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## Influence of spin fluctuations on the electrical resistance of $\text{UAl}_2$ and $\text{UPt}_3$ at high pressures and low temperatures

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The compounds  $\text{UAl}_2$  and  $\text{UPt}_3$  are thought to exhibit ferromagnetic spin fluctuations. We have measured the electrical resistance of both materials to over 1000 K at zero pressure and from room temperature to 1 K at pressures up to 18 kbar. The primary effect of pressure is to reduce the low-temperature slope  $\partial R/\partial T$  and thus shift the inflection point in the resistance to higher temperatures. We interpret these observations as arising from an increase in the spin-fluctuation temperature  $T_s$  with increasing pressure. Using a Fermi-liquid description of these materials, we calculate the pressure dependence of the  $T=0$  susceptibility from the pressure dependence of  $T_s$ . We also find that the temperature-dependent resistance at various fixed pressures scales as  $T/T_s(P)$  over a remarkably large temperature interval.

### I. INTRODUCTION

Recently, increased activity has focused on experimental and theoretical descriptions of materials showing nearly magnetic behavior. Within this class of materials are those that display signatures believed to be characteristic of ferromagnetic spin fluctuations,<sup>1</sup> namely a Curie-Weiss susceptibility at high temperatures that evolves with decreasing temperature into enhanced paramagnetism, a low-temperature resistivity proportional to  $T^2$ , and a  $T^3 \ln T$  contribution to the low-temperature heat capacity. Both  $\text{UAl}_2$  (Refs. 2 and 3) and  $\text{UPt}_3$  (Refs. 4 and 5) are known to comply satisfactorily with all of these properties. Of these two,  $\text{UPt}_3$  is particularly interesting because of the recent demonstration<sup>4</sup> that bulk superconductivity and possibly spin fluctuations coexist in this material.

Preliminary band-structure calculations indicate that in both  $\text{UAl}_2$  (Ref. 6) and  $\text{UPt}_3$  (Ref. 7) the  $5f$  electrons form a narrow band at the Fermi energy, a condition favoring spin fluctuations. Decreasing the U-U separation by the application of hydrostatic pressure should increase the  $5f$ -wave-function hybridization and broaden the band causing a decrease in the density of states at the Fermi level. Provided pressure increases the  $f$ - $f$  Coulomb repulsion less rapidly than it broadens the  $5f$ -band width, decreasing the U-U separation should lower the magnetic susceptibility ( $\chi$ ). Such behavior should be reflected as a systematic change with volume in physical properties, e.g., the magnetic susceptibility and resistivity, that depend sensitively on  $5f$ -conduction-band interactions. Evidence substantiating this view has been found in susceptibility measurements<sup>8</sup> on  $\text{UAl}_2$  and through resistivity measurements on  $\text{UPt}_3$  (Ref. 9) at pressures up to, respectively, 6.65 and 4.2 kbar.

To study the effect of U-U separation on spin fluctuations in  $\text{UAl}_2$  and  $\text{UPt}_3$ , we have measured the temperature-dependent resistance of polycrystalline  $\text{UAl}_2$  and single crystals of  $\text{UPt}_3$  (along both the  $c$  axis and in the  $a$ - $b$  plane) subjected to hydrostatic pressure. We show that the suppression of spin fluctuations with pressure, as

deduced from susceptibility measurements,<sup>8</sup> is reflected directly in the temperature-dependent resistance and that, over an appropriate temperature interval, the resistance scales with a pressure-dependent parameter which may be identified with the spin-fluctuation temperature.

