[17] R. S. Raghavan and P. Raghavan, Nucl. Instrum. Methods **92**, 435 (1971).

[18] P. G. E. Reid, M. Sott, N. J. Stone, D. Spanjaard, and H. Bernas, Phys. Lett. A **25**, 396 (1968).

[19] R. B. Alexander, N. J. Stone, D. V. Morgan, and J. M. Poate, in *Hyperfine Interactions in Excited Nuclei,* edited by G. Goldring and R. Kalish (Gordon and Breach, New York, 1971), p. 229.

[20] K. Kumar and M. Baranger, Nucl. Phys. A. **110**, 529 (1968); Nucl. Phys. A **122**, 273 (1968).

PHYSICAL REVIEW B VOLUME 7, NUMBER 9 1 MAY 1973

Electrical and Magnetic Properties of Some Cubic Intermetallic Compounds of Plutonium with Ru, Rh, Ir, Pd, and Pt[†]

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The electrical resistivities and magnetic susceptibilities of the cubic intermetallic compounds of the form $\mathrm{Pu}X_2$ (X =Ru, Rh, Ir, Pt) and $\mathrm{Pu}X_3$ (X =Rh, Pd, Pt) have been measured from 2 to 300 °K. The $\mathrm{Pu}X_3$ compounds order antiferromagnetically with Néel temperatures T_N of 6.6, 24, and 40 °K, respectively. The resistivities of the $\mathrm{Pu}X_3$ compounds decrease rapidly below T_N, and there is also an abrupt change in the slope of the resistivity-versus-temperature curve at T_N in $\mathrm{PuRh_3}$. $\mathrm{PuPt_2}$ orders ferromagnetically at a Curie temperature of $T_C = (6.0\pm0.3)$ °K, and the resistivity falls dramatically below T_C. $\mathrm{PuRh_2}$ has a temperature-dependent susceptibility but there is no evidence for magnetic order, while the susceptibilites of $\mathrm{PuRu_2}$ and $\mathrm{PuIr_2}$ are temperature independent. However, the resistivities of $\mathrm{PuRh_2}$, $\mathrm{PuRu_2}$, and $\mathrm{PuIr_2}$ have anomalous negative curvature at high temperatures, although the slopes remain positive throughout the temperature range investigated. The results are discussed in terms of the interatomic distance between plutonium atoms and the localized-spin-fluctuation model.

I. INTRODUCTION

A wealth of interesting magnetic and transport behavior has been observed recently in the actinide elements and their intermetallic compounds,[1] and the unusual nature of the phenomena in these systems is intimately related to how the actinide 5*f* electrons respond to a given environment. The results of Nellis and Brodsky[2] on $\mathrm{PuPd_3}$ and $\mathrm{NpPd_3}$ and of Hill and Elliott[3] on actinide-Pt compounds indicate that a study of actinide–transition-metal compounds should yield considerable information on the properties of actinide 5*f* electrons.

This paper presents the electrical resistivities and magnetic susceptibilities of the cubic intermetallic compounds of the form $\mathrm{Pu}X_2$ (X= Ru, Rh, Ir, Pt) and $\mathrm{Pu}X_3$ (X=Rh, Pd, Pt). These compounds were chosen because the crystal structures are relatively simple—the $\mathrm{MgCu_2}$ cubic Laves phase and ordered fcc $\mathrm{AuCu_3}$ structures, respectively[4]—and because the transition metals themselves are nonmagnetic. A preliminary account of the resistivity measurements has already been given.[5] A study of the magnetic properties has also been reported,[6] but new data on better samples of $\mathrm{PuRh_2}$ and $\mathrm{PuPt_3}$ are included in the present paper as a supplement to the previous investigation. The susceptibility measurements show that the $\mathrm{Pu}X_3$ compounds order antiferromagnetically, and this finding is supported by the resistivity results. The $\mathrm{Pu}X_2$ compounds show a spectrum of magnetic behavior: $\mathrm{PuRu_2}$ is strongly paramagnetic, $\mathrm{PuRh_2}$ is nearly magnetic, and $\mathrm{PuPt_2}$ is a weak ferromagnet. The results are discussed in terms of the interatomic distance between plutonium atoms and the localized-spin-fluctuation model.

