Resistivity of Some 5*d* Elements and Alloys Containing Iron*

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(Received 8 January 1968)

The resistivity has been measured as a function of temperature for Fe dissolved in Ir, and in some Os-Ir and Ir-Pt alloys. The resistivity due to the Fe has a strong anomalous temperature dependence which scales linearly with Fe concentration and changes gradually with host composition. No discontinuity in the behavior of the resistivity was found at Ir-Fe to correspond to the discontinuity in susceptibility observed by Geballe *et al.* The anomalous scattering persists in the Os-Ir alloys, where magnetic measurements indicate that no magnetic moment resides on the Fe impurities.

THE magnetic properties of dilute solutions of Fe in alloys made from the neighbor 5*d* transition elements Os, Ir, and Pt have been studied by Gegalle *et al.*[1] Although their data could not be interpreted on a simple localized moment model, it was concluded that the Fe atoms carry a magnetic moment when the 5*d* band is fuller than that of Ir (namely in the Ir-Pt alloys), and that Fe is at most weakly magnetic in pure Ir. It has been suggested[2,3] that the behavior of the susceptibility[1,4] and heat capacity[1] of the Ir-Fe system may be understood if one postulates a fairly high Kondo temperature for this system in the neighborhood of 100°K to room temperature.

The purpose of the present article is to present experimental results on the resistivity of alloys of the Os-Ir-Pt series containing Fe. The resistivity of all measured alloys decreases with decreasing temperature, and the anomalous scattering changes gradually as the alloy composition is varied through the series. Although the susceptibility[1] shows a discontinuous dependence on host composition at Ir-Fe, there is no corresponding discontinuity in the behavior of the resistivity.

EXPERIMENTAL PROCEDURE

The alloys were made by arc melting the constituent elements in an arc furnace. High-purity elements were used for all the alloys. Analyses of the Ir-Fe alloys showed only trace impurities, and the consistency of sample preparation is demonstrated by the fact that the excess resistivity per percent Fe was found to be the same for Ir containing $\frac{1}{2}$ and 1 at.% Fe. The samples of $(Os_{0.05}\,Ir_{0.95})_{0.99}\,Fe_{0.01}$, $(Ir_{0.95}\,Pt_{0.05})_{0.99}\,Fe_{0.01}$, and $(Ir_{0.90}\,Pt_{0.10})_{0.99}\,Fe_{0.01}$ were obtained from a different source. High-purity elements were used, but no trace analyses were performed.

Standard four-terminal techniques were used to measure the resistance of small rods cut from the arc-melted samples. Relative readings are accurate to better than 5×10^{-4} $\mu\Omega$ cm. Absolute values of the resistivity, however, are limited by sample dimensions and irregularities, and are accurate to no better than ±5% of the total resistivity for the Os-Ir and Ir-Pt alloys. Careful cutting and determination of sample dimensions yielded an accuracy of ±0.5% for the absolute value of the resistivity of the Ir alloys.

A germanium thermometer was used to measure temperatures to ±0.1°K. Measurements were taken between 1.35 and about 40°K, and at 77, 145.1, 191.7, 232.3, and 273°K, which are, respectively, the boiling points of nitrogen, freon-14, freon-13, freon-22, and the melting point of ice.

RESULTS AND DISCUSSION

The resistivity of pure Ir and of Ir containing $\frac{1}{2}$ and 1 at.% Fe is shown in Fig. 1. (Note the broken scale.) The resistivity of the pure metal is constant below about 20°K, and the rise above 20°K is attributable to phonon scattering. In contrast, the resistivity of the Ir-Fe alloys is temperature-dependent down to the lowest measured temperature. Figure 2 shows the excess resistivity per percent of Fe due to the presence of Fe impurity. Thus, the phonon resistivity has been

