FERROMAGNETIC INTERACTION IN EuO

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We have found that a europium oxide of the formula EuO becomes truly ferromagnetic at 77°K with a saturation moment of close to 7 Bohr magnetons. This is thus the first rare earth oxide to be found to become ferromagnetic, and with the exception of CrO_2 the only oxide to our knowledge that has true ferromagnetic coupling.

We were led to this discovery by somewhat contradictory results on ferromagnetic intermetallic rare earth compounds.[1] There it was found that $EuIr_2$ becomes ferromagnetic near 70°K and has an extremely small saturation moment. It was clear from measurements of lattice constants of this cubic compound that europium had a $4f^6$ configuration corresponding to trivalent europium and so would not be expected to have a ferromagnetic moment.[2] A compound having a Curie point of 70°K and very small moment seemed to be a severe contradiction. One possible explanation was the presence of an impurity strongly ferromagnetic below 70°K. $EuIr_2$ had been formed in a quartz tube by having molten europium react with finely divided iridium powder, and the presence of oxides was thus a likely possibility. The magnetic behavior of Eu_2O_3 is known and normal. EuO was the other alternative.

The latter compound was formed by reacting stoichiometric amounts of Eu and Eu_2O_3 at 1220°C in a quartz tube. The product was a brown crystalline powder. X-ray examination by Mrs. V. B. Compton showed it to have a NaCl structure with a lattice constant of 5.141 A, corresponding to a density of 8.21. A few unidentified faint lines were present on the x-ray film. This lattice constant agrees with that previously reported for material obtained by the reduction of Eu_2O_3 with lanthanum metal.[3]

The existence of strong ferromagnetism in EuO, and a Curie point (77°) very near to that observed for $EuIr_2$ (70°) shows immediately that the presence of a few percent of EuO might easily give rise to the anomalous results obtained with $EuIr_2$.

As shown in Fig. 1, above the Curie point the susceptibility of EuO is represented within the experimental error by a formula of the type $\chi = C/(T-\theta)$, where the Curie constant C has the value $7.9N\beta^2/3k$ to be expected for an ^8S configuration. This fact shows unequivocally that the europium ion is divalent and isoelectronic with Gd^{+++} as one would expect from the degree of oxidation. The linearity of $1/\chi$ in T is, if anything, more accurate than one would expect, for the Weiss-Curie law is always but an approximation theoretically.

Figure 2 shows the data for the ferromagnetic region. The saturation at 0°K, determined by extrapolation linear in $1/H$, is 6.9 Bohr magnetons, and within the limits of error is equal to the theoretical $Jg = 7$. The broken line is that calculated for spontaneous magnetization using the Brillouin function for $J = 7/2$ with the parameter $a = (7/3) \times (M/M_0)/(T/\theta)$. At low temperatures the triangular points are obtained by extrapolation (using $1/H$) of the smoothed data for $H = 8$ and 12 koe at selected temperatures. Just below the Curie point (obtained by the Weiss-Forrer method, W.F. in the figure) the extrapolation is to $H = 0$, on the as-

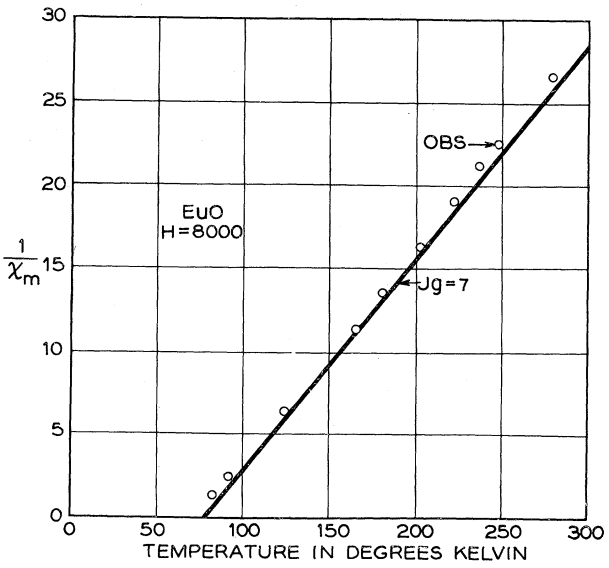

FIG. 1. Reciprocal molecular susceptibility of EuO: experimental points, and theoretical line drawn through ferromagnetic Curie point (77°K) with slope for $Jg = 7$, $\mu_{eff} = 7.94$.

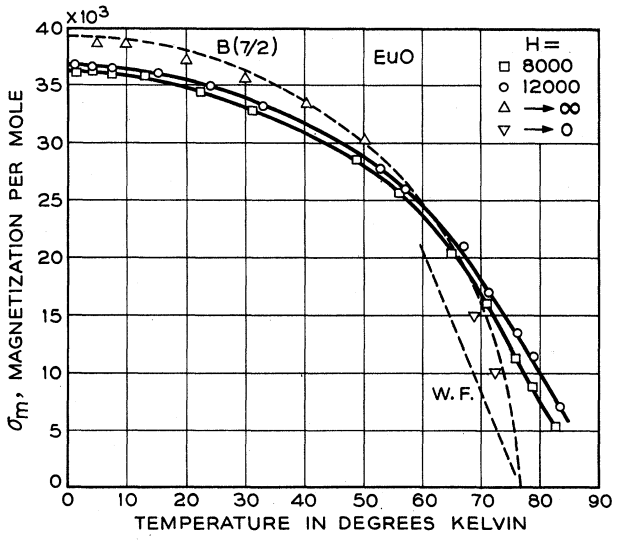

FIG. 2. Magnetization of EuO vs temperature in ferromagnetic region. Broken line, Brillouin curve for $J=\frac{7}{2}$, $\theta=77°$. Triangles, extrapolation of experimental data to $H=\infty$ (high M) or $H=0$ (low M). W.F., Weiss-Forrer extrapolation $(\sigma_m)_{H=0}$ vs T, to determine the Curie point.

sumption that here the crystal anisotropy is zero and the applied field increases the magnetization above the spontaneous value.

At low temperatures the magnetic moment per unit volume, based on 7β and a density of 8.25, is high:

$$4\pi M = 24\,100.$$

This may be compared with the values of $4\pi M$ for iron (21 700), gadolinium (about 25 000), and for metallic dysprosium[4] (about 38 000).

Measurement of the pressed powder on a megohm meter indicated a resistivity of 10^9 to 10^{10} ohms.

The measurements are of interest as furnishing one of the clearest examples of exchange interaction in a material in which the atomic orbitals are substantially the same as for the free ions, since this is always the case for $4f$ electrons in the middle of the rare earth period in nonconducting compounds.

We will not attempt to enter into the question of the precise mechanism responsible for the ferromagnetic exchange coupling. It is certainly not the Yosida mechanism resulting from the polarization of conduction electrons, since EuO is an insulator. Conceivably, direct overlap may be the cause, but in our opinion indirect exchange via excited states is more likely.

We are grateful to Mrs. V. B. Compton for permission to quote the results of her x-ray measurements on $EuIr_2$ and EuO.

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