$\hbar\omega\beta(1-e^{-\hbar\omega\beta})^{-1}=1$ for our data, and that we have incorporated the factor $g^2\mu_B^2 N^{-1}$ into our definition of R.

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Magnetomechanical Ratios for Ferrites with Composition $Zn_xM_{1-x}Fe_2O_4$

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Magnetomechanical ratios have been measured for 21 different ferrites having the compositional formula $Zn_xM_{1-x}Fe_2O_4$. Room-temperature g' values were determined for four different series where $M = Mg^{2+}$, Ni^{2+}, Fe^{2+}, and ($0.5\ Li^+$, $0.5\ Fe^{3+}$), and g' values near the Néel temperature were determined for $M = Ni^{2+}$, $x = 0.73$.

INTRODUCTION

Magnetomechanical ratios (g') have been determined by the Einstein–de Haas method for 21 different ferrites fitting the compositional formula $Zn_xM_{1-x}Fe_2O_4$, where M is Mg^{2+}, Ni^{2+}, Fe^{2+}, or ($0.5\ Li^+$, $0.5\ Fe^{3+}$). Details of the experiments and a discussion of errors are given in earlier papers.[1,2]

The samples used for all of these determinations were made by the usual powder sintering process and furnace cooled. They were then accurately ground to cylinders having a diameter of 0.561 in. and a length of about 0.75 in. These short cylinders were placed in a hollow pendulum[1] producing a cylindrical sample about $8\frac{1}{4}$ in. long.

$M = (0.5\ Li^+, 0.5\ Fe^{3+})$

Magnetomechanical ratios g' were measured at (295 ± 2) °K on seven different ferrites in the lithium series with the results shown in Table I. In these ferrites, Fe^{3+} is the only magnetic ion involved. Although the values of g' are all close to 2, there is (except for $x = 0.65$) a very definite trend toward lower g' values for higher values of x.

In this ferrite series it is known that Zn^{2+} always occupies a tetrahedral (A) position and Li^+ an octahedral (B) position in the spinel structure.[3,4] A formula for this series can therefore be written as

$$A(Zn_x Fe_{1-x})B(Li_{0.5-0.5x}Fe_{1.5+0.5x})O_4 \ .$$

Using this ionic distribution, we have accounted for the saturation magnetization values appearing in the literature[5] by assuming a Yaffet-Kittel (YK) structure in which the B site Fe^{3+} ions are arranged in two sublattices having magnetizations directed at an angle α_{YK} to their resultant magnetization which is in turn antiparallel to a single A-site configuration as is apparently the case for the NiZn series.[6] With $5\mu_B$ for Fe^{3+}, the expression for the resultant magnetization for this model would be

$$M = 5(1.5+0.5x)\cos\alpha_{YK} - 5(1-x).$$

$\cos\alpha_{YK}$ was calculated from this expression for each value of x using values of M from Ref. 5.

If we now speculate that the g' values for Fe^{3+} ions on the sublattices are dependent on the value of the YK angle and have the spin-only value of 2.000 for $\alpha_{YK}=0$, we can compute values of g'_B using our measured values of g' effective. Table

TABLE I. g' measurements for the ferrite series $Zn_xLi_{0.5-0.5x}Fe_{2.5-0.5x}O_4$.

x	g'
0.00	2.005 ± 0.002
0.50	1.998 ± 0.002
0.60	1.994 ± 0.003
0.625	1.989 ± 0.003
0.65	2.000 ± 0.002
0.70	1.982 ± 0.005
0.75	1.964 anomalous at room temp. (measured below 20 °C)

TABLE II. Saturation magnetization, cosine of Yaffet-Kittel angles, and calculated g'_B values for the ferrite series $Zn_xLi_{0.5-0.5x}Fe_{2.5-0.5x}O_4$. g'_A is assumed to have a constant value of 2.000.

x	M[a] Bohr magnetons	$\cos\alpha_{YK}$	g'_{eff} Experimental	g'_B[b]
0	2.6	1.00	2.005	2.002
0.5	4.0	0.74	1.998	1.999
0.6	3.0	0.56	1.994	1.996
0.625	2.7	0.52	1.989	1.994
0.65	2.3	0.44	2.000	2.001
0.70	1.8	0.36	1.982	1.990
0.75	1.2	0.26	1.964	1.981

[a]See Ref. 5.
[b]g'_A assumed = 2.000. Since g'_B is not strongly dependent on $\cos\alpha_{YK}$ the accuracy obtained from experimental curves for M is sufficient for these calculations.

