Review of Gyromagnetic Ratio Experiments

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INTRODUCTION

DURING recent years, techniques for making g-factor determinations by direct magnetomechanical experiments have undergone considerable development and it appears at present that such experiments can produce g factors with somewhat greater precision than those obtained using ferromagnetic resonance.

There are two converse magnetomechanical effects; rotation by magnetization (Einstein-de Haas effect) and magnetization by rotation (Barnett effect). Recent experimental development has been confined entirely to the Einstein-de Haas effect.

In addition to producing g factors of considerable precision, Einstein-de Haas experiments have a further unique importance in the directness of their approach. No theoretical manipulation is required in obtaining the results and the experimental conditions do not alter the natural motion of the electric carriers. For these reasons, interest in magnetomechanical experiments has persisted, from the earliest work in 1914 to the present time.

In principle, Einstein-de Haas experiments are extremely simple. One merely changes the magnetic moment of a delicately suspended sample and observes the resulting change in angular momentum about the magnetic axis. The gyromagnetic ratio is the ratio between these angular momentum and magnetic moment changes. This ratio is obviously the same for the entire sample as it is for the smallest complete magnetic unit of which the sample is composed. For orbital motion this ratio is twice the mass charge ratio of the carrier. For electron spin the ratio is exactly one m/e.

Most ferromagnetic materials have gyromagnetic ratios which are less than 10% higher than the spin-only value. Hence the theoretically important differences in the gyromagnetic ratio are small and considerable experimental accuracy is required for the results to have significance. Such accuracy is, however, difficult to obtain because the highly-sensitive suspended systems required are very easily distributed by very small magnetic fields.

HISTORICAL

Rotation of a ferromagnetic rod by magnetization was predicted by Richardson[1] in 1908 and was qualitatively observed by Einstein and de Haas[2] in 1915. More precise experiments were carried out in 1918 by Stewart.[3] The converse effect of magnetization by rotation was observed by Barnett[4] in 1914. These early experiments resulted in gyromagnetic ratios close to one m/e, which was half the value anticipated by consideration of electron orbital motion. Since the concept of electron spin was not known then, the discrepancy was originally called the gyromagnetic anomaly. After recognition of the spinning electron it was thought for some time that the gyromagnetic ratio for all ferromagnetic materials is exactly one m/e. However, the extensive work of Barnett showed that gyromagnetic ratios are significantly larger than m/e and that this difference depends on the particular ferromagnetic material investigated.

In 1946 ferromagnetic resonance[5] was observed by Griffiths. From these and subsequent experiments by other investigators, gyromagnetic ratios could be calculated. However, these calculated values were always *less* than m/e rather than *greater* as determined by magnetomechanical methods. This was explained theoretically by Kittel[6] in 1949 and independently by Van Vleck[7] soon thereafter. They showed that $1/g'+1/g=1$, where g' refers to the result of a magnetomechanical experiment and g refers to the corresponding result obtained by ferromagnetic resonance. The relationship between g' which is known as the magnetomechanical factor and ρ the gyromagnetic ratio is:

$$g'=\frac{2}{\rho e/m}, \quad (e \text{ in emu}).$$

The Kittel-Van Vleck relation did not fit the available experimental data, so there existed what was sometimes called a g, g' dilemma. The experiments conducted by the author over the past several years have been primarily directed toward resolving this dilemma. This article reviews these experiments.

EXPERIMENTAL

Significant g' determinations depend on the successful elimination of a large variety of disturbing effects. The most important disturbances have their source in torques generated by coupling between the delicately suspended magnetic system and extraneous magnetic fields. To appreciate the problem involved it should be recognized that the torque which can act on a

[1] O. W. Richardson, Phys. Rev. **26**, 194, 248 (1908).
[2] A. Einstein and W. J. de Haas, Verhandl. deut. physik. Ges. **17**, 152 (1915); **18**, 173, 423 (1916).
[3] J. Q. Stewart, Phys. Rev. **11**, 110 (1918).
[4] S. J. Barnett, Phys. Rev. **6**, 171, 239 (1915).
[5] J. H. E. Griffiths, Nature **158**, 670 (1946).
[6] C. Kittel, Phys. Rev. **76**, 743 (1949).
[7] J. H. Van Vleck, Phys. Rev. **78**, 266, (1950).