II. EXPERIMENTAL PROCEDURE

The transition metals used in this study had purities which were typically ~99.995%. The high-purity plutonium was obtained from Los Alamos Scientific Laboratory and the impurities it contained were (in ppm by weight) Mg, 3; Al, 10; Si, 5; Ca, < 3; Zn, < 5; Am, 55 (on 2-18-71); Fe, 4; Ta, 11; Th, 9; W, 2.5; U, 25; N, 3; C, < 10; H, 15; and all others, < 2. From these starting materials, 1-g quantities of the intermetallic compounds were prepared by arc-melting appropriate amounts of the constituents in an argon-helium atmosphere. Resistivity samples with the approximate dimensions 1×1×7 mm were machined out of the buttons with a spark-erosion apparatus, and magnetic-susceptibility samples were prepared from pieces of the remaining material. $\mathrm{PuPt_3}$, $\mathrm{PuPd_3}$, $\mathrm{PuRh_3}$, and $\mathrm{PuRu_2}$ formed congruently from the melt,[4] and consequently no further heat treatment was given. $\mathrm{PuPt_2}$, $\mathrm{PuRh_2}$, and $\mathrm{PuIr_2}$ were given one-week anneals at 1100, 1250, and 1000 °C, respectively. Powder x-ray-diffraction techniques were used to confirm that the desired compound had in fact been formed. Lattice parameters a_0 determined from the x-ray patterns are listed in Table I, and the values agree quite well with those reported in the literature.[4] In addition, the absence of extraneous lines in the patterns indicated that with the exception of $PuIr_2$, all of the samples were single phase. In the case of $PuIr_2$, the intensities of the extraneous lines indicated that 5–10% of the sample was a second phase (possibly Pu_5Ir_4 or Pu_5Ir_3).

Electrical-resistivity measurements were made from 1.5 to 300 °K using the standard dc four-probe technique and an automated system described previously.[7] With this system, data were recorded at either 20- or 48-sec intervals while the sample warmed at the rate of $\frac{1}{3}$ °K/min; the data were processed using a computer. The susceptibility measurements were made from 2.5 to 300 °K using the Faraday method and an experimental arrangement similar to one described previously.[8] The susceptibilities $\chi = M/H$ of the PuX_3 compounds, $PuRh_2$ and $PuPt_2$, were obtained by taking data at six fields up to 14.5 kOe, fitting the results to a two-term equation linear in $1/H$, and extrapolating to $1/H = 0$. The susceptibilities of $PuRu_2$ and $PuIr_2$ were independent of the magnetic field up to 14.5 kOe.

III. RESULTS

A. Magnetic Susceptibility

An account of the magnetic properties has already been given.[6] Since that time better samples of $PuPt_3$ and $PuRh_2$ have been prepared, and their susceptibilities are shown in Fig. 1. The peak in the curve for $PuPt_3$ is characteristic of antiferromagnetic order with a Néel temperature T_N of 40 °K. The results for $PuRh_3$ and $PuPd_3$ were similar, and values of T_N for these samples are listed in Table I. The earlier data for a two-phase sample of $PuPt_3$ also showed characteristic antiferromagnetic behavior. For reasons not understood at this time, the value of p_{eff} is the same for the two samples, but T_N is now 20 °K lower.

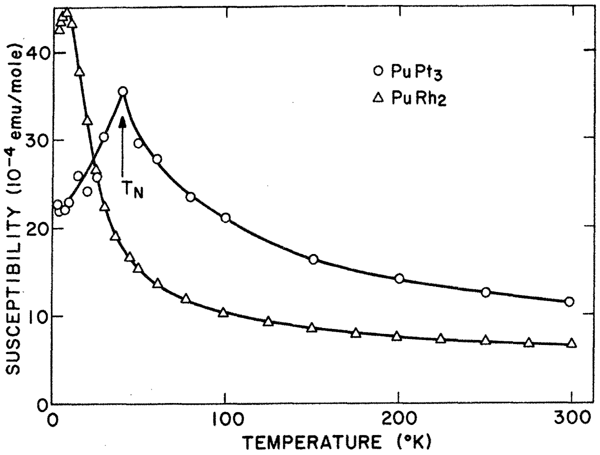

FIG. 1. Magnetic susceptibilities of $PuPt_3$ and $PuRh_2$ as a function of temperature.

