

interband tunneling operator is nonlocal [Eq. (40)] and therefore is not quite so affected by the fact that where one wave function is large, the other is small. The second reason for the dominance of the indirect mechanism is

of course that there is a nearby band of intermediate states to be mixed in by the nonlocal operator.

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Effective Hyperfine Fields at the Nuclei of Os and Pt Dissolved in Fe*

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The heat capacities of two alloys containing, respectively, 0.75 at.% Os and 3.21 at.% Pt dissolved in Fe have been measured from 0.08 to 1.15°K. From the coefficients of the T^{-2} terms, the hyperfine fields at the nuclei were found to be 1400 kOe for Os and 1390 kOe for Pt.

IN recent years a number of experimental techniques have been used to measure the product of the nuclear magnetic-dipole moment μ and the effective magnetic hyperfine field H_e for a dilute impurity in a ferromagnetic metal. The results are of interest because they give information about nuclear moments and also because a systematic study of H_e values may contribute to a better understanding of ferromagnetism. The calorimetric determination of μH_e is based on measurement of the contribution to the hyperfine heat capacity associated with the impurity nuclei. For 1 mole of sample, and at temperatures $T \gg \mu H_e/k$ (k is Boltzmann's constant), this contribution C is given by

$$\frac{C}{fR} = \frac{1}{3} \left\langle \frac{I+1}{I} \mu^2 \right\rangle_{\text{av}} \left(\frac{H_e}{kT} \right)^2 - \frac{1}{30} \left\langle \frac{(I+1)(2I^2+2I+1)}{I^3} \mu^4 \right\rangle_{\text{av}} \left(\frac{H_e}{kT} \right)^4 + \dots, \quad (1)$$

where f is the atomic fraction of impurity, R is the gas constant, I is the nuclear spin, and the average is taken over the isotopic composition of the impurity. The calorimetric method is limited to alloys for which the contribution from nuclei of the impurity is large relative to that from nuclei of the host metal, but it is a useful complement to the methods based on nuclear orientation and the Mössbauer effect, each of which can also be used only in certain cases. Furthermore, Eq. (1) involves μ for the nuclear ground state, which is usually known, whereas the nuclear orientation method—and in some cases the Mössbauer method—give the product of H_e and μ for an excited state. A combination of two experiments may therefore give both H_e and the ex-

cited-state μ . We present here a calorimetric determination of H_e for Os and Pt dissolved in Fe.

An alloy of iron with 3.21 at.% Pt was prepared by melting 99.999% iron sponge and 99.9% Pt foil chips in a helium atmosphere, and was homogenized by annealing for 20 h at 1300°C. A sample containing 0.75 at.% Os in iron of the same purity was supplied by Johnson, Matthey and Company, Ltd. The heat-capacity measurements were carried out in the temperature range 0.08 to 1.15°K with an apparatus previously described by O'Neal and Phillips.¹

The experimental data were analyzed by plotting CT^2 versus T^3 , as shown in Figs. 1 and 2. The straight-line regions of these plots gave the T^{-2} and T terms in the heat capacities,

$$C(\text{mJg}^{-1} \text{deg}^{-1}) = 8.36 \times 10^{-2} T + 1.12 \times 10^{-4} T^{-2} \quad (2)$$

for 0.75 at.% Os in Fe, and

$$C(\text{mJg}^{-1} \text{deg}^{-1}) = 8.25 \times 10^{-2} T + 1.40 \times 10^{-3} T^{-2} \quad (3)$$

for 3.21 at.% Pt in Fe. The observed T^{-2} terms were corrected by subtracting the contribution expected for the Fe nuclei in pure iron (the corrections were 3.3% and 0.25% for the Os and Pt samples, respectively) and were then used to calculate H_e values by comparison with Eq. (1). The comparison was based on the following data² for the isotopic abundances, spins, and nuclear moments: 1.64% Os¹⁸⁷ with $I = \frac{1}{2}$, $\mu = 0.12$ nm; 16.1% Os¹⁸⁹ with $I = \frac{3}{2}$, $\mu = 0.6507$ nm; 33.8% Pt¹⁹⁵ with $I = \frac{1}{2}$, $\mu = 0.6004$ nm. The resulting values of H_e —1400 kOe for Os and 1390 kOe for Pt—were used to calculate the expected T^{-4} terms in the heat capacity. (The contributions of the Fe nuclei to the T^{-4} terms are completely negligible.) On this basis, the hyperfine heat

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¹ H. R. O'Neal and N. E. Phillips, Phys. Rev. **137**, A748 (1965).