II summarizes the results of these procedures, and Fig. 1 shows the relationship between g'_B for Fe^{3+} and $\cos\alpha_{YK}$ for the assumed model of the lithium zinc ferrites.

$M = Mg^{2+}$

g' values were measured for five different ferrites in the magnesium series at (295 ± 2) °K. The results are tabulated in Table III. Since both Zn^{2+} and Mg^{2+} are nonmagnetic ions the magnetization on both the A and B sites is again caused entirely by Fe^{3+}. With the exception of $MgFe_2O_4$ ($x = 0$) these g' values are all very close to 2.000 and indicate no trend toward smaller values for higher values of x as was observed in the lithium series. The g' value for our $MgFe_2O_4$ sample is 0.75% below the spin-only value which is well outside the error limits of these experiments. This value apparently cannot be accounted for by assuming YK angles since it has been shown by Corliss *et al.*[7] using neutron diffraction techniques that $MgFe_2O_4$ has a

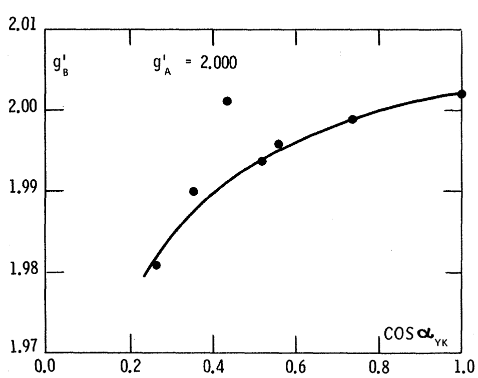

FIG. 1. Plot of g'_B vs $\cos\alpha_{YK}$ for the ferrite series $Zn_xLi_{0.5-0.5x}Fe_{2.5-0.5x}O_4$. $\cos\alpha_{YK}$ calculated from saturation magnetization data of Ref. 5.

TABLE III. g' measurements for the ferrite series $Zn_xMg_{1-x}Fe_2O_4$.

x	g'
0.00	1.985 ± 0.002
0.15	2.008 ± 0.003
0.30	2.000 ± 0.001
0.50	2.003 ± 0.004
0.56	2.006 ± 0.001

simple Néel structure. We offer no explanation for the relatively large orbital magnetization found in our g' measurements for this ferrite.

$M = Fe^{2+}$

Magnetite ($x = 0$) was the only ferrite studied in this series. Since Fe^{2+} occupies the octahedral site, the Fe^{3+} ions are in an antiparallel configuration and the net magnetization should be caused entirely by Fe^{2+}. The g' value for magnetite should therefore be a value characteristic of Fe^{2+}. We have made two series of measurements on magnetite. One series of eight measurements was made some time ago when our magnetics laboratory was located at Dayton, Ohio. This resulted in $g' = 1.940 \pm 0.003$. A second set of five measurements taken more recently at our present laboratory gave a value of $g' = 1.939 \pm 0.001$. Both series of experiments were conducted on the same sample.

$M = Ni^{2+}$

Eight different ferrites were studied in this series at (295 ± 2) °K with values of x between 0.00 and 0.73. In this series two magnetic ions Fe^{3+} and Ni^{2+} having quite different g' values are involved. Hence the g' values measured for this series can be expected to cover a much wider range than was noted for either the magnesium or lithium groups. The results and interpretation of our measurements have been previously reported[8] and the g' values of Table IV are given here merely for completeness.