Recent neutron-diffraction results[9] confirm that $PuPd_3$ is a simple antiferromagnet with an ordered moment per plutonium atom at 4.2 °K of $(0.8 \pm 0.1)\mu_B$ and a magnetic lattice similar to that found in $NpPd_3$[10] in which nearest-neighbor neptunium atoms have their moments oppositely directed. The susceptibility data in the paramagnetic region were analyzed by fitting the susceptibilities to an equation of the form $\chi = \chi_0 + C/(T - \Theta_p)$, where χ_0 is a temperature-independent contribution and $C/(T - \Theta_p)$ is the usual Curie-Weiss expression. The effective paramagnetic moment p_{eff} per formula unit (F.U.) was determined from the fitting constant C in the usual way, and values of χ_0, Θ_p, and p_{eff} for the PuX_3 compounds are listed in Table I.

The susceptibility of $PuRh_2$ increases with decreasing temperature down to about 10 °K, where a small maximum develops. However, this behavior is not indicative of magnetic order, because the maximum is rounded and because there is no supporting evidence in the resistivity data. The maximum was not seen in the earlier sample, but powder x-ray-diffraction patterns indicated that it

TABLE I. Magnetic parameters of cubic plutonium compounds.

Compound	Ordering temperature (°K)	Θ_p (°K)	p_{eff} (μ_B/F. U.)	χ_0 (10^{-4} emu/mole)	a_0 (Å)
$PuRh_3$	$T_N = 6.6$	−63	1.0	6.2	4.008 ± 0.001
$PuPd_3$	$T_N = 24$	−34	1.0	1.4	4.102 ± 0.001
$PuPt_3$	$T_N = 40$	−36	1.3	4.9	4.103 ± 0.002
$PuRu_2$	•••	•••	•••	9.31	7.474 ± 0.001
$PuRh_2$	•••	−49	0.88	3.7	7.488 ± 0.001
$PuIr_2$	•••	•••	•••	5.75	7.531 ± 0.001
$PuPt_2$	$T_C = 6$	+6	0.89	2.4	7.652 ± 0.001

was a multicomponent system and not pure $PuRh_2$. The other three PuX_2 compounds have magnetic properties which are in marked contrast to $PuRh_2$.[8] $PuIr_2$ and $PuRu_2$ have temperature-independent susceptibilities, and their values are listed under χ_0 in Table I. $PuPt_2$ orders ferromagnetically at a Curie temperature of $T_C = (6.0 \pm 0.3)$ °K as indicated by plots of M^2 vs H/M, has a magnetization which does not saturate at 2.5 °K in fields up to 14.5 kOe, and has a small spontaneous moment of $\sim 0.2 \mu_B/\mathrm{F.U.}$ These results indicate that the magnetism in $PuPt_2$ is probably itinerant in nature. The high-temperature data for both $PuRh_2$ and $PuPt_2$ were also analyzed by the modified Curie–Weiss law, and the various fitting parameters are listed in Table I.