² D. Strominger, I. M. Hollander, and G. T. Seaborg, Rev. Mod. Phys. **30**, 585 (1958).

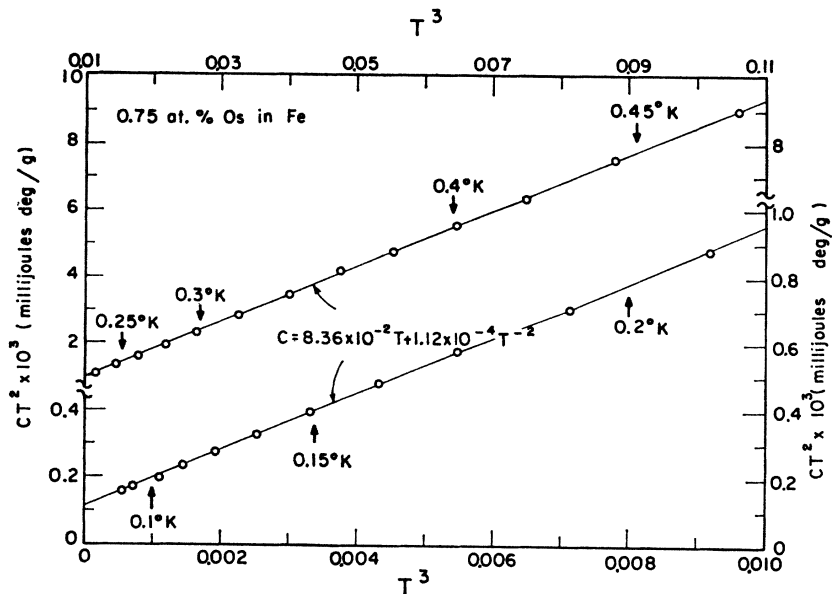


FIG. 1. The heat capacity of an alloy of 0.75 at.% Os in Fe.

capacities of the *solute nuclei alone* are

$$C(\text{mJg}^{-1} \text{deg}^{-1}) = 1.08 \times 10^{-4} T^{-2} - 4.53 \times 10^{-8} T^{-4} \quad (4)$$

and

$$C(\text{mJg}^{-1} \text{deg}^{-1}) = 1.40 \times 10^{-3} T^{-2} - 1.31 \times 10^{-6} T^{-4} \quad (5)$$

for the Os-in-Fe and Pt-in-Fe samples, respectively. As shown in Fig. 2, the expected T^{-4} term is in good agreement with experiment for the Pt-in-Fe sample. For the Os-in-Fe sample, the expected T^{-4} term is 2% of the total heat capacity at 0.1°K, which is only slightly more than the scatter in the data. It is difficult to put limits on the accuracy of the H_e values; we expect an error of no more than 2% in the total heat capacity near 0.1°K,

which would introduce a comparable error in H_e , but errors associated with the presence of trace quantities of elements with large nuclear moments might add to the error. It seems unlikely that changes in H_e at Fe nuclei brought about by the presence of the Os or Pt impurities would contribute significantly to the error.

In Table I we have compared the H_e values for Os and Pt with those for neighboring third-transition-group elements, all in dilute solution in Fe. For Os, Ir, Pt, and Au, the values are approximately the same, but for W and Re the values are smaller by approximately a factor of 2.

The Mössbauer effect has been observed for the 99-keV ($I = \frac{3}{2}$) state of Pt^{195} dissolved in Fe, but the ex-