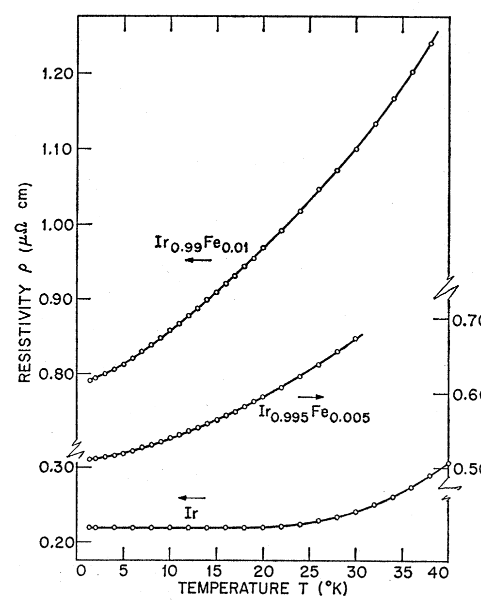

FIG. 1. Resistivity of Ir and of Ir containing $\frac{1}{2}$ and 1 at.% Fe as a function of temperature. (Note the broken scale.)

* Work supported by Air Force Office of Scientific Research, Office of Aerospace Research, under Grant No. AFOSR 894-67.
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[2] J. R. Schrieffer, J. Appl. Phys. **37**, 1143 (1967).
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subtracted and this excess resistivity would be a constant independent of temperature for an ordinary nonmagnetic impurity, except for possible small deviations from Matthiessen's rule at the higher temperatures. The curves for $\frac{1}{2}$ and 1 at.% Fe in Ir coincide above 10°K, but differ slightly below that temperature. Data for a 5 at.% Fe in Ir alloy are also shown, and it is apparent that it does not behave like the more dilute alloys, so that iron-iron interactions must play a significant role. Figure 3 presents data for the excess resistivity per percent Fe to 273°K, using data obtained for the $\frac{1}{2}$ and 1 at.% samples.

It is clear from these results that the resistivity due to the Fe in Ir-Fe alloys has a strong anomalous temperature dependence, and that it scales linearly with impurity concentration for concentrations below 1%. The anomalous or "magnetic" scattering decreases quite linearly as the temperature is decreased from 77 to about 10°K, and then begins to level off as the temperature is lowered further. The fact that the more dilute $\frac{1}{2}$ at.% Fe sample levels off more rapidly than the 1 at.% sample indicates that the deviation from linear behavior at low temperature does not result from the onset of cooperative effects between Fe impurity atoms, and is a real property of the noninteracting Fe impurities in dilute Ir-Fe alloys. The slope of the curve decreases at higher temperatures, as is shown in Fig. 3. It is possible that at least part of the temperature dependence in this temperature range is due to a change in the phonon scattering when Fe is dissolved in Ir. That is, it is possible that deviations from Matthiessen's rule account for part of the temperature dependence at temperatures above 77°K, as is often true in the case of nonmagnetic impurities. For instance, if the phonon-induced resistivity of Ir-Fe rises more steeply than that of pure Ir, then the subtraction of this effect would yield a curve which is flatter at high temperatures than that shown in Fig. 3, and the curve would have a more pronounced knee.

We now examine the behavior of the resistivity of alloys to which have been added Os or Pt, the neighbors of Ir directly to the left and directly to the right in the

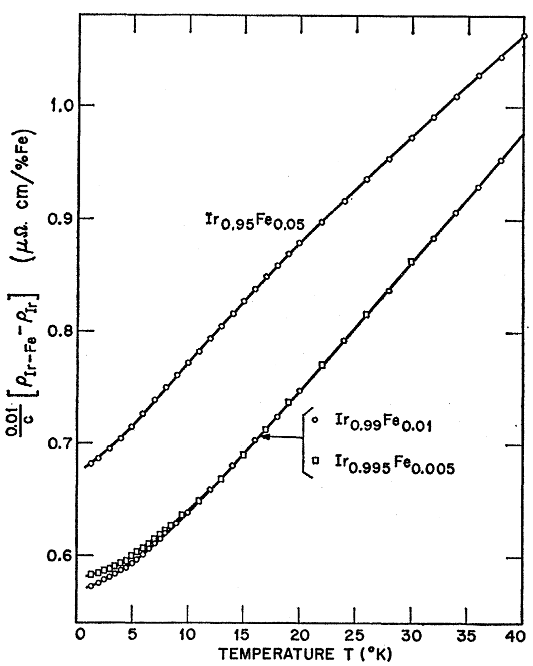

FIG. 2. Excess resistivity per percent Fe impurity in Ir, as a function of temperature. (c refers to iron concentration.)