TABLE IV. g' measurements for the ferrite series $Zn_xNi_{1-x}Fe_2O_4$.

x	g'
0.00	1.849 ± 0.002
0.10	1.885 ± 0.005
0.15	1.989 ± 0.003
0.20	1.953 ± 0.006
0.35	1.936 ± 0.002
0.50	1.953 ± 0.003
0.63	1.959 ± 0.003
0.73	1.967 anomalous at room temp. (measured below 20 °C)

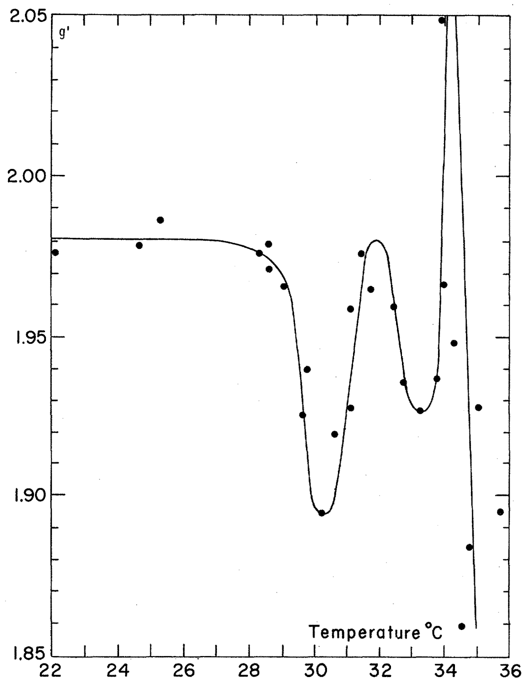

FIG. 2. g' values for the ferrite $Zn_{0.73}Ni_{0.27}Fe_2O_4$ in the Néel temperature range.

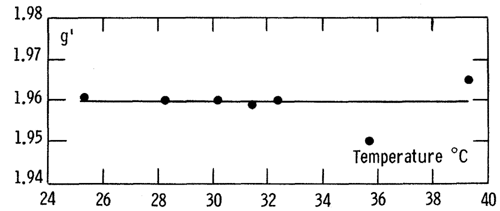

FIG. 3. Plot of g' vs temperature for the ferrite $Zn_{0.63}Ni_{0.37}Fe_2O_4$. Néel temperature well above the measurement range.

g' MEASUREMENTS NEAR THE NEEL TEMPERATURE

Ferrites having the compositional formula $Zn_x M_{1-x} Fe_2O_4$ have Néel temperatures close to room temperature for properly chosen values of x. We have made some attempt to make g' measurements in this temperature-sensitive region for the Ni^{2+} series. Figure 2 shows a curve of g' vs temperature for $x = 0.73$ where the Néel temperature is about 32 °C. Figure 3 which is shown for comparison is for $x = 0.63$ where the Néel temperature is well above the room temperature. Owing to the rapid changes in permeability of $Zn_{0.73}Ni_{0.27}Fe_2O_4$ in the temperature range of these experiments,

