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### Publication Date

1965-05-01

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**Berkeley, California**

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UCRL-16119

UNIVERSITY OF CALIFORNIA  
Lawrence Radiation Laboratory  
Berkeley, California

AEC Contract No. W-7405-eng-48

EFFECTIVE HYPERFINE FIELDS AT THE  
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May 1965

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.

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\*Work supported by the U. S. Atomic Energy Commission.

†Alfred P. Sloan Research Fellow 1962-64. We are grateful to the Alfred P. Sloan Foundation for this support during the period in which the experiments were carried out.

In recent years a number of experimental techniques have been used to measure the product of the nuclear magnetic-dipole moment  $\mu$  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  $\mu H_e$  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

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

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  $\mu$  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  $\mu$  for an excited state. A combination of two experiments may therefore give both  $H_e$  and the excited-state  $\mu$ . 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 Co., 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.<sup>1</sup>

The experimental data fit the equations

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

for 0.75 at.% Os in Fe, and

$$C(\text{mJ g}^{-1} \text{ deg}^{-1}) = 8.25 \times 10^{-2} T + 1.4 \times 10^{-3} T^{-2} - 1.31 \times 10^{-6} T^{-4} \quad (3)$$

for 3.21 at.% Pt in Fe, as shown in Figs. 1 and 2. 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 data<sup>2</sup> for the isotopic abundances, spins, and nuclear moments: 1.64% Os<sup>187</sup> with  $I = \frac{1}{2}$ ,  $\mu = 0.12$  nm; 16.1% Os<sup>189</sup> with  $I = \frac{3}{2}$ ,  $\mu = 0.6507$  nm; 33.8% Pt<sup>195</sup> 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. For the Pt in Fe sample the calculated  $T^{-4}$  term is that given in Eq. (3) and fits the data within the precision of the measurement. For the Os in Fe sample, at 0.1°K, the calculated  $T^{-4}$  term amounts to only 2% of the total heat capacity, which is only slightly more than the scatter in the experimental points. 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, or large changes in  $H_e$  at Fe nuclei brought about by the presence of the Os or Pt impurities, might add 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 two.

The Mössbauer effect has been observed for the 99-keV ( $I = 3/2$ ) state of Pt<sup>195</sup> dissolved in Fe, but the expected six-line spectrum is incompletely resolved,<sup>3,4</sup> and no unambiguous assignment of  $H_e$  and the excited-state moment  $\mu_{exc}$  has been made. Experiments on 10 at.% Pt in Fe give<sup>5</sup>  $1200 \text{ kOe} \leq H_e \leq 2900 \text{ kOe}$  and  $-0.8 \text{ nm} \leq \mu_{exc} \leq 0.17 \text{ nm}$ . The value of  $H_e$  reported here therefore suggests the assignment  $\mu_{exc} = -0.7 \text{ nm}$ .

Cameron et al.<sup>6</sup> have measured the temperature dependence of the  $\gamma$ -ray anisotropy from 4.7-sec Ir<sup>191m</sup> formed in the decay of Os<sup>191</sup>, 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<sup>191</sup>, 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<sup>191</sup>. 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<sup>191m</sup>, 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.

We are grateful to J. A. Cameron for providing the Os-Fe sample and suggesting the experiment, and to N. Benczer-Koller, G. M. Rothberg, and J. R. Harris for communicating the result of their measurement in advance of publication.



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  $\beta$  rays from polarized nuclei.<sup>a</sup>

Alloy	$H_e$ at solute nucleus (kOe)	Method <sup>b</sup>	Reference
W-Fe	760	ME	c
Re-Fe	610 670	C C	d 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) [Translation: Soviet Phys-JETP 16, 586 (1963)].

