The results are: Eu^{151}, $a' = 0.013°K$ ($= 270$ Mc/sec); Eu^{153}, $a' = 0.0057°K$ ($= 120$ Mc/sec).

Finally, it should be mentioned that our C_E and C_N results [cf. Eq. (9)] can be interpreted in a different way. The experimental C_E is in between the values $C_E = 10.5T$ and $C_E = 2.9T$ as observed for trivalent lanthanides[13] and for divalent ytterbium.[28] Similarly, our experimental C_N is near the mean of $C_N = 0$ and $C_N = 4.2T^{-2}$ as calculated by Bleaney[22] for Eu^{3+} and Eu^{2+}. In fact, if we assume that at low temperatures 43% of our sample showed trivalent and 57% divalent character and use the above values for C_E and C_N, we get (C_E and C_N in mJ/mole °K):

$$C_E = 0.43 \cdot 10.5T + 0.57 \cdot 2.9T = 6.2T, \qquad (12)$$

$$C_N = 0.57 \cdot 4.2T^{-2} = 2.4T^{-2}. \qquad (13)$$

These results agree well with our experimental C_E and C_N. The possibility that europium is at low temperatures a mixture of di- and trivalent phases is an interesting one, particularly in view of the magnetization measurements by Bozorth and van Vleck,[21] which were discussed earlier in this section. However, this interpretation is made less attractive by the excellent agreement of H_{eff}, calculated from our experimental C_N assuming 100% of Eu^{2+}, with the Mössbauer result of Barrett and Shirley,[31] and by the fact that electrical resistivity[17] and neutron diffraction[18] studies did not in Fig. 3 demonstrates quite conclusively that the average electronic specific heat of our europium sample is not as low as $C_E = 2.9T$ mJ/mole °K.

The present results reveal interesting possibilities for the behavior of europium metal at low temperatures. It would be particularly desirable to extend the measurements of C_p to higher temperatures in the hope of finding a heat capacity anomaly. If such an anomaly is found, magnetization measurements are also in order.

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Magnetization of Cubic Laves Phase Compounds of Rare Earths with Cobalt

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These compounds are strongly magnetic. For the heavier rare earths, the gross magnetic moment appears to arise from opposed alignment of the rare earth and the cobalt atoms. If we assume the rare earths to have characteristic localized magnetic moments Jg, the moments on the cobalt atoms are about 1.7 μ_B in the Tb, Dy, Ho, and Er compounds, a little less in the Gd compound, and zero in the Pr, Nd, and Sm compounds. The basic coupling mechanism is that of indirect exchange through the conduction electrons between rare-earth spins.

BINARY intermetallic compounds existing between rare-earth metals and cobalt, having the $MgCu_2$ (cubic Laves) type of structure have been found by Wernick and Geller.[1] We have measured the magnetization of most of the members of this series.

The compounds of cobalt with Ce, Pr, Nd, Sm, Gd, Tb, Dy, Ho, and Er were prepared by arc melting the pure constituents together in an argon atmosphere. Chemical analysis was not carried out, but the weight loss on melting the stoichiometric amounts was only 1.5% in the case of $CeCo_2$ and less than half this in all the others. Also, the measured lattice parameters which are shown in Table I agree well with those of Wernick and Geller.

Magnetizations (σ) were measured in the temperature range 10 to 430°K in ten different magnetic field strengths (H) between 6.2 and 17.6 kOe. They were measured using a Sucksmith ring balance,[2] relative to pure iron, to which the absolute data of Weiss and Forrer[3] were assumed to apply. Spontaneous magnetiza-

TABLE I. Lattice parameters in Å.

	Present work (±0.002)	Wernick and Geller[a] (±0.005)
$CeCo_2$	7.162	7.161
$PrCo_2$	7.305	7.312
$NdCo_2$	7.300	7.300
$SmCo_2$	7.260	7.260
$GdCo_2$	7.257	7.255
$TbCo_2$	7.209	7.206
$DyCo_2$	7.188	7.187
$HoCo_2$	7.168	7.168
$ErCo_2$	7.151	7.144

[a] See Ref. 1.

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[1] J. H. Wernick and S. Geller, Trans. AIME **218**, 806 (1960).

[2] W. Sucksmith, Proc. Roy. Soc. (London) **A170**, 551 (1939).

[3] P. Weiss and R. Forrer, Ann. Phys. (Paris) **12**, 297 (1929).

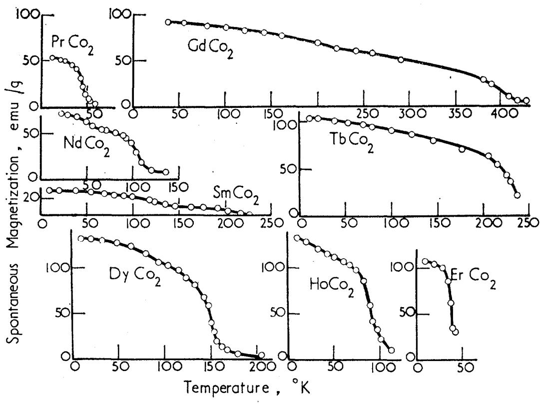

FIG. 1. Spontaneous magnetization, temperature curves for A Co_2 compounds, where A = rare earth.

tions at all temperatures were estimated by linear extrapolation to $H=0$ of the magnetization field isothermals. There is little uncertainty in the values of spontaneous magnetization derived in this way since the compounds are not magnetically very hard. Curie temperatures were also estimated using the technique of Belov and Goryaga[4] and Arrott[5] by finding the temperature at which the graph of H/σ against σ^2 was linear and passed through the origin.