B. Resistivity

The electrical resistivities of the PuX_3 compounds are shown in Fig. 2 as a function of temperature. These materials are metallic in nature with room-temperature resistivities of 125, 90, and 54 $\mu\Omega$ cm for $PuPd_3$, $PuPt_3$, and $PuRh_3$, respectively. The resistivities show strong temperature dependences below T_N. There is also a pronounced change in the slope of the resistivity-versus-temperature curve at T_N in $PuRh_3$, whereas the slope changes are more gradual at T_N in $PuPd_3$ and $PuPt_3$. In the temperature range $7 < T < 13$ °K, the resistivity of $PuRh_3$ varies as $\rho = (16.8 + 0.181 T/°\mathrm{K}) \mu\Omega\,\mathrm{cm}$. Also, it should be noted that the $PuPd_3$ resistivity curve has a negative slope above 60 °K. The dramatic decreases in the resistivities below T_N are most certainly related to a decrease in magnetic scattering of the conduction electrons. A measure of the magnetic scattering ρ_m above T_N was determined for $PuRh_3$ and $PuPt_3$ by extrapolating the high-temperature data to 0 °K, taking the resistivity value thus obtained, and subtracting the residual resistivity ρ_0. Because of the negative slope at high temperatures in $PuPd_3$, the procedure was modified by subtracting the residual resistivity from the value at the peak. The values obtained for ρ_m are listed in Table II.

TABLE II. Values of the parameters associated with the resistivities of cubic plutonium compounds.

Compound	ρ_m ($\mu\Omega$ cm)	ρ_0 ($\mu\Omega$ cm)	A ($\mu\Omega$ cm/(°K)^2)	B (10^{-4} $\mu\Omega$ cm/(°K)^3)
$PuRh_3$	13.8	3.0	···	···
$PuPd_3$	131.3	19.7	···	···
$PuPt_3$	77.3	11.2	···	···
$PuRu_2$	···	10.40	···	5.27
$PuRh_2$	···	22.80	0.127	···
$PuIr_2$	···	17.05	···	3.27
$PuPt_2$	80.0	8.0	···	···

The electrical resistivities of the PuX_2 compounds are shown in Fig. 3. These materials are also metallic in nature, with room-temperature resistivities of 117, 113, 112, and 80 $\mu\Omega$ cm for $PuRh_2$, $PuPt_2$, $PuRu_2$, and $PuIr_2$, respectively. The resistivity of $PuPt_2$ shows a pronounced drop as the temperature is lowered through T_C, while the other PuX_2 compounds behave less dramatically. An estimate of the resistivity associated with the ordering in $PuPt_2$ was made in the manner described above, and the value $\rho_m = 82$ $\mu\Omega$ cm was obtained. The resistivity of $PuRh_2$ varies initially as T^2, and the results below 12 °K are described by the equation $\rho = \rho_0 + AT^2$, where ρ_0 is the residual resistivity and A is a fitting parameter. The values of ρ_0 and A are listed in Table II. The resistivities of $PuRu_2$ and $PuIr_2$ show temperature dependences of the form $\rho = \rho_0 + BT^3$ below 16 and 15

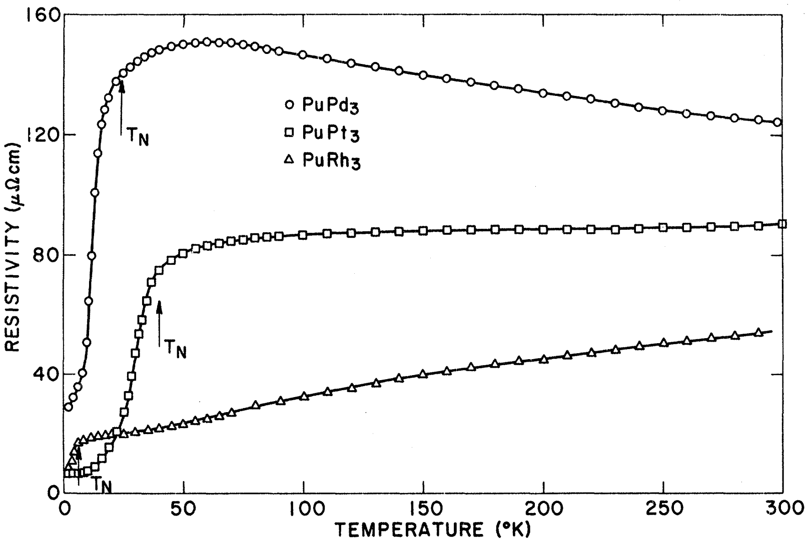

FIG. 2. Electrical resistivities of $PuRh_3$, $PuPd_3$, and $PuPt_3$ as a function of temperature.