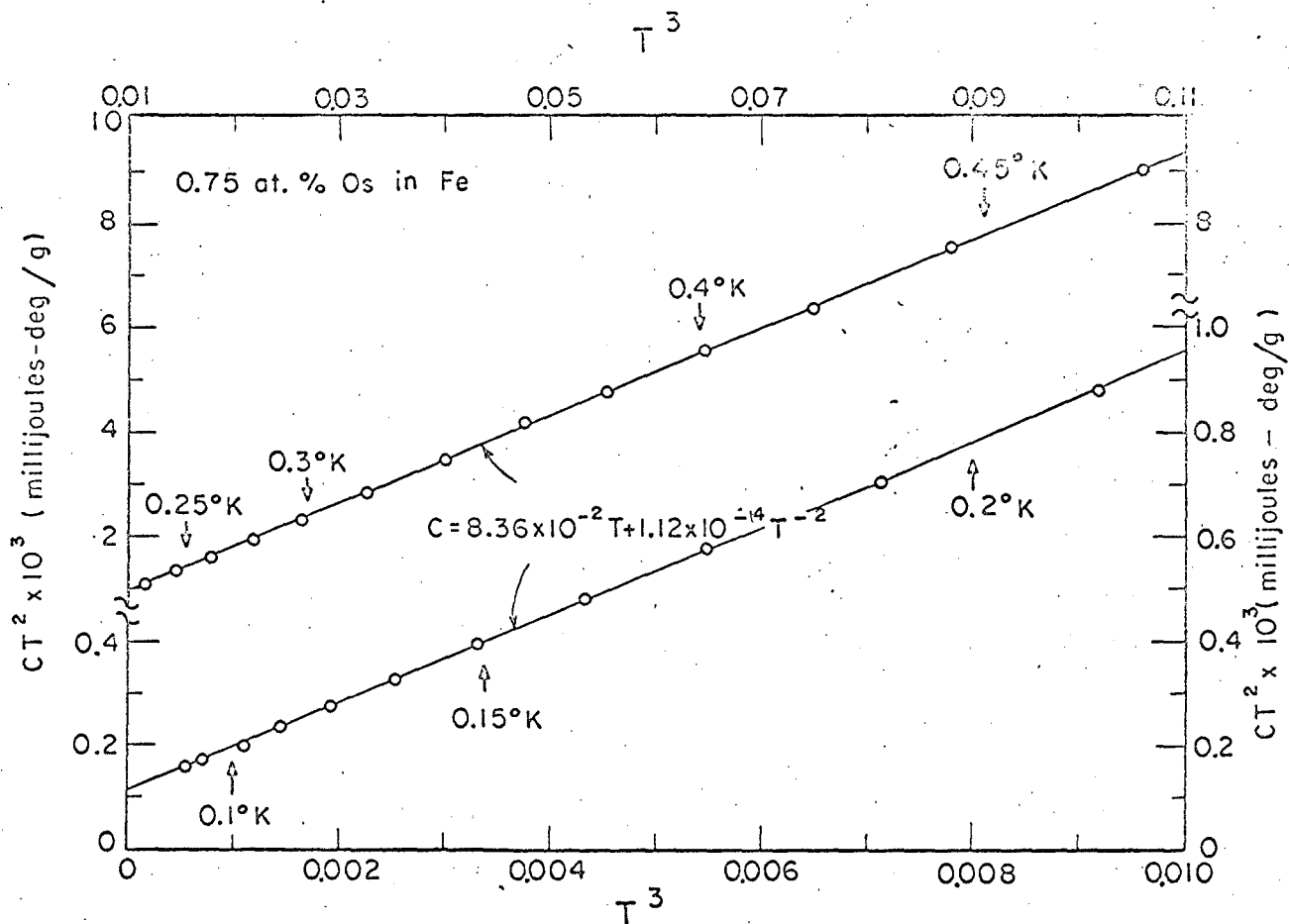
b. Method: ME = Mössbauer effect;  
C = heat capacity.

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).