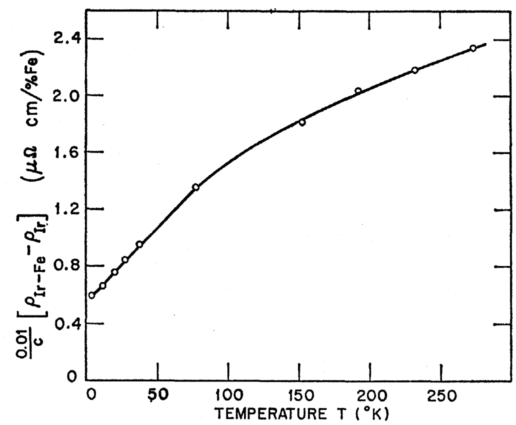

FIG. 3. Excess resistivity per percent Fe in Ir as a function of temperature. The curve represents data obtained for Ir containing $\frac{1}{2}$ and 1 at.% Fe. (c refers to iron concentration.)

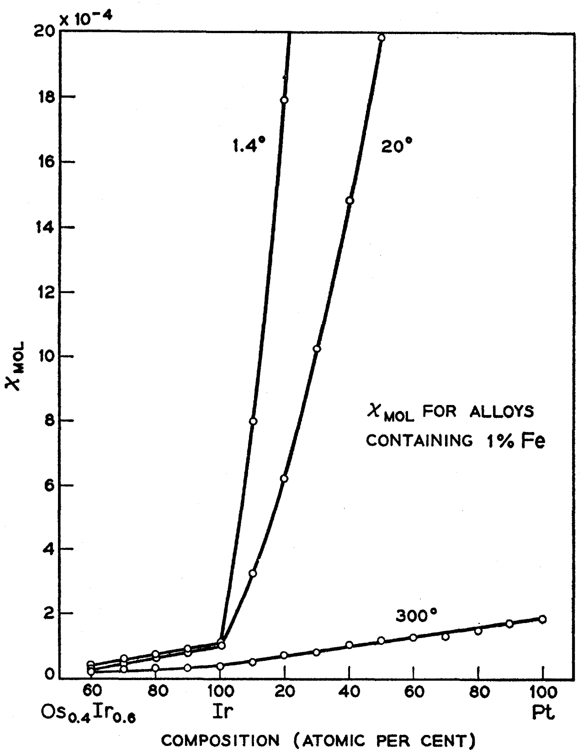

FIG. 4. Susceptibility/mole for 5d alloys containing 1 at.% Fe at three different temperatures, taken from paper by Geballe *et al.* (see Ref. 1).

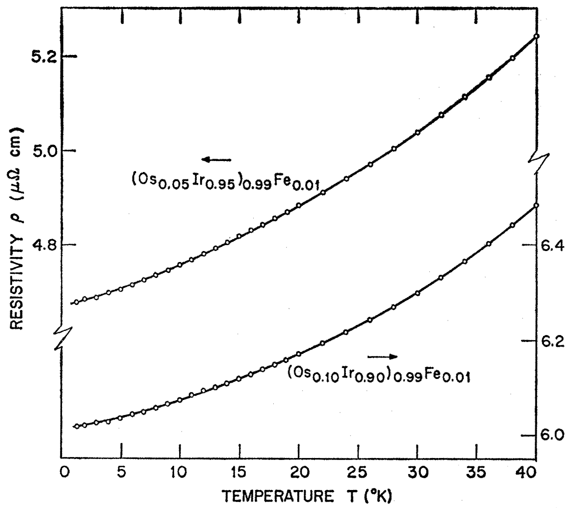

FIG. 5. Resistivity of two Os-Ir alloys containing 1 at.% Fe, as a function of temperature. (Note the broken scale.)

periodic table. Figure 4 shows data for susceptibility versus host composition, obtained by Geballe *et al.*[1] for 1 at.% Fe dissolved in the Os-Ir-Pt series. The behavior of the susceptibility changes abruptly at Ir, and the authors concluded from this and from heat-capacity data that Fe is a nonmagnetic impurity to the left of Ir and magnetic to the right.