### II. EXPERIMENTAL PROCEDURE

Our polycrystalline  $\text{UAl}_2$  sample was prepared by arc melting the pure elements together on a water-cooled copper hearth in a zirconium-gettered argon atmosphere. Needle-shaped single crystals of  $\text{UPt}_3$  were grown from a bismuth flux. Both the  $\text{UAl}_2$  and the  $\text{UPt}_3$  samples were shown to be single phase by x-ray diffraction and metallographic techniques. Because of geometrical considerations, two separate  $\text{UPt}_3$  samples were studied, one on which the resistance was measured along the hexagonal  $c$  axis and one for measurements in the  $a$ - $b$  plane. As a measure of the quality of our samples, the residual resistance ratios for  $\text{UAl}_2$ ,  $\text{UPt}_3$   $c$  axis, and  $\text{UPt}_3$   $a$ - $b$  plane were, respectively, 14, 130, and 47. The superconducting transition temperatures for  $\text{UPt}_3$   $c$  axis and  $a$ - $b$  plane were 0.51 and 0.38 K, respectively. This difference and that of the residual resistance ratios for the two  $\text{UPt}_3$  samples result from the annealing process given the  $c$ -axis sample.

Resistance measurements were made by a standard four-lead ac technique at 23 Hz. Platinum leads were attached to the samples by spot welding ( $\text{UAl}_2$ ) or by silver-filled epoxy ( $\text{UPt}_3$ ). The samples were subjected to hydrostatic pressures exceeding 17 kbar in a self-clamping pressure cell, described elsewhere,<sup>10</sup> which used a 1:1 mixture of  $n$ -pentane and isoamyl alcohol as the pressure medium. The pressure was determined from a lead manometer situated adjacent to the sample. Resistance measurements in the cell were performed in the temperature range  $1 \leq T \leq 300$  K, measured by a calibrated carbon-glass thermometer embedded in the side of the cell.

Resistance measurements made above room tempera-

ture were a by-product of heat-capacity measurements performed at zero pressure. The method, described in detail elsewhere,<sup>11</sup> relied on a dc transient-pulse-heating technique.

### III. RESULTS AND DISCUSSION

We show in Fig. 1 the temperature-dependent resistance of  $\text{UAl}_2$  at four different pressures. From measurements on samples of well-defined geometry cut from the same arc-melted button, we estimate the zero-pressure room-temperature resistivity to be approximately  $110 \mu\Omega \text{ cm}$ . With increasing pressure, the most notable change is a shift of the inflection point to higher temperatures resulting from a decrease in the low-temperature slope  $\partial R/\partial T$ . Qualitatively similar behavior is found for  $\text{UPt}_3$  when measured along the  $c$  axis and in the  $a$ - $b$  plane (Fig. 2); however, there are notable differences. In particular, the resistance near room temperature is still increasing noticeably with temperature and is not saturated. This difference is seen most clearly in Fig. 3 where we plot the zero-pressure temperature-dependent resistivity of polycrystalline  $\text{UPt}_3$  and  $\text{UAl}_2$  for temperatures to over  $1000 \text{ K}$ .<sup>11</sup> We see that the resistivity of polycrystalline  $\text{UPt}_3$  continues to increase above room temperature and eventually passes through a maximum near  $800 \text{ K}$ , while the resistivity of  $\text{UAl}_2$  is nearly saturated at temperatures as low as  $200 \text{ K}$ . What is not apparent in Figs. 2 and 3 is that the resistivity of  $\text{UPt}_3$  is markedly anisotropic. Measurements performed by others<sup>9</sup> on single crystals of  $\text{UPt}_3$  have shown that the room-temperature resistivity along the  $c$  axis is about  $130 \mu\Omega \text{ cm}$ , while the resistivity in the basal plane is estimated to be  $240 \mu\Omega \text{ cm}$ . A comparably huge anisotropy also has been observed<sup>5</sup> in the paramagnetic susceptibility of  $\text{UPt}_3$  single crystals in which  $\chi(T=0)$  in the  $a$ - $b$  plane is approximately twice the value measured along the  $c$  axis, suggesting that the resistivity and susceptibility may be dominated by the same physical effect.