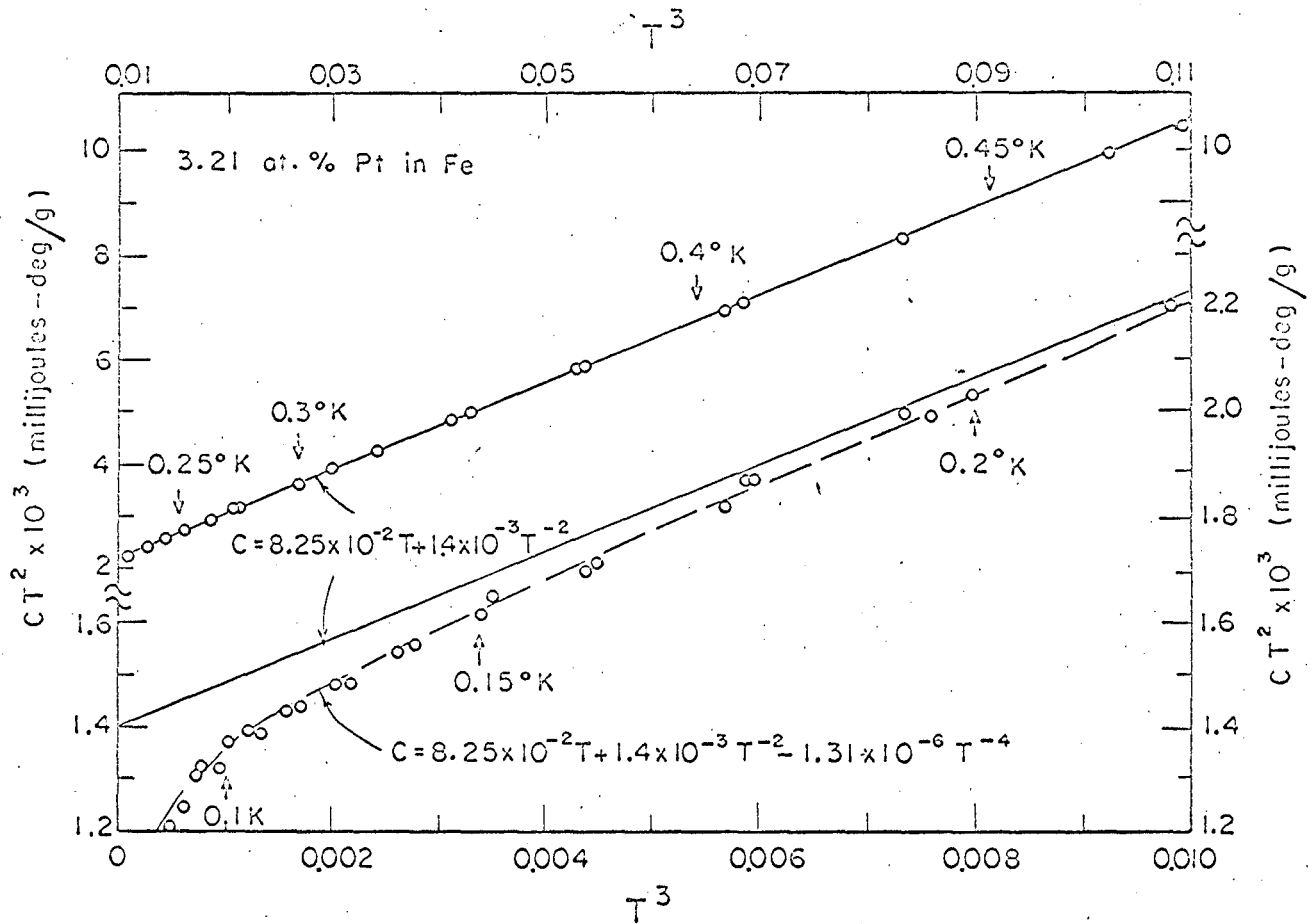
e. A. V. Kogan, V. D. Kul'kov, L. P. Nikitin, N. M. Reinov, and M. F. Stel'makh, Zh. Eksperim. i Teor. Fiz. 45, 1 (1963) [Translation: Soviet Phys.-JETP 18, 1 (1964)].

f. R. W. Grant, M. Kaplan, D. A. Keller, and D. A. Shirley, Phys. Rev. 133, 1062 (1964).



MUB-4799

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



MUB-4800

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.

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5. N. Benczer-Koller, G. M. Rothberg, and J. R. Harris (Physics Department, Rutgers University), private communication.
6. J. A. Cameron, I. A. Campbell, J. P. Compton, and R. A. G. Lines, Phys. Letters 10, 24 (1964).

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