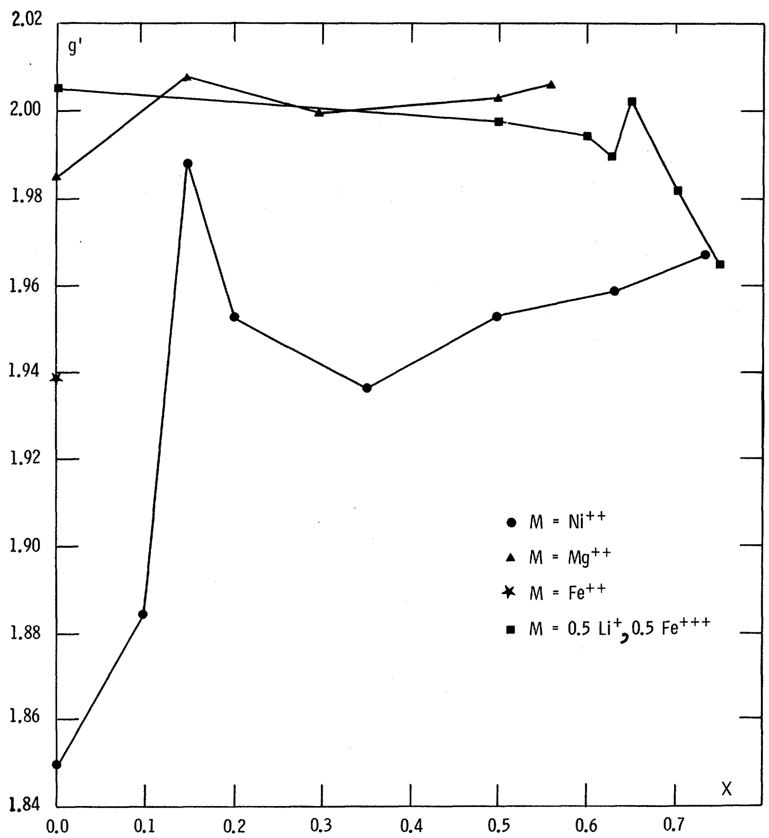

FIG. 4. Summary of Einstein–de Haas measurements for the ferrites $Zn_x^{++}M_{1-x}^{++}Fe_2^{+++}O_4^{--}$.

the induced magnetic moment of our cylindrical specimen decreased by a factor of about 4 between 25 and 35 °C. Although this decreases the measurement accuracy, the decrease is < 4 since magnetic coupling errors are also reduced. Errors in these g' measurements are estimated as ± 0.005 at 25 °C and ± 0.010 at 35 °C. It appears that temperature changes of only 1 °C in this critical range can result in large changes in the measured g' values.

In this experiment the temperature was raised above ambient by the simple expedient of increasing the current in the magnetizing winding which is an integral part of the torsional pendulum. All data were taken after thermal equilibrium had been established. The sample temperatures were determined by a careful measurement of the resistance of the magnetizing coil, or by measuring the magnetic induction which, as has been noted, is very temperature dependent in this range. Both methods gave essentially the same temperature values. These temperatures are, of course, average values and it is likely that temperature differences throughout the sample do exist. Under conditions of complete temperature uniformity one might expect considerably larger changes in g' to occur over a narrower temperature range. We hope to repeat these experiments under conditions which would assure temperature uniformity.

SUMMARY

Figure 4 summarizes the g' values measured for the 21 ferrites studied in these experiments.

In the magnesium series, Fe^{3+} is the only magnetic ion involved and, with the exception of $MgFe_2O_4$, all of the measured g' values are very close to 2.000. In the lithium series it is again Fe^{3+} which produces the net magnetization, but in this series there is evidence that the development of large Yaffet-Kittel angles produces a reduction of about 1% in the value of g'. From these observations it appears that g' values are determined largely by the individual magnetic ions. Local fields apparently produce only very minor effects.

For the ferrite $NiFe_2O_4$ the two Fe^{3+} ions are antiparallel. Hence the g' value of 1.849 should be characteristic of Ni^{2+}. Likewise for magnetite the two Fe^{3+} ions are again antiparallel and the g' value of 1.939 should be characteristic of Fe^{2+}.

Finally, when Einstein—de Haas experiments are conducted near the Néel temperature for a ferrite having different magnetic ions, small changes in temperature can produce very large changes in the measured value of g'.

These Einstein—de Haas measurements have been conducted at the Kettering Magnetics Laboratory of Oakland University, Rochester, Michigan.

Note added in proof. Ferromagnetic resonance experiments on magnetite conducted by Bickford [L. R. Bickford, Phys. Rev. 76, 137 (1949)] indicated a variation in the g factor with temperature from 2.15 at 20 °C to 2.08 at − 143 °C. It is interesting to note that it is the low-temperature value of g which checks our room-temperature value of g' via the Kittel-Van Vleck conversion equation $g' = g(g-1)^{-1} = 1.93$.

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