One feature common to nearly all theoretical models of spin fluctuations is that, for temperature much less than the characteristic spin-fluctuation temperature  $T_s$ , the resistance is predicted<sup>12</sup> to increase as  $T^2$ , with a slope  $\partial R/\partial T^2 \propto 1/T_s^2$ . However, if the material is highly disor-

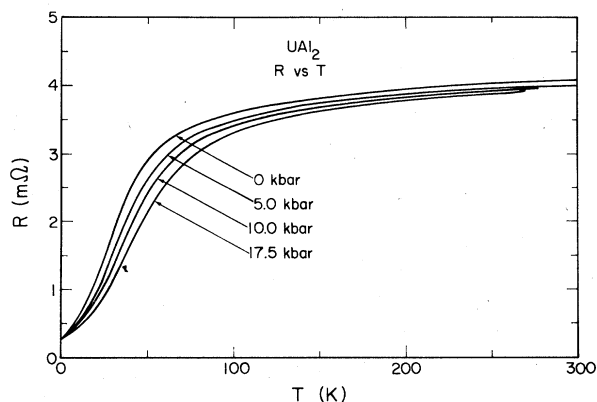


FIG. 1. Resistance as a function of temperature for polycrystalline  $\text{UAl}_2$  at four different clamp pressures. For clarity, data at  $14 \text{ kbar}$  are not shown.

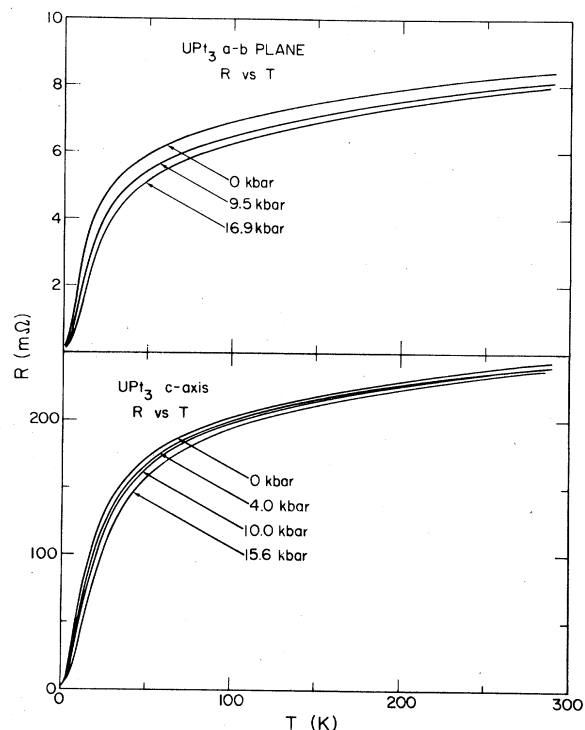


FIG. 2. Resistance vs temperature of single crystal  $\text{UPt}_3$  at various fixed clamp pressures. The top set of curves are those measured in the  $a$ - $b$  plane and the bottom set measured along the  $c$  axis.

dered (large residual resistivity), Riseborough<sup>13</sup> has shown that one obtains a  $T^{3/2}$  dependence of the scattering rate due to spin fluctuations. We have looked closely for a power-law dependence of the low-temperature ( $T < 20 \text{ K}$ ) resistance of  $\text{UAl}_2$  and  $\text{UPt}_3$  and have found  $R \propto T^{3/2}$  in all cases. However, in light of the high residual resistance ratios of our samples, it is not clear that this represents a confirmation of Riseborough's prediction. Indeed, as we shall discuss momentarily, the measured low-temperature dependence may not be a true representation of the ideal (theoretical) resistance when, at higher temperatures, the resistance approaches a saturation limit.