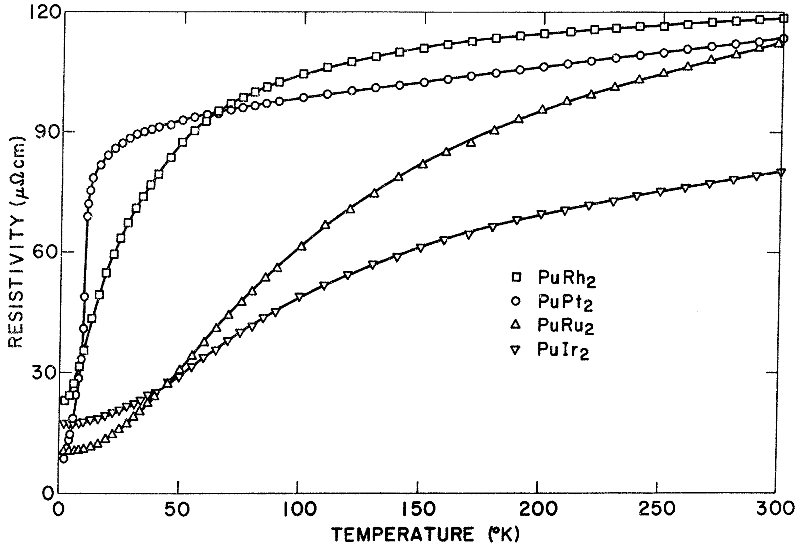

FIG. 3. Electrical resistivities of $PuRh_2$, $PuPt_2$, $PuRu_2$, and $PuIr_2$ as a function of temperature.

°K, respectively, and values of ρ_0 and B for both samples are also listed in Table II. In addition, the high-temperature resistivity curves of $PuRh_2$, $PuRu_2$, and $PuIr_2$ do not behave in a simple manner in that they show a tendency to bend over; i.e., they have negative curvature. However, the slopes of the curves do remain positive throughout the temperature range covered.

A note of caution should be sounded here with regard to the values of ρ_m and the temperature dependences cited above. ^{239}Pu is radioactive and damages by self-irradiation. This damage has an effect on the low-temperature resistivity of plutonium,[11] and, furthermore, the resistivity caused by the damage does not obey Matthiessen's rule.[12] It is not known at this time what effect the self-irradiation damage has on the compounds discussed in this paper, but an attempt was made to minimize the effect of this phenomenon by measuring the resistivities and susceptibilities as soon as possible after fabrication or annealing.

IV. DISCUSSION

Recent band calculations on the actinides[13] and on actinide compounds with the NaCl type of structure[14] indicate that the actinide $5f$ electrons give rise to narrow f bands at or near the Fermi level which are strongly hybridized with the conduction band. This leads naturally to the idea that the degree of hybridization and the stability of the f band have a direct bearing on whether or not magnetism is observed in actinide systems. For example, plutonium does not order magnetically,[15] whereas in actinide compounds with the NaCl type of structure, local-moment behavior is observed.[16] These considerations correlate with Hill's qualitative argument[17] concerning the relation between the interatomic actinide distance and the appearance of magnetic order. In particular, Hill indicates that if the interatomic plutonium-plutonium distance d_{Pu-Pu} is less than the critical value of ~3.4 Å, nonmagnetic behavior is observed because of f-f overlap (the average d_{Pu-Pu} in α-Pu is ~3.2 Å), but if d_{Pu-Pu} is greater than 3.4 Å, long-range magnetic order can be expected. In the PuX_3 compounds studied here, $d_{Pu-Pu} = a_0$, the lattice parameter, and is about 4.1 Å. In the PuX_2 compounds, $d_{Pu-Pu} = \frac{1}{4} a_0 3^{1/2}$ and is about 3.3 Å. Consequently, on this simple basis, long-range magnetic order in the PuX_3 compounds is expected. The PuX_2 samples have a d_{Pu-Pu} very close to the critical value, and here the situation is not as clear. However, it seems reasonable to assume that the tendency to exhibit magnetism is less strong in the PuX_2 compounds, and the conclusion that the magnetism observed in $PuPt_2$ has itinerant rather than local-moment character is in agreement with the arguments for f-band formation discussed in Refs. 13, 14, and 17. Since the value of d_{Pu-Pu} is so close to the critical value, it is not surprising that the magnetic behavior of the PuX_2 compounds is very sensitive to the particular transition metal used.