Figure 5 presents the total resistivity of two Os-Ir alloys containing 1 at.% Fe, and Fig. 6 shows data for two Ir-Pt alloys containing 1 at.% Fe. Figure 7 gives the excess resistivity due to 1 at.% Fe in an Os-Ir and in an Ir-Pt alloy (i.e., the resistivity of the host Os-Ir and Ir-Pt alloys have been subtracted off, and the curves shown in Fig. 7 would be constants independent of temperature for a nonmagnetic impurity.) Although the resistivity changes gradually in character, it is clear that the resistivity of all the measured alloys is temperature-dependent down to the lowest measured temperature. Thus, it seems that the anomalous resistivity persists throughout the series, to the left as well as to the right of Ir, and that the anomalous scattering increases gradually as the host composition is varied toward the Pt side. This is to be contrasted with the sharp change in the behavior of the magnetic susceptibility with host composition as shown in Fig. 4. One may argue that the continuous change in resistivity can be explained by a model such as the one proposed by Jaccarino and Walker,[5] which uses near-neighbor statistics to account for the apparent continuous change in physical properties of such alloys. However, their model would also predict a gradual change in moment, which is not observed for this series. It is striking that anomalous scattering persists in the Os-Ir alloys, where magnetic measurements seem to indicate that no magnetic moment resides on the Fe impurities.

[5] V. Jaccarino and L. R. Walker, Phys. Rev. Letters **15**, 258 (1965).

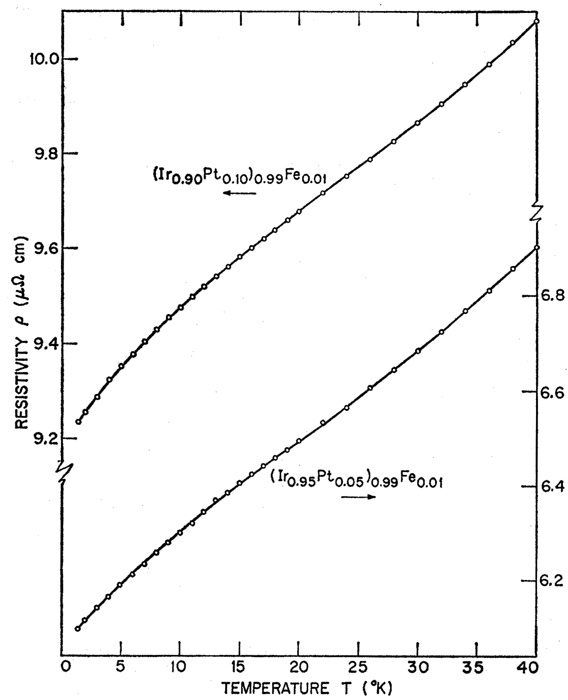

FIG. 6. Resistivity of two Ir-Pt alloys containing 1 at.% Fe, as a function of temperature. (Note the broken scale.)

A tentative explanation for the detailed behavior of the temperature dependence of the susceptibility and heat capacity of Ir-Fe was offered by Geballe *et al.*[1] Assuming an independent single-particle model, they postulated an extra density of states at the Fermi energy. Such an extra state or scattering resonance at

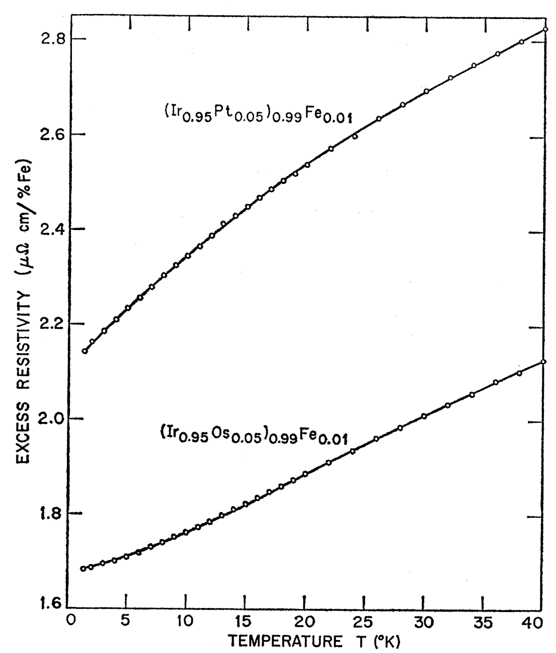

FIG. 7. Excess resistivity due to 1 at.% Fe dissolved in $Os_{0.05}Ir_{0.95}$ and in $Ir_{0.95}Pt_{0.05}$, as a function of temperature.