The temperature-dependent resistance of  $\text{UAl}_2$  and  $\text{UPt}_3$  is reminiscent of that observed in  $A15$  compounds<sup>14</sup>

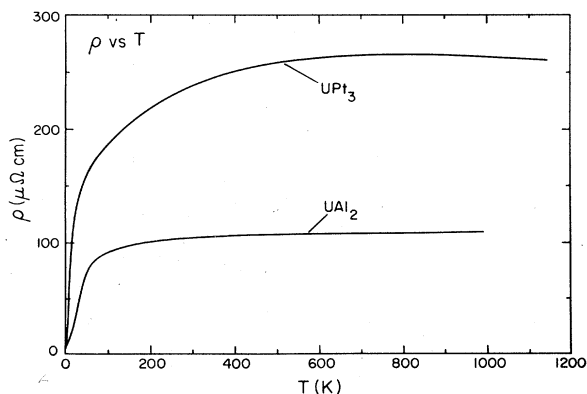


FIG. 3. Resistivity vs temperature for polycrystalline  $\text{UAl}_2$  and  $\text{UPt}_3$  at zero pressure.

and in some valence-fluctuation materials.<sup>15</sup> In these systems, it is believed that a resistivity saturation limit at high temperatures is reached when the electronic mean free path becomes comparable to an interatomic spacing.<sup>16</sup> Empirically, it has been found<sup>17,18</sup> that the measured resistance can be described reasonably well as the parallel combination of an ideal resistance  $R_i$  and a shunt resistance  $R_s$ , whose magnitude is near the saturation value, i.e.,

$$\frac{1}{R} = \frac{1}{R_i} + \frac{1}{R_s}. \quad (1)$$

Although not firmly established, there is some theoretical justification<sup>19</sup> for Eq. (1).

We have applied the "parallel resistor model" [Eq. (1)] to the data of Figs. 1 and 2. Using values of  $R_s > R$  (300 K, 0.1 kbar), we find that for each of the samples the "ideal" resistance at low temperatures is proportional to  $T^2$  over an appreciable temperature interval. These results are summarized in Figs. 4–6 where we plot  $R_i$  versus  $T^2$  for  $\text{UAl}_2$ ,  $\text{UPt}_3$   $c$  axis, and  $\text{UPt}_3$   $a$ - $b$  plane, respectively. The small deviation from  $T^2$  behavior near 4 K in Figs. 4–6 is an experimental artifact due to immersion of the pressure clamp into the liquid-helium bath. Therefore, when allowance is made for saturation effects, the ideal resistance exhibits a temperature dependence in agreement with that expected for a "clean" spin fluctuator. We also note in these figures a clearly systematic decrease in the slope of  $R_i$  versus  $T^2$  with increasing pressure that is similar for each sample.

If we assume that  $R_i$  in Figs. 4–6 accurately reflects the spin-fluctuation contribution to the resistance, then we may extract the pressure dependence of  $T_s$  from the slope  $\partial R_i / \partial T^2 = A / T_s^2$ . Because we do not have reliably quantitative resistivities for our samples and because theories are at best semiquantitative, we have chosen the proportionality constant  $A$  such that at  $P=0$  our value of  $T_s$  agrees with that determined from other measurements. Once the appropriate normalization is made at  $P=0$ , we assume that a reasonable description of  $T_s(P)$  is provided

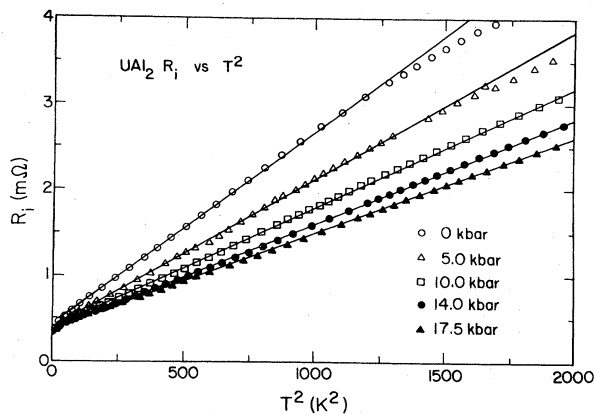


FIG. 4. Ideal resistance as a function of temperature squared for  $\text{UAl}_2$  at fixed pressures up to 17.5 kbar. For clarity, only a fraction of the data are shown. To determine the ideal resistance, the value used for  $R_s$  in Eq. (1) was 7 mΩ. Lines drawn through the points were used to determine  $\partial R_i / \partial T^2$ .