Graphs of spontaneous magnetization against temperature are shown in Fig. 1. The inflections that occur in some of them appear to be real, and further work is in progress to try to elucidate their nature. They do not seem to be simple compensation points such as those found by Nesbitt *et al.*[6] in A Co_5 compounds (A = rare earth), nor do they seem to arise from the presence of a second ferromagnetic phase as an impurity. $CeCo_2$ was found to show paramagnetism almost independent of temperature.

Experimental values of the magnetic moment (in Bohr magnetons) per formula unit, obtained by extrapolating the various lines of Fig. 1 to $T=0$, are shown in Fig. 2. Also shown are the values gJ of the expected magnetic moment contributed by tripositive rare-earth ions alone (full line), and also the calculated dependence of moment on the atomic number of the rare earth for part of the series, if we assume the rare-earth atoms to have magnetic moments Jg and the cobalt atoms to have a moment of about 1.7 magnetons (the value in metallic cobalt) aligned oppositely to the rare-earth moment (broken line). Such a model has been applied[6] to explain the properties of the A Co_5 compounds containing the heavier rare earths [whose quantum number $J=(L+S)$]. The agreement between the broken line in Fig. 2 and the experimental points is good for the heavier rare earths, but the model does not hold for the lighter ones. The effective cobalt moment would have to be nearly zero.

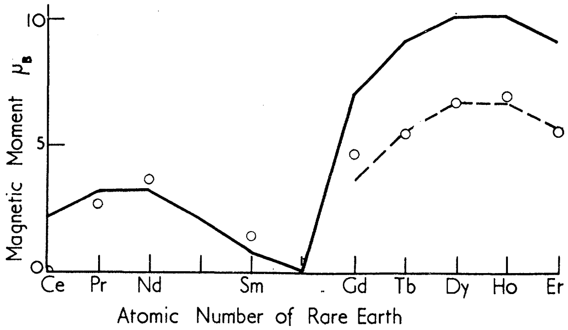

FIG. 2. Experimental magnetic moment in Bohr magnetons per formula unit plotted against atomic number of the rare-earth element (circles). The full line shows the variation of the full moment of the rare earth Jg, and the broken line is that calculated assuming the cobalt spins to be aligned oppositely to the rare-earth moments, and equal to 1.7 Bohr magnetons per cobalt atom.

The Curie points might be expected to yield some information as to the mechanism of magnetic coupling in the compounds. Bozorth *et al.*[7] have shown that in similar compounds containing platinum metals instead of cobalt, applying the Ruderman-Kittel-Yosida[8,9] mechanism of indirect exchange interaction of f-shell magnetic moments through the conduction electrons, the Curie temperature (θ) is proportional to either $J(J+1)(g-1)^2$ or $S(S+1)$, depending on the range through which the interaction works. In their compounds they concluded that the former applied more nearly, indicating a relatively long range. We find, in the case of the cobalt compounds, that a better fit (Fig. 3) is obtained with $S(S+1)$, although a different coefficient for the dependence of θ on $S(S+1)$ applies between the light and the heavy rare earths. Like them, we conclude that the basic magnetic coupling mechanism is that of indirect exchange through the conduction electrons between rare-earth spins.

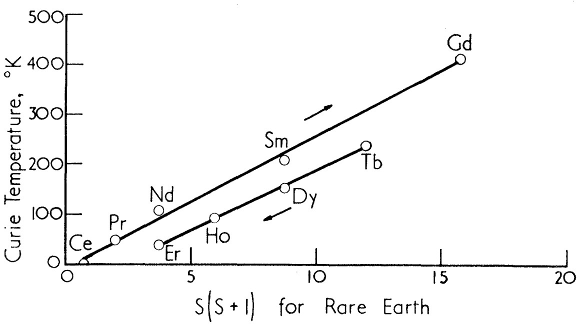

FIG. 3. Curie temperatures of A Co_2 compounds plotted against $S(S+1)$ for the rare-earth components. The arrows show the direction of increasing atomic number of the rare earth.

Further work on these and related compounds is at present in progress.

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[4] K. P. Belov and A. N. Goryaga, Fiz. Metal. i Metalloved **2**, 3 (1956).

[5] A. Arrott, Phys. Rev. **108**, 1394 (1957).

[6] E. A. Nesbitt, H. J. Williams, J. H. Wernick, and R. S. Sherwood, J. Appl. Phys. **32**, 342S (1961).

[7] R. M. Bozorth, B. T. Matthias, H. Suhl, E. Corenzwit, and D. D. Davis, Phys. Rev. **115**, 1595 (1959).

[8] M. A. Ruderman and C. Kittel, Phys. Rev. **96**, 99 (1954).

[9] K. Yosida, Phys. Rev. **106**, 893 (1957).