then applying a 10 Oe field, for single-crystal specimens of the \( \text{RPd}_2\text{Pb} \) compounds which were found to be superconducting. The data for \( R = \text{Tm} \) and \( \text{Yb} \) were corrected for the magnetic background contribution of the \( R \) ions.](image1)

![FIG. 6. Curie-Weiss temperatures \( \theta_{CW} \) (solid circles), Néel temperatures \( T_N \) (open circles), and onset superconducting critical temperatures \( T_c \) (open squares) of the \( \text{RPd}_2\text{Pb} \) compounds, derived from magnetic-susceptibility measurements. The values \( \theta_{CW} \) and \( T_N \) are compared to the de Gennes factor \( (g_j - 1)^2J(J+1) \), represented by the solid line, and normalized to the values for \( R = \text{Gd} \).](image2)
Superconductivity and magnetism in the heusler...  

This coexistence has been attributed to the small deg the magnetic moment of the inverse magnetic susceptibility from 1.8 to 10 K as unless the CEF splittings are very small compared to 1.8 K. Approximately linear down to 1.8 K. The dashed line in the inset measurements on TmPd2Sn, Malik, Umarji, and Shenoy10 deduced that the Tm3+ ions have a nonmagnetic CEF ground state. There does not appear to be any sign of magnetic order for TmPd2Pb or YbPd2Pb down to 1.8 K from our magnetic-susceptibility measurements.

From magnetic-susceptibility and 199Sn Mössbauer measurements on TmPd2Sn, Malik, Umarji, and Shenoy10 deduced that the Tm3+ ions have a Γ3 nonmagnetic ground state with a first excited triplet state ~1 meV (~10 K) above the ground state. Shown in Fig. 7 are magnetization M(H) data for TmPd2Pb crystals at 1.8 K, measured in fields H up to 7 T. The M(H) data are nonlinear and consist of a contribution that appears to saturate like a Brillouin function in high fields and a linear term with a slope χ0=0.07 emu/mol, represented by the dashed line. The linear term could be a second-order van Vleck susceptibility term. Extrapolation of the linear term to zero yields the saturation magnetization of ~19×10^3 emu/mol, corresponding to gμB=3.4μB, which is less than the saturation moment of 7μB for the full Tm3+ multiplet. This reduced value could be due to the cubic CEF which splits the multiplet such that the Γ[2] triplet, which has the magnetic moment gJ(Γ[2]|J|Γ[2])=3.13μB, lies lowest.11 A nonmagnetic ground state appears to be ruled out unless the CEF splittings are very small compared to 1.8 K.

Shown in the inset is a plot of the temperature dependence of the inverse magnetic susceptibility from 1.8 to 10 K as measured in a low field of 1 kOe where M(H) is approximately linear down to 1.8 K. The dashed line in the inset represents a fit to a Curie-Weiss law in this temperature range, which has nearly the same μeff and θCW as the high-temperature fits, again suggesting that the CEF splitting is very small, or that the Γ[5] triplet lies lowest in energy. In either case, it is surprising that superconductivity exists in TmPd2Pb despite the highly magnetic character of the Tm ions even at low temperatures T~Tc.

FIG. 7. Isothermal magnetization M vs magnetic field H of TmPd2Pb single crystals at T=1.8 K. The solid line is a guide to the eye. The dashed line represents a linear fit to the high-field data with the slope χ0=0.07 emu/mol. Inset: Low-field (H=0.1 T) inverse magnetic susceptibility χ−1 vs temperature below 10 K. The dashed line represents a fit of the data to a Curie-Weiss law for 1.8<T<10 K with μeff=7.3μB and θCW=−1.4 K, revealing magnetic behavior of the Tm ions.

In a previous study of uranium-based ternary compounds with the chemical formula UT2X with T=Pd, Au and X=In, Si, Ge, Sn, Sb, it was found that only those with M=In formed the cubic Heusler structure.4 The others revealed a more complicated structure in the x-ray-diffraction patterns, believed to be orthorhombic. None of those materials studied were superconducting down to 80 mK. The compound UPd2Sn, however, displayed characteristics of valence fluctuation or Kondo lattice phenomena below a characteristic temperature ~10 K, and is considered to be a nonmagnetic, nonsuperconducting heavy-electron material. In particular, the electronic specific-heat coefficient γ=Ceff/T was found to be strongly temperature dependent with a maximum value of ~270 mJ/mol K^2 at 9.7 K and an extrapolated value of ~70 mJ/mol K^2 at T=0 K.

We have synthesized polycrystalline samples of UPd2Pb and found that it forms the cubic L21 Heusler structure. The cubic lattice parameter a=6.85±0.01 Å is the largest of all the MPd2X L21 Heusler compounds (see Table I), except perhaps for a mixed-phase ThPd2Pb sample which had a comparable value a=6.88±0.05 Å. It is interesting that this compound forms while MPd2Pb compounds with M=Sm and Eu, which would have smaller or comparable lattice parameters, do not. It is possible that the hybridization of the 5f electrons with the conduction-band states stabilizes this
crystal structure. We subsequently measured $\rho(T)$, $\chi(T)$, and $C(T)$ in order to characterize it for possible heavy-fermion behavior.

The temperature dependence of the normalized electrical resistivity and magnetic susceptibility of UPd$_2$Pb are shown in Figs. 8(a) and 8(b), respectively. The electrical resistivity $\rho(T)$ increases by only a few percent with decreasing temperature down to $\sim$100 K, below which $\rho(T)$ decreases. The negative temperature coefficient of resistance above 100 K is indicative of Kondo-like magnetic scattering and is a typical feature of heavy-fermion materials, as is the subsequent drop below 100 K. A small kink in the $\rho(T)$ data is observed at $T=35$ K, which we attribute to antiferromagnetic ordering of the U ions, inferred from the magnetic-susceptibility data in Fig. 8(b). Like the other MPd$_2$Pb polycrystalline samples, $\rho(T)$ drops suddenly below 7.2 K due to Pb inclusions. The low-temperature resistivity of MPd$_2$Pb could be studied by applying a magnetic field sufficient to destroy the superconductivity of Pb and Pb-Pd impurity phases.

The magnetic susceptibility of UPd$_2$Pb is shown in Fig. 8(b). A sharp cusp is observed at $T=35$ K, which we attribute to AFM order of the U ions. In contrast to the RPd$_2$Pb compounds which exhibit AFM order, the ratio $\chi(0)/\chi(T_N)\sim 0.75$ for UPd$_2$Pb, which is only slightly larger than the theoretical value of $2/3$ for an isotropic, uniaxial AFM powder specimen. At higher temperatures, the $\chi(T)$ data can be described by a Curie-Weiss law plus a constant $\chi_0$, $\chi(T) = N_\mu^2 \omega^2(3k_B(T-\theta_CW)) + \chi_0$, represented by the solid line, with $\mu_0=2.77 \mu_B$, $\theta_CW=-50$ K, and $\chi_0=6.2\times 10^{-4}$ emu/mol. The effective moment is somewhat smaller than the free-ion values for trivalent ($3.62 \mu_B$) and tetravalent ($3.58 \mu_B$) U ions. The paramagnetic constant $\chi_0$ could be due to an enhanced Pauli susceptibility for a heavy-fermion compound. Significant CEF splitting ($\Delta_{CEF} \sim 100$ K) might also give rise to the observed deviation from free-ion behavior. Not shown in Fig. 8(b), the $\chi(T)$ data reveal slightly irreversible behavior at temperatures below $T_N$.

Shown in Fig. 9 are low-temperature specific-heat data for UPd$_2$Pb, plotted as $C/T$ vs $T^2$, for 0.5$\leq T \leq 10$ K. The solid line represents a least-squares fit of the data to the equation $C(T) = \gamma T + \beta T^3$, with $\gamma=98$ mJ/mol K$^2$ and $\beta=3.8$ mJ/mol K$^4$. The value of the Sommerfeld coefficient $\gamma$ is at least an order of magnitude larger than that of a normal metal, although it is small compared to prototypical heavy-fermion compounds for which $0.25 \lesssim \gamma \lesssim 1$ J/mol K$^2$. However, the U ions are antiferromagnetically ordered at these temperatures, which might be responsible for the observed values of the coefficients $\gamma$ and $\beta$. Measurements of $C(T)$ to higher temperatures will give information about the ordering, as well as a measure of $\gamma$ above $T_N$.

**CONCLUSION**

Single crystals of RPd$_2$Pb with very small amounts of impurity phases were fabricated. Measurements of magnetic susceptibility revealed bulk superconductivity for $R=$Sc, Y, Tm, Yb, and Lu, with $T_c=2$–3 K. These values are lower than expected; a $T_c$ value as high as 4.76 K was previously reported for YPd$_2$Pb. The discrepancy is most likely due to differences in sample composition and/or quality. In particular, the $T_c$'s of these Heusler compounds are known to be sensitive to exact stoichiometry; off-stoichiometric polycrystalline samples might yield higher $T_c$ values. The magnetic rare-earth ions order antiferromagnetically with very low Néel temperatures $T_N < 4.5$ K. Both $T_N$ and $\theta_CW$ scale approximately with the de Gennes factor. It is unlikely that the Tm ions in TmPd$_2$Pb have a nonmagnetic ground state, making it more surprising that it is superconducting. ThPd$_2$Pb was not superconducting above 1.8 K. The Heusler compound UPd$_2$Pb orders antiferromagnetically below 35 K, and displays many characteristics of a low effective mass heavy-fermion material.

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