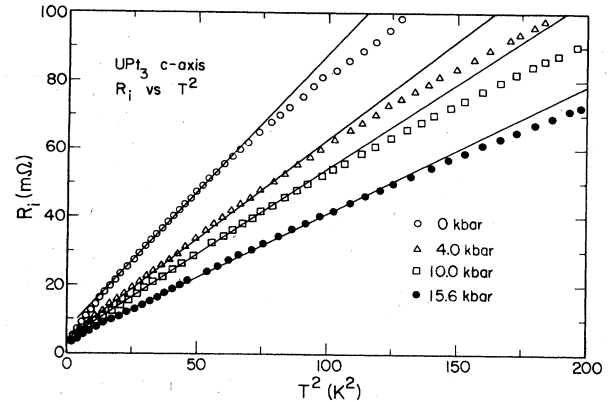


FIG. 5. Ideal resistance vs temperature squared for  $\text{UPt}_3$  measured along the  $c$  axis at fixed clamped pressures. For clarity, only a fraction of the data points are shown. The shunt resistance used in Eq. (1) was 300 mΩ. Lines drawn through the data were used to determine  $\partial R_i / \partial T^2$ .

through the pressure dependence of  $\partial R_i / \partial T^2$ .

Several recent measurements, e.g., specific heat,<sup>20</sup> susceptibility,<sup>21</sup> and magnetoresistance,<sup>21</sup> place  $T_s(P=0)$  at 25–30 K for  $\text{UAl}_2$ . We assume the value 26 K. The spin-fluctuation temperature of  $\text{UPt}_3$  is less clearly defined. Heat-capacity measurements<sup>22</sup> indicate a  $T_s$  of  $40 \pm 25$  K for single crystal  $\text{UPt}_3$ , while the magnetic susceptibility<sup>5</sup> shows a departure from Curie-Weiss behavior below  $\sim 25$  K in both the basal plane and along the  $c$  axis. Within the framework of a Fermi-liquid description of  $\text{UPt}_3$  (which appears to be quite reasonable), one expects the relationship  $\chi(T=0) = C / T_s$  to be valid,<sup>23</sup> where  $C$  is a constant. The large anisotropy in the  $T=0$  susceptibility of  $\text{UPt}_3$  (Ref. 5) would then imply that  $T_s$  for the  $c$  axis is about twice  $T_s$  in the  $a$ - $b$  plane. If we arbitrarily assume  $T_s(P=0) = 42$  K along the  $c$  axis, then  $T_s(P=0) \approx 20$  K in the basal plane. Because, to our knowledge, there is no theory that treats anisotropic spin-fluctuation scattering, we have no basis justifying this ap-

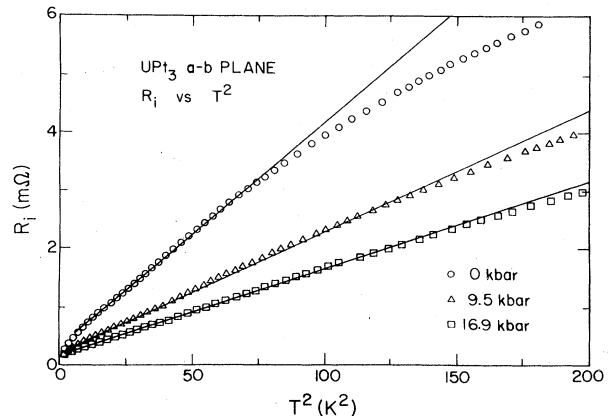


FIG. 6. Ideal resistance vs temperature squared for  $\text{UPt}_3$  measured in the  $a$ - $b$  plane at pressures up to 16.9 kbar. For clarity, only a fraction of the data points are shown. The shunt resistance used in Eq. (1) was 8.5 mΩ. Lines drawn through the points were used to determine  $\partial R_i / \partial T^2$ .

proach, although this procedure agrees qualitatively with experimental observations. We emphasize, however, that we attach no significance to the absolute values of  $T_s$  but are only using  $T_s$  to parametrize the spin-fluctuation characteristics of these materials.

The pressure dependence of the spin-fluctuation temperature, obtained as outlined above, is shown in Fig. 7. We see that  $T_s$  increases approximately linearly with pressure for all three samples, suggesting that decreasing the U-U separation drives these materials to a less magnetic state. Again using  $\chi(0) = C/T_s$ , we can infer the pressure dependence of  $\chi(T=0)$  from the slope  $\partial T_s / \partial P$ , i.e.,

$$\partial \ln \chi(0) / \partial P = -\partial \ln T_s / \partial P. \quad (2)$$

Application of Eq. (2) to the results on  $\text{UAl}_2$  shown in Fig. 7 gives

$$\partial \ln \chi(0) / \partial P |_{T \approx 0} = -24 \text{ Mbar}^{-1}.$$

This value agrees remarkably well with the average pressure dependence  $\partial \ln \chi / \partial P = -25 \text{ Mbar}^{-1}$  measured directly by Fournier and Beille<sup>8</sup> and lends credibility to our use of the simple scaling relationship between  $\chi(0)$  and  $T_s$ . We also point out that our result is *independent* of the value chosen for  $T_s(P=0)$ . Similar calculations for  $\text{UPt}_3$  yield  $\partial \ln \chi(0) / \partial P = -30$  and  $-36 \text{ Mbar}^{-1}$ , respectively, for the *c* axis and *a-b* plane. To the extent that Eq. (2) may be applied to  $\text{UPt}_3$ , these results imply that pressure suppresses the  $T=0$  susceptibility of  $\text{UPt}_3$  more rapidly than it does in  $\text{UAl}_2$  and that the pressure dependence is anisotropic but not to the extent of  $\chi(T=0, P=0)$  or the room-temperature resistivity. [As an aside, we note that a similar analysis of preliminary resistance measurements<sup>24</sup> on  $\text{TiBe}_2$  under pressure are also consistent with direct measurements<sup>25</sup> of  $\chi(P)$ .]

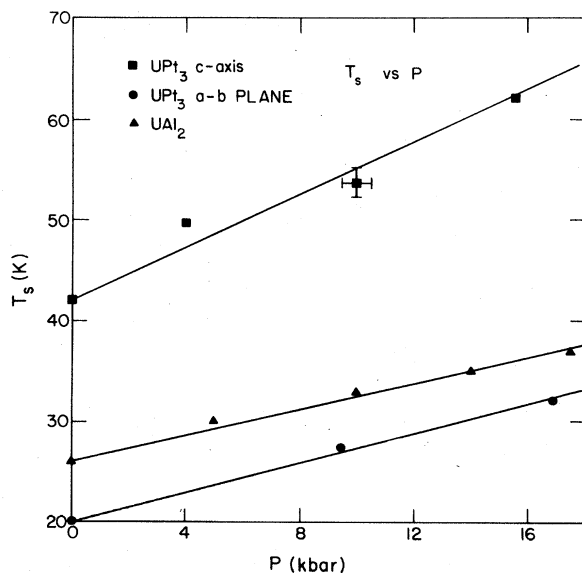


FIG. 7. Spin-fluctuation temperature as a function of pressure for  $\text{UAl}_2$ ,  $\text{UPt}_3$  *c* axis, and  $\text{UPt}_3$  *a-b* plane. Values for  $T_s$  were deduced from the data presented in Figs. 4–6 as outlined in the text.

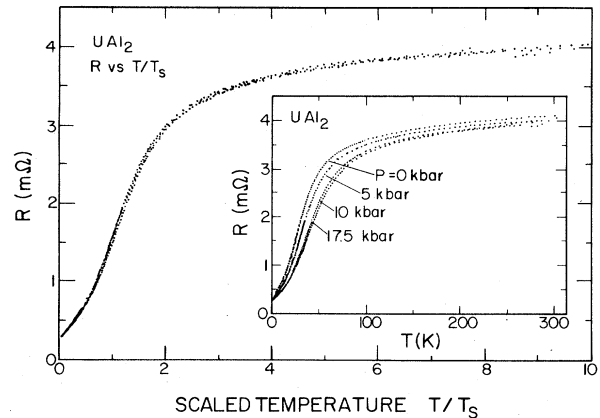


FIG. 8. Resistance vs temperature divided by the pressure-dependent spin-fluctuation temperature for  $\text{UAl}_2$ . Values for  $T_s(P)$  are given in Fig. 7. Note that this scaling maps all the data at different pressures, shown in the inset and in Fig. 1, onto a single curve.

Because of the way we have derived  $T_s(P)$ , we expect  $R(T, P)$  to be a function of scaled temperature  $T/T_s(P)$  over the interval in which  $R_i \propto T^2$ .<sup>12</sup> However, for  $\text{UAl}_2$  this scaling, shown in Fig. 8, holds to at least room temperature. That is, a plot of  $R$  versus  $T/T_s(P)$  maps all the different pressure curves (Fig. 1) onto a single, unique curve covering the entire temperature range. Such behavior suggests that the resistance is dominated by spin-fluctuation scattering and is consistent with the observation of Fournier and Beille<sup>8</sup> that the shape of  $\chi$  versus  $T$  is unchanged by pressures up to 6.65 kbar. For  $\text{UPt}_3$ , scaling is observed to 50 K for the *c* axis and to 70 K for the *a-b*—plane resistance. We note that quantitatively similar scaling is achieved by using the coefficient of  $T^{3/2}$  temperature dependence of the *measured* resistance. Departure from scaling at relatively lower temperatures in  $\text{UPt}_3$  may arise from (1) the presence of additional scattering mechanisms, e.g., electron-phonon scattering and/or whatever is responsible for the high-temperature peak in the resistance, (2) a temperature-dependent  $T_s$ , (3) thermally induced mixing of the anisotropic spin-fluctuation scattering, or (4) possible combinations of the above.

#### IV. CONCLUSIONS

We have shown that the pressure dependence of the resistance in  $\text{UAl}_2$  and  $\text{UPt}_3$  is consistent with an increase in the spin-fluctuation temperature and a concomitant decrease in magnetic scattering as the U-U separation becomes smaller. Using a Fermi-liquid description of these materials, we have presented a new method allowing a determination of  $\partial \ln \chi(0) / \partial P$  from resistance measurements on spin-fluctuation materials that is independent of a precise knowledge of  $T_s(P=0)$ . Results so obtained are

in very good agreement with direct determinations. Finally, we have discovered rather remarkable scaling of the resistance over an extended temperature interval. However, why the scaling regimes in  $\text{UAl}_2$  and  $\text{UPt}_3$  differ by a factor of 4–5 in apparently similar materials remains an open question. We hope that these results will stimulate additional experimental and theoretical investigations leading to a better understanding of spin-fluctuation behavior in these interesting materials.

*Note added in proof.* In further support of our observations, we note that others<sup>9,26</sup> have found the coefficient of the  $T^2$  term in the resistivity to decrease with increasing pressure. In addition, a recent measurement<sup>26</sup> of the pres-

sure dependence of  $\chi$  in polycrystalline  $\text{UPt}_3$  has given a value of  $\partial \ln \chi(0) / \partial P = -24 \text{ Mbar}^{-1}$ , in satisfactory agreement with our results.