the Fermi energy, in order to account for the observed temperature dependence of the resistivity, must be of width kT which is comparable with the temperature at which the resistivity varies rapidly, i.e., of the order of 100°K for these alloys, or about 0.01 eV. So narrow a state would not be able to account for the temperature dependence of the resistivity of both the Os-Ir and Ir alloys, for which the Fermi energies differ by far more than 0.01 eV, unless the resonance were locked to the Fermi energy. This is not possible within a single-particle model. However, the many-body effects associated with the Kondo anomaly produce just such a resonance locked to the Fermi surface. In this sense, the behavior of the resistivity of these alloys clearly supports a many-body approach to the problem.

Most dilute alloys which exhibit a localized magnetic moment have a minimum in their ρ versus T characteristic.[6] In contrast, the Os-Ir-Pt alloys containing Fe have a resistivity which decreases with decreasing temperature. This behavior is similar to that observed for Fe or Co dissolved in the Ru-Rh-Pd series,[7,8] which are the corresponding 4d elements. Possible explanations for this behavior have been proposed by Knapp,[3] using a two-band model, and by Fischer[9] and Kondo.[10]

Measurements by Knapp[4] indicate that the susceptibility of Ir-Fe and Rh-Fe alloys deviates from a Curie law, and this effect can be interpreted in terms of a decreasing moment as the temperature is lowered. Knapp[3] suggests that the sharply decreasing resistivity in these alloys can be accounted for by assuming that near and below the Kondo temperature, it is the d electrons of the transition-metal host which reduce the moment by forming a spin-compensated state[11–13] with the magnetic impurity. The s electrons carry most of the current, and since they undergo spin-disorder scattering by a net moment which decreases, they contribute a resistivity which decreases as the temperature is lowered.

An alternative explanation is given in recent calculations which do not use a two-band model. Fischer[9] and Kondo[10] have shown that the resistivity may decrease with decreasing temperature as a result of the interference between exchange and ordinary potential scattering. A detailed calculation by Kondo and Appelbaum[14] based on this second alternative provides a good fit to the Ir-Fe resistivity versus temperature data shown in Fig. 3 over the entire temperature range.

It is possible that the Kondo temperature T_K is of the order of 100°K for Ir-Fe, since this is approximately where the resistivity deviates from its low-temperature linear behavior. If the excess resistivity due to Fe in Ir shown in Fig. 3 represents a universal curve of magnetic scattering as a function of T/T_K, then the behavior of the resistivity due to Fe as one varies host composition from Os to Ir to Pt may be interpreted in terms of a continuously decreasing Kondo temperature as one moves through the system filling the d band. Thus, for an Os-Ir alloy which might have a high Kondo temperature, one would observe an expanded version of the low-temperature behavior shown in Fig. 3. As Os is removed and Pt added to the host, the Kondo temperature would decrease, and the knee which appears at about 100°K in Fig. 3 would gradually move down into the measured range of temperature. The data shown in Fig. 7 support this view in a qualitative way. However, no definite or quantitative conclusions can be drawn since the data do not extend over a wide enough temperature range, and the error incurred when the host resistivity is subtracted is more serious for the Os-Ir and Ir-Pt alloys than in the case of the Ir alloys.

ACKNOWLEDGMENTS

The author wishes to thank J. Kondo and J. Appelbaum for the use of their paper prior to publication, D. R. Hamann and P. W. Anderson for many helpful discussions, and E. Corenzwit for the Ir-Fe samples. Special thanks are due D. R. Hamann for reading and commenting on the manuscript prior to publication.

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