ferromagnetic rod in the earth's magnetic field is between 10^7 and 10^8 times larger than the torque which must be measured to determine the mechanical moment of the electric carriers. It is therefore of extreme importance to conduct such experiments in a region in which magnetic fields have been reduced to an absolute minimum. This in general involves utilizing an isolated laboratory facility and setting up an elaborate coil system to neutralize the earth's magnetic field in the working space. The laboratory now being used was constructed by the Charles F. Kettering Foundation with the objective of obtaining a working space in which magnetic fields could be reduced to between 10^{-5} and 10^{-6} oersteds. This laboratory is located south of Dayton, Ohio, and is about 0.3 mile from the nearest public road. It is built entirely of nonferromagnetic materials. Vehicle motion to the laboratory is eliminated when maximum field neutralization is being maintained.

At a carefully located and constructed laboratory such as this, the earth's magnetic field is highly homogeneous. It is, however, continually changing both in magnitude and in direction. The records in Fig. 1 for four different 24-hr periods show the varying degrees of magnetic activity encountered. Such variations must, of course, be followed if field levels of the order of 10^{-5} oe are to be obtained. Although it is important to produce low field levels in the working space, it is even more important to do so without introducing appreciable magnetic gradients. The neutralizing system must therefore produce a variable and directable field of

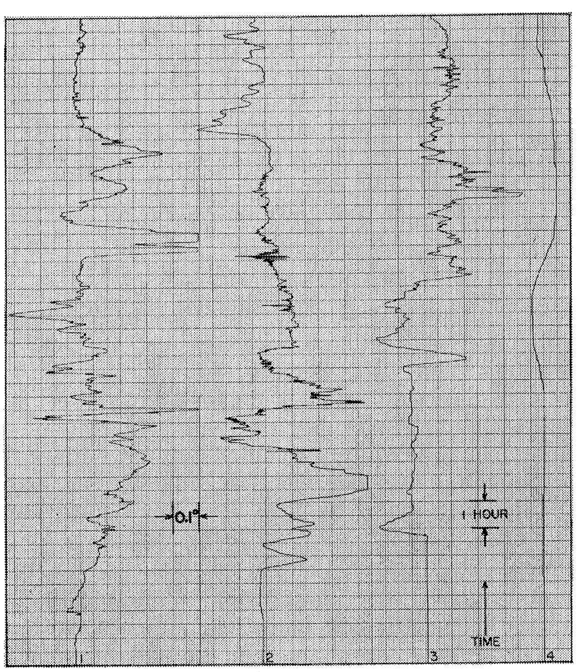

FIG. 1. Variation in magnetic declination for four different 24-hour periods.

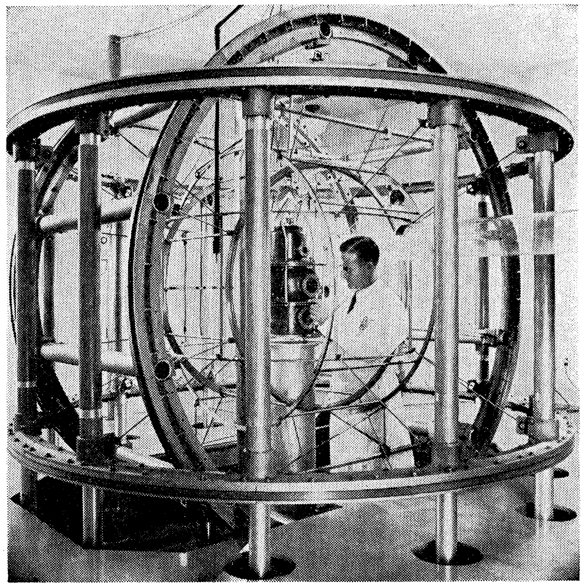

FIG. 2. Coil system used for neutralizing the earth's magnetic field.

high homogeneity.[8] Figure 2 shows the three component system used. The largest coils in this array consist of a Helmholtz pair 9 ft in diameter, used to neutralize the vertical component. A smaller symmetrically placed Helmholtz pair is used to improve the homogeneity of the vertical field produced. The north-south component is neutralized by a similar four-coil system. Components occurring in the east-west direction are much smaller in magnitude and can therefore be compensated by a single Helmholtz pair.

Currents in both the N-S and E-W groups are modulated, to follow the earth's magnetic field changes, by servo systems activated by suitable variometers.

These field-neