

FIG. 2. The angular momentum of the helium ( $L$ ) compared to the classical value ( $L_c$ ) as a function of temperature. Circles are the present experiment and the dashed curve is Pellam's result (reference 1). The rotational velocity in all runs was near 2 rpm.

The most obvious difference between our technique and that of Pellam lies in the fact that his Rayleigh disk provides a semimicroscopic measure of the velocity field whereas ours provides an average over such a field. But this fact alone can hardly explain the vast difference in results which the two experiments show. It must be pointed out that earlier experiments on angular momentum by

Hall<sup>3</sup> and Walmsley and Lane<sup>4</sup> are at variance with both of the above experiments and, of course, with the theory. Plausible, though not entirely certain, reasons can be advanced to explain this discrepancy with our present result but not, at all obviously, with Pellam's.

The present experiment is the only one of those cited which is in concordance with current theories of He II. Further, our method appears to subject the helium to much less extraneous disturbance, such as induced turbulence in the liquid, than do any of the others. We suggest, in consequence, that Pellam's result is possibly connected with some such extraneous effect.

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<sup>1</sup>J. R. Pellam, Phys. Rev. Letters **5**, 189, 282(E) (1960).

<sup>2</sup>R. P. Feynman, Progress in Low-Temperature Physics, edited by J. C. Gorter (Interscience Publishers, New York, 1955), Vol. 1.

<sup>3</sup>H. E. Hall, Trans. Roy. Soc. (London) **250**, 359 (1957).

<sup>4</sup>R. H. Walmsley and C. T. Lane, Phys. Rev. **112**, 1041 (1958).

## MAGNETIC MOMENT OF TRANSITION METAL ATOMS IN DILUTE SOLUTION AND THEIR EFFECT ON SUPERCONDUCTING TRANSITION TEMPERATURE

B. T. Matthias, M. Peter, H. J. Williams, A. M. Clogston, E. Corenzwit, and R. C. Sherwood  
Bell Telephone Laboratories, Murray Hill, New Jersey

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We have found a decisive experiment which shows the conditions under which the magnetic moment of a transition metal atom remains localized when in dilute solution in another transition metal. We have correlated this effect with a drastic lowering of the superconducting transition temperature in a particular superconductor.

Some time ago a series of observations was reported which showed that the superconducting transition temperature of various metals and alloys could be greatly decreased by the presence of small amounts of rare earth metals.<sup>1</sup> This effect has been identified as due to an exchange interaction between the conduction electrons and the localized  $f$ -shell electrons.<sup>2</sup> In contrast to this behavior, it has been reported that the addition of transition metal impurities raises the superconducting temperature of titanium by an

order of magnitude<sup>3</sup> and that of zirconium somewhat less.<sup>4</sup> In the case of the fifth column elements vanadium and niobium, dilute transition-metal impurities lower the transition temperature in a way strictly in accord with the electron concentration.<sup>5</sup> This behavior is consistent with the fact that even large concentrations of iron dissolved in Ti, V, or Nb do not show any magnetic interaction or temperature-dependent susceptibility. As far as we are aware no localized moment has been observed for a transition-metal impurity in dilute solution in another transition metal of the fourth or fifth column.

In this paper we now report a strong lowering of the transition temperature of the superconducting alloy  $\text{Mo}_{0.8}\text{Re}_{0.2}$  by the solution of small amounts of metals belonging to the first-row transition series. These experiments are re-

conciled to those previously reported by showing that the 3d metals in dilute solution in metals of the fourth row acquire a magnetic moment abruptly between the fifth and sixth columns. This result is consistent with the fact that very dilute solutions of iron in palladium are known to become ferromagnetic with an effective moment for the iron exceeding two Bohr magnetons per atom.<sup>6</sup>

The sixth column element Mo is not a superconductor. To study the effects of 3d impurities upon transition metals in the sixth column and beyond, we have therefore made use of the molybdenum-rhenium alloys whose high superconducting transition temperatures were discovered by Hulm.<sup>7</sup> This temperature decreases linearly with iron concentration at a rate of 22° per atomic percent Fe. In these concentrations the addition of nonmagnetic elements has little effect. The specific depression is about 150 times greater in  $\text{Mo}_{0.8}\text{Re}_{0.2}$  than in the neighboring elements Nb and V.

Susceptibility measurements have been made on the  $\text{Mo}_{0.8}\text{Re}_{0.2}$  alloys with iron as an impurity which show a Curie-Weiss law for the susceptibility.<sup>8</sup> The constant  $c$  in the relation  $\chi = c/(T - T_C)$  is plotted in Fig. 1 as a function of concentration.