The susceptibility measurements on the PuX_3 compounds indicate that the transition element has little effect on the magnetic order except to shift T_N. This is in contrast to the case for the PuX_2 compounds and probably results from the fact that d_{Pu-Pu} is so much larger than the critical value. The susceptibility data also indicate that the f electrons are reasonably well localized in the PuX_3 compounds. The fits of the data to $\chi = \chi_0 + C/(T - \Theta_p)$ were quite good, and values of p_{eff}/F.U. were all about $1\mu_B$/F.U. The latter result implies that the plutonium atoms are in the same electronic configuration for all three samples; i.e., assuming that the plutonium atoms are trivalent and in the $5f^5$ configuration, application of Hund's rules yields paramagnetic and ordered moments of $0.85\mu_B$ and $0.72\mu_B$, respectively. The ordered moment is in good agreement with the neutron-diffraction results[9] on $PuPd_3$ which indicate an ordered moment per F.U. of $(0.8 \pm 0.1)\mu_B$. However, since p_{eff} for $PuPt_3$ is slightly greater than p_{eff} for $PuRh_3$ and $PuPd_3$, some of the moment may lie on the platinum atoms, or crystal field effects may be entering. Neutron-diffraction and Mössbauer data are needed to obtain information on the ordered moments and to resolve these questions. The resistivity results also indicate local-moment behavior in the PuX_3 compounds. The sharp resistivity drops below T_N are similar to the spin-disorder resistivities in the heavy rare-earth metals[18] in which local moments are well formed. However, note the differences between the values of ρ_m in the PuX_3 compounds. If the plutonium atoms are in the same electronic configuration, then the coupling between the conduction electrons and the f electrons is sensitive to the nonactinide element.

There remains the problem of the negative slope of the resistivity-versus-temperature curve of $PuPd_3$ above 60 °K. This behavior can be explained if the temperature dependence of the Fermi level is taken into account and the band structure of the material has special properties.[19] However, the authors favor an alternative approach based on the localized-spin-fluctuation (LSF) model[20-23] which has been successful in explaining the results on several actinide systems.[1,15(a),24-27] Briefly, the model for intermetallic compounds[21] predicts that the resistivity should drop to zero at $T = 0$ °K because in atomically ordered materials the f band hybridizes with the conduction band to generate a Fermi-surface structure. As T is increased from 0 °K, the conduction electrons begin to scatter from spin fluctuations in the f band and the resistivity rises rapidly, initially as T^2, and then goes into a region linear in T. However, because of the high concentration of actinide atoms, the scattering is quite strong and has a drastic effect on the mean free paths of the f electrons themselves. As a result, in the regime $T > T_{sf}$, where T_{sf} is the characteristic spin-fluctuation temperature, the scattering is self-limiting, and the resistivity will level off or even decrease with temperature. In this approach, the self-limiting aspect of the spin-fluctuation scattering accounts for the negative slope of the resistivity-versus-temperature curve of $PuPd_3$, and could explain the negative curvature of the resistivity-versus-temperature curves of $PuPt_3$ and $PuRh_3$ at high temperatures as well. Further evidence that the LSF model applies to all of the PuX_3 compounds is the linear variation with temperature of the resistivity of $PuRh_3$ above T_N and, more qualitatively, the rounded behavior of the resistivity-versus-temperature curves of $PuPd_3$ and $PuPt_3$ in the vicinity of T_N. Implicit in this interpretation is the suggestion of Buschow and van Daal[25] that $T_{sf} < T_N$ and that spin fluctuations are quenched in the magnetically ordered state below T_N.

