Exchange Integral in Cobalt from Spin-Wave Resonance

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The exchange constant A and exchange integral J, and their temperature dependences, have been measured in cobalt metal films by spin-wave resonance. At room temperature, $A=1.30\times10^{-6}$ erg/cm and $J=155k$. J is temperature independent between 4°K and 295°K. Comparison is made with recent data obtained by other experimental methods.

THE method of spin-wave resonance[1] has been applied to cobalt metal in order to measure the exchange constant A, exchange integral J, and their temperature dependences. The cobalt samples, in the form of evaporated films on glass substrates, turned out to have resonance lines sufficiently narrow to resolve the spin-wave modes. This is in contrast to bulk cobalt metal, ordinarily having hexagonal crystal structure, in which the extremely large magnetocrystalline anisotropy makes observation of even ferromagnetic resonance difficult. The cobalt films used here have predominantly cubic structure with a lattice constant $a=3.55$ A as shown by x-ray diffraction, have a uniaxial anisotropy of about 23 oe (independent of temperature) in the plane of the film, and have a g factor and saturation magnetization close to bulk material.

The observations made at room temperature, 77°K, and 4°K all appear similar to the curve shown in Fig. 1. From the spacings of the subsidiary peaks, measurement of thickness L, and the relation $\omega/\gamma=H+(2A/M_s)(\pi n/L)^2$, the exchange constant A is determined. Independent determinations of g and $4\pi M_s$ are made from resonance measurements with the dc field H applied parallel and perpendicular to the plane of the sample. J is computed from the relations $A=Na^2J\bar{S}^2$ and $M=Ng\beta\bar{S}$, where N is the number of atoms per unit volume, β is the Bohr magneton, and $\bar{S}$ is the effective spin per atom. The results are given in Table I. The uncertainty associated with the *temperature variation* of A and J is $\pm2\%$. Thus, J is constant with temperature within experimental error, as might be the most reasonable *a priori* expectation.

TABLE I. Summary of results.

Temp.	A (ergs/cm)	$4\pi M_s$ (oe)	g	$\bar{S}$	J (ergs)
295°K	1.30×10^{-6}	16 100	2.10	0.728	155 k
77°K	1.42×10^{-6}	16 700	2.09	0.759	155 k
4°K	1.43×10^{-6}	16 800	2.07	0.772	152 k
	$\pm5.5\%$	$\pm1.2\%$	$\pm0.8\%$	$\pm2.0\%$	$\pm5.7\%$

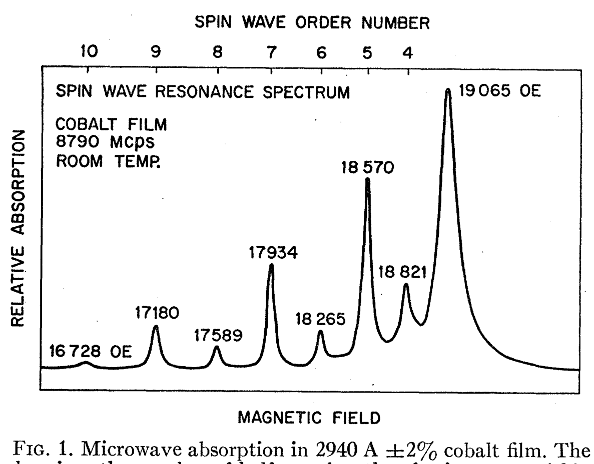

FIG. 1. Microwave absorption in 2940 A $\pm2\%$ cobalt film. The order gives the number of half-wavelengths of spin waves within the sample thickness.

Experimental determinations of the exchange constant A seem to be independent of any particular model for the ferromagnetic electrons.[2] Even though calculations of J values, as carried out above as well as from other experiments, raise the dilemma of nonintegral spin values in a localized electron model, brief comparison on this basis of the results of different experiments seems worthwhile.

Recently, nuclear resonance has been employed in cobalt to measure the temperature variation of the effective field at the nucleus.[3] On the assumption that the proportionality between the field at the cobalt nucleus and the spontaneous magnetization is temperature independent, these data yield the temperature variation of the magnetization and hence a quantity proportional to the exchange integral. From reference 3, $M_s(T)=M_s(0°\text{K})[1-3.3\times10^{-6}(°\text{K})^{-3/2}T^{3/2}]$, so that identification of the $T^{3/2}$ coefficient with $(0.0294/2S)(k/2SJ)^{3/2}$ according to the standard spin-wave treatment for a fcc crystal, yields $J=135k/S^{5/3}$. Assuming that the effective number of Bohr magnetons $g\bar{S}$ in the nuclear resonance experiment was 1.76, corresponding to bulk magnetization measurements in cubic material, and taking g from the present experiment, one obtains $\bar{S}=0.85$ and hence $J=177k$. A further comparison can be made with recent neutron spectroscopy data.[4] The dispersion relation of spin waves was measured in a single crystal of fcc cobalt *containing 8% iron* and gave a value of $J=185k\pm10\%$.

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[1] M. H. Seavey, Jr., and P. E. Tannenwald, Phys. Rev. Letters **1**, 168 (1958); and J. Appl. Phys. **30**, 227S (1959).

[2] C. Herring and C. Kittel, Phys. Rev. **81**, 869 (1951).

[3] V. Jaccarino, Bull. Am. Phys. Soc. **4**, 461 (1959).

[4] R. N. Sinclair and B. N. Brockhouse, Phys. Rev. **120**, 1638 (1960).