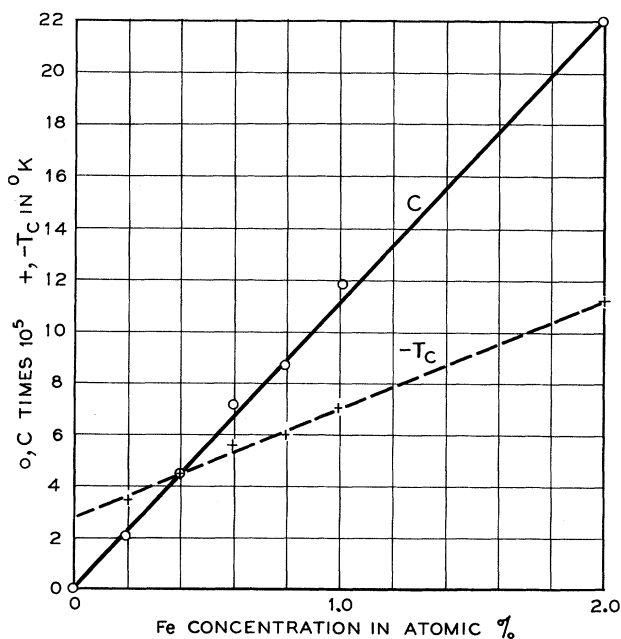


FIG. 1. The constant  $c$  in  $\chi = c/(T - T_C)$  corresponds to  $2.3\mu_B$  per atom of iron in  $\text{Mo}_{0.8}\text{Re}_{0.2}$ .  $T_C$  is negative and a smooth function of concentration (broken line).

From it we derive  $p = g[S(S+1)]^{1/2} = 3.2$ , which for  $S = 1$  leads to a saturation moment of  $2.3\mu_B$  per iron. We conclude that the lowering of the transition temperature of  $\text{Mo}_{0.8}\text{Re}_{0.2}$  by these impurities is due to an exchange interaction with the localized spin and is analogous to the effects produced by rare earth ions in lanthanum and other metals and alloys.<sup>1</sup> We have also plotted in Fig. 1 the Curie temperature  $T_C$  which turns out to be negative and a smooth function of the concentration.

Both niobium and molybdenum crystallize in a body-centered cubic structure and form a continuous series of solid solutions. The presence of a localized moment for iron atoms dissolved in  $\text{Mo}_{0.8}\text{Re}_{0.2}$ , and the absence of such a moment in Nb, suggests that a localized moment will appear somewhere in the series between Nb and Mo. In Fig. 2 we show the effective magnetic moment per iron atom,  $p$ , as a function of Mo concentration, obtained from susceptibility data taken on Nb - Mo solid solutions containing 1 atomic percent iron. An appreciable moment appears first at 50% Mo. The Nb - Mo alloys up

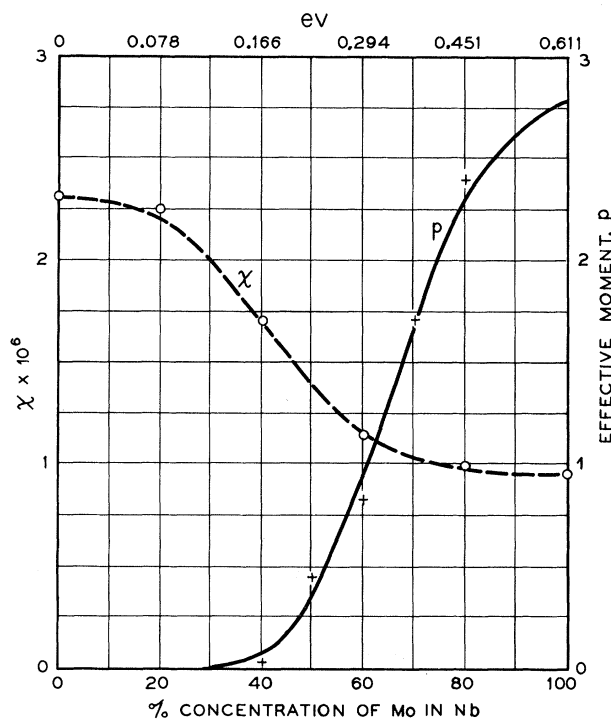


FIG. 2. Effective magnetic moment per iron atom,  $p$ , in Nb-Mo solutions containing 1 atomic percent Fe. The broken line gives the susceptibility at 300° in the absence of Fe. From it is derived the energy scale explained in the text.

to 30% Nb remain superconducting and no appreciable reduction in  $T_s$  due to the iron was observed in the present experiments, consistent with the conclusion advanced above.