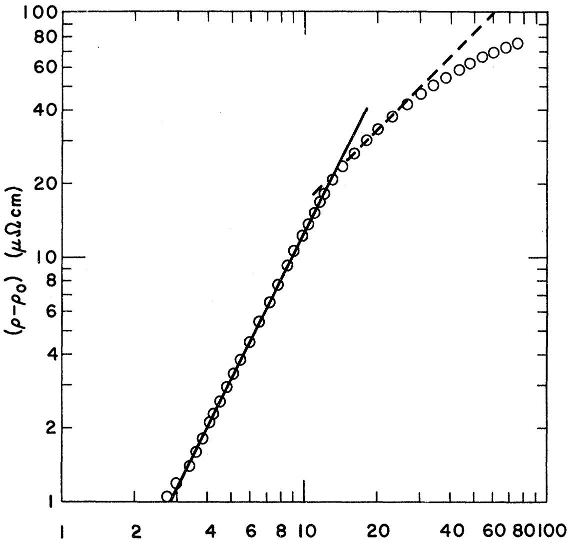

FIG. 4. Bilogarithmic plot of the resistivity of $PuRh_2$ as a function of temperature.

In the PuX_2 compounds, $PuRh_2$ appears to be a good candidate for the LSF model. Figure 4 shows a bilogarithmic plot of the resistivity-versus-temperature curve for $PuRh_2$, and the solid and dashed curves show the regions of T^2 and T behavior, respectively. Assuming that $T_{sf} \simeq T_1$, the upper limit of the T^2 region of the resistivity, $T_{sf} \simeq 12$ °K for $PuRh_2$. The Curie–Weiss susceptibility above 30 °K is indicative of the magnetic behavior expected at temperatures above T_{sf}. The LSF model model may also be applicable to $PuPt_2$ in the same way that it is for the PuX_3 compounds, and if this is the case, $T_{sf} < 6$ °K for $PuPt_2$. The large temperature-independent magnetic susceptibilities of $PuRu_2$ and $PuIr_2$ indicate a broad, hybridized $6d$-$5f$ band with little structure and a high density of states at the Fermi level. The T^3 temperature dependences of the resistivities of $PuRu_2$ and $PuIr_2$ are characteristic of the s-$d(f)$ interband scattering[28] that could be expected in such materials. The strong negative curvature of the resistivity-versus-temperature curves of $PuRu_2$ and $PuIr_2$ at high temperatures is similar to the behavior of other actinide metals and compounds. However, the origin of this strong curvature is at present not understood. The absence of a contribution to the resistivity, which varies as T^2, argues against the LSF model, and the magnetic susceptibilities do not vary with temperature in the manner that would be expected if the thermal smearing explanation were appropriate.

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[1] For a review of magnetism in the actinides and extensive list of references, see (a) M. B. Brodsky, in *Conference on Rare Earths and Actinides* (Institute of Physics, London and Bristol, 1971), pp. 75-83; (b) in *Magnetism and Magnetic Materials, 1971*, edited by C. D. Graham, Jr and J. J. Rhyne (AIP, New York, 1972), Part 2, pp. 611-629.

[2] W. J. Nellis and M. B. Brodsky, Bull. Am. Phys. Soc. **16**, 326 (1971).

[3] H. H. Hill and R. O. Elliott, Phys. Lett. A **35**, 75 (1971).

[4] V. I. Kutaitsev, N. T. Chebotarev, M. A. Andrianov, V. N. Konev, I. G. Lebedev, V. I. Bagrova, A. V. Beznosikova, A. A. Kruglow, P. N. Petrov, and E. S. Smotritskaya, Sov. J. At. Energy **23**, 1279 (1967).

[5] A. R. Harvey, M. B. Brodsky, and W. J. Nellis, Bull. Am. Phys. Soc. **17**, 236 (1972).

[6] W. J. Nellis and M. B. Brodsky, in Ref. 1(b), pp. 1483–1487.

[7] M. B. Brodsky, N. J. Griffin, and M. D. Odie, J. Appl. Phys. **40**, 895 (1969).