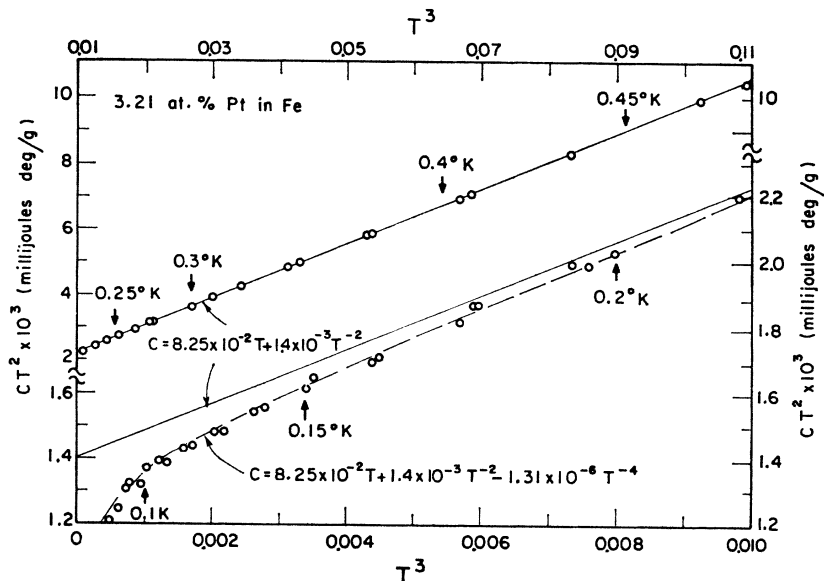


FIG. 2. The heat capacity of an alloy of 3.21 at.% Pt in Fe. The dashed curve represents the T^{-4} term calculated from the observed T^{-2} term.

TABLE I. Hyperfine fields at the nuclei of third-transition-group elements dissolved in iron. For W, Os, and Pt, the sign of H_e is not determined by the experiments. For Re and Ir, the sign of H_e has been determined in separate experiments based on anisotropy of β rays from polarized nuclei.^a

Alloy	H_e at solute nucleus (kOe)	Method ^b	Reference
W-Fe	760	ME	c
Re-Fe	-610	C	d
	-670	C	e
Os-Fe	1400	C	This work
Ir-Fe	-1350	C	e
Pt-Fe	1390	C	This work
Au-Fe	-1420	ME	f

^a A. V. Kogan, V. D. Kul'kov, L. P. Nikitin, N. M. Reinov, M. F. Stel'mach, and M. Schott, Zh. Eksperim. i Teor. Fiz. **43**, 828 (1962) [English transl.: Soviet Phys.—JETP **16**, 586 (1963)].

^b Method: ME = Mössbauer effect; C = heat capacity.

^c E. Kankeleit, Bull. Am. Phys. Soc. **10**, 65 (1965).

^d O. V. Lounasmaa, C. H. Cheng, and P. A. Beck, Phys. Rev. **128**, 2153 (1962).

^e A. V. Kogan, V. D. Kul'kov, L. P. Nikitin, N. M. Reihov, and M. F. Stel'mach, Zh. Eksperim. i Teor. Fiz. **45**, 1 (1963) [English transl.: Soviet Phys.—JETP **18**, 1 (1964)].

^f R. W. Grant, M. Kaplan, D. A. Keller, and D. A. Shirley, Phys. Rev. **133**, A1062 (1964).

pected six-line spectrum is incompletely resolved,^{3,4} and no unambiguous assignment of H_e and the excited-state moment μ_{exo} has been made. Experiments on 10 at.% Pt in Fe give⁵ $1200 \text{ kOe} \leq H_e \leq 2900 \text{ kOe}$ and -0.8

³ G. M. Rothberg, N. Benczer-Koller, and I. R. Harris, Rev. Mod. Phys. **36**, 357 (1964).

⁴ A. B. Buyrn and L. Grodzins, Bull. Am. Phys. Soc. **9**, 410 (1964).

⁵ N. Benczer-Koller, G. M. Rothberg, and J. R. Harris, Physics Department, Rutgers University (private communication).

$\text{nm} \leq \mu_{\text{exo}} \leq 0.17 \text{ nm}$. The value of H_e reported here, therefore suggests the assignment $\mu_{\text{exo}} \approx -0.7 \text{ nm}$.

Cameron *et al.*⁶ have measured the temperature dependence of the γ -ray anisotropy from 4.7-sec Ir^{191m} formed in the decay of Os^{191} , which was dissolved in Fe. The interpretation of their experiment depends on whether the spin-lattice relaxation time of Ir in Fe is greater than or less than 4.7 sec. If it is much greater than 4.7 sec., the observed anisotropy is characteristic of the Os^{191} , and the assumption of the Schmidt single-particle value of the magnetic moment for the excited state leads to the assignment $H_e = 5000 \text{ kOe}$. Cameron *et al.* concluded that this was unreasonably high, that the relaxation time must be smaller than 4.7 sec., and that the observed anisotropy was characteristic of Ir^{191m} . They then used the value of H_e for Ir in Fe quoted in Table I to calculate $|\mu| = 7.3 \pm 1.5 \text{ nm}$ for Ir^{191m} , which is in reasonable agreement with theoretical predictions. The value of H_e for Os in Fe reported here supports their analysis to the extent of showing that H_e for Os in Fe is in fact much less than 5000 kOe.

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⁶ J. A. Cameron, I. A. Campbell, J. P. Compton, and R. A. G. Lines, Phys. Letters **10**, 24 (1964).