We have also plotted in Fig. 2 the susceptibility  $\chi$  per gram of the Nb - Mo alloys without iron. If we assume that the susceptibility measures the density of states at the Fermi surface, we may relate an increase in the average number of electrons per atom  $N$  to an increase in the Fermi energy  $E_F$  by the relation  $\Delta E_F = \mu_B^2 \Delta N / \chi M_0 A$ , where  $M_0$  is the mass of an atom of unit atomic weight and  $A$  is the average atomic weight. The energy scale derived in this way is shown in Fig. 2.

The sharp rise in magnetic moment per atom seen in Fig. 2 is a remarkable new phenomenon and provides some insight into the electronic structure of iron present as an impurity in the Nb - Mo crystal. A possible interpretation of the observations is the following. Each iron atom has 5  $d$  states. Following suggestions by Mott and Stevens<sup>9</sup> that apply to the bcc structure, we may assume that 3 of these states of symmetry  $t_{2g}$  become part of the conduction band of the host lattice. The remaining two states of symmetry  $e_g$  we suppose to be only weakly coupled to surrounding wave functions and therefore essentially localized. For the alloys of less than 50% Mo we assume that the Fermi level lies below the  $e_g$  states and no moment is observed. Above 80% Mo we suppose that the Fermi level

has crossed these states and that they are occupied by two electrons whose spins align according to Hund's rule to give the observed moment. The antiparallel spin states will be split off by exchange and correlation energy so that they lie above the Fermi surface and are unoccupied. From the energy scale in Fig. 2 we may estimate the effective width of the  $e_g$  band to be about 0.3 ev.

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<sup>2</sup>H. Suhl and B. T. Matthias, Phys. Rev. **114**, 977 (1959).

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<sup>4</sup>B. T. Matthias and E. Corenzwit, Phys. Rev. **100**, 626 (1955).

<sup>5</sup>G. Busch and J. Müller, Proceedings of the Kamerlingh Onnes Conference on Low-Temperature Physics, Leiden, 1958 [Suppl. Physica **24**, S152 (1958)]. The explanation given by Busch and Müller for lowering of the transition temperature in V-Fe alloys has since been withdrawn (private communication).

<sup>6</sup>J. Crangle, Phil. Mag. **5**, 335 (1960).

<sup>7</sup>J. K. Hulm, Phys. Rev. **98**, 1539 (1955).

<sup>8</sup>Our samples were prepared by arc-furnace melting under an argon atmosphere. Our calculations are based on the percentage of iron added to the melt. While the linearity of the plot in Fig. 1 indicates internal consistency, there remains some uncertainty as to the calibration due to the possibility of iron losses from the melt.

<sup>9</sup>N. F. Mott and K. W. H. Stevens, Phil. Mag. **2**, 1364 (1957).

## EFFECT OF SPIN-ORBIT SPLITTING ON THE FERMI SURFACES OF THE HEXAGONAL-CLOSE-PACKED METALS\*

Morrel H. Cohen and L. M. Falicov

Institute for the Study of Metals, University of Chicago, Chicago, Illinois

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All theories of the electronic properties of metals and alloys having the hexagonal-close-packed (hcp) structure have supposed that the energy gaps vanish across the hexagonal face of the first Brillouin zone.<sup>1,2</sup> The simple argument based on the vanishing of the structure factor put forward first by Jones<sup>3</sup> was not correct for a general potential. A rigorous basis for the sticking together of the bands was provided by the symmetry properties and time-reversal arguments of Herring.<sup>4</sup> These were generalized to include spin-orbit coupling by Elliott for various

crystal structures.<sup>5</sup> In particular, one sees from his results that the degeneracy is removed at the point  $H$  and along the symmetry lines  $S$  and  $S'$ , but not at  $A$  and  $L$  nor along the line  $R$  (Fig. 1). The implications of Elliott's work for the electronic properties of hcp metals and alloys appear to have been overlooked. Two questions arise: How big is the splitting, and what modification of the existing theories is required?

We have extended Elliott's analysis to a general point in the plane, and have found, as expected, the degeneracy to be lifted. Near  $A$  the splitting