[8] J. W. Ross and D. J. Lam, Phys. Rev. **165**, 617 (1968).

[9] G. H. Lander and M. H. Mueller (unpublished).

[10] G. H. Lander, M. B. Brodsky, B. D. Dunlap, W. J. Nellis, and M. H. Mueller, Bull. Am. Phys. Soc. **17**, 338 (1972).

[11] C. E. Olsen and R. O. Elliott, J. Phys. Chem. Solids **23**, 1225 (1962).

[12] E. King, J. A. Lee, K. Mendelssohn, and D. A. Wigley, Proc. R. Soc. A **284**, 325 (1965).

[13] (a) D. D. Koelling, A. J. Freeman, and G. O. Arbman, in *Plutonium 1970 and the Other Actinides*, edited by W. N. Miner (The Metallurgical Society of AIME, New York, 1970), Part I, pp. 194–208; E. A. Kmetko and H. H. Hill, in *Plutonium 1970 and the Other Actinides*, edited by W. N. Miner (The Metallurgical Society of AIME, New York, 1970), Part I, pp. 233–243; (b) R. Jullien, E. Galleani d'Agliano, and B. Coqblin, Phys. Rev. B **6**, 2139 (1972).

[14] H. L. Davis, in Ref. 13(a), pp. 209–218.

[15] (a) A. J. Arko and M. B. Brodsky, in Ref. 13(a), pp. 364–373; (b) F. Y. Fradin and M. B. Brodsky, Int. J. Magn. **1**, 89 (1970); (c) B. D. Dunlap, S. L. Ruby, M. B. Brodsky, and D. Cohen, Bull. Am. Phys. Soc. **16**, 850 (1971).

[16] S. K. Chan and D. J. Lam, in Ref. 13(a), pp. 219–232; J. Grunzweig-Genossar, M. Kuznietz, and F. Friedman, Phys. Rev. **173**, 562 (1968).

[17] H. H. Hill, in Ref. 13(a), pp. 2–19.

[18] S. Legvold, Phys. Rev. B **3**, 1640 (1971), and references cited therein.

[19] See, for example, H. Jones, in *Handbuch der Physik*, edited by S. Flügge (Springer-Verlag, Berlin, 1956), Vol. XIX, p. 227.

[20] A. B. Kaiser and S. Doniach, Int. J. Magn. **1**, 11 (1970).

[21] S. Doniach, in Ref. 1(b), pp. 549–557.

[22] N. Rivier and M. J. Zukerman, Phys. Rev. Lett. **21**, 904 (1968).

[23] M. T. Béal-Monod (report of work prior to publication).

[24] W. J. Nellis and M. B. Brodsky, Phys. Rev. B **4**, 1594 (1971).

[25] K. H. J. Buschow and H. J. van Daal, in Ref. 1(b), pp. 1464–1477.

[26] A. J. Arko, M. B. Brodsky, and W. J. Nellis, Phys. Rev. B **5**, 4564 (1972).

[27] C.-H. de Novion and P. Costa, J. Phys. (Paris) **33**, 257 (1972).

[28] A. H. Wilson, Proc. R. Soc. A **167**, 580 (1938).

PHYSICAL REVIEW B VOLUME 7, NUMBER 9 1 MAY 1973

Refraction of Thermal Neutrons by Shaped Magnetic Fields[*]

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The refractive bending of thermal neutrons by shaped magnetic fields has been studied experimentally and compared with that calculated from the field distribution. The small deflections, a few seconds arc, were measured on a double-crystal spectrometer utilizing matched perfect silicon crystals. Deflections were measured for a beam of polarized neutrons upon its polarization reversal for field regions of both prismatic and cylindrical configuration. The focusing and polarizing character of a magnetic lens have been observed.

I. INTRODUCTION

When slow neutrons carrying a magnetic moment μ are introduced into a region of space where a magnetic field B is present, there occurs a Zeeman splitting of the potential energy of magnitude $\pm\mu B$, corresponding to the two quantized spin states of the neutron. This occurs at the expense