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- <sup>1</sup>See, for example, B. Coqblin, J. R. Iglesias-Sicardi, and R. Julien, *Contemp. Phys.* **19**, 327 (1978), and references cited therein.
- <sup>2</sup>R. J. Trainor, M. B. Brodsky, and H. V. Culbert, *Phys. Rev. Lett.* **34**, 1019 (1975).
- <sup>3</sup>M. B. Brodsky, *Phys. Rev. B* **9**, 1381 (1974).
- <sup>4</sup>G. R. Stewart, Z. Fisk, J. O. Willis, and J. L. Smith, *Phys. Rev. Lett.* **52**, 679 (1984).
- <sup>5</sup>P. H. Frings, J. J. M. Franse, F. R. de Boer, and A. Menovsky, *J. Magn. Magn. Mater.* **21-24**, 240 (1982).
- <sup>6</sup>A. M. Boring, D. D. Koeling, R. C. Albers, and G. R. Stewart (unpublished).
- <sup>7</sup>R. C. Albers and A. M. Boring (unpublished).
- <sup>8</sup>J. M. Fournier and J. Beille, *J. Phys. (Paris) Colloq.* **4**, C-145 (1979).
- <sup>9</sup>A. deVisser, J. J. M. Franse, and A. Menovsky, *J. Magn. Mater.* **43**, 43 (1984).
- <sup>10</sup>J. D. Thompson, *Rev. Sci. Instrum.* **55**, 231 (1984).
- <sup>11</sup>M. S. Wire, Ph.D. thesis, University of California—San Diego, 1984.
- <sup>12</sup>P. Lederer and D. L. Mills, *Phys. Rev.* **165**, 837 (1968); A. B. Kaiser and S. Doniach, *Int. J. Magn.* **1**, 11 (1970); P. S. Riseborough, *Phys. Rev. B* **27**, 5775 (1983).
- <sup>13</sup>P. S. Riseborough, *Phys. Rev. B* **29**, 4134 (1984).
- <sup>14</sup>Z. Fisk and G. W. Webb, in *Treatise on Materials Science and Technology*, edited by F. Y. Fradin (Academic, New York, 1981), Vol. 21, p. 332.
- <sup>15</sup>See, for example, *Valence Instabilities*, edited by P. Wachter and H. Boppert (North-Holland, Amsterdam, 1982).
- <sup>16</sup>Z. Fisk and G. W. Webb, *Phys. Rev. Lett.* **36**, 1084 (1976).
- <sup>17</sup>H. Weissman, G. Gurvitch, H. Lutz, A. Ghosh, B. Schwartz, M. Strongin, P. B. Allen, and J. W. Halley, *Phys. Rev. Lett.* **38**, 782 (1977).
- <sup>18</sup>D. Muller, S. Hussain, E. Cattaneo, H. Schneider, W. Schlambitz, and D. Wohlleben, in *Valence Instabilities*, Ref. 15, p. 463; H. Schneider and D. Wohlleben, *Z. Phys. B* **44**, 193 (1981).
- <sup>19</sup>B. Chakroborty and P. B. Allen, *Phys. Rev. Lett.* **42**, 736 (1979); M. Gurvitch, *Phys. Rev. B* **24**, 7404 (1981).
- <sup>20</sup>G. R. Stewart, A. L. Giorgi, B. L. Brandt, S. Foner, and A. J. Arko, *Phys. Rev. B* **28**, 1524 (1983).
- <sup>21</sup>J. J. M. Franse, P. H. Frings, F. R. de Boer, A. Menovsky, C. J. Beers, A. P. J. Van Deursen, H. W. Myron, and A. J. Arko, *Phys. Rev. Lett.* **48**, 1749 (1982).
- <sup>22</sup>G. R. Stewart (private communication); see also Ref. 4.
- <sup>23</sup>J. M. Lawrence, P. S. Riseborough, and R. D. Parks, *Rep. Prog. Phys.* **44**, 1 (1981).
- <sup>24</sup>J. D. Thompson, M. S. Wire, and Z. Fisk (unpublished).
- <sup>25</sup>W. Gerhardt, J. S. Schilling, H. Olijnyk, and J. L. Smith, *Phys. Rev. B* **28**, 5814 (1983).
- <sup>26</sup>J. J. M. Franse, P. H. Frings, A. Menovsky, and A. de Visser, in *Electronic Structure and Properties of Rare Earth and Actinide Intermetallics*, St. Pölten, Austria, 1984 [*Physica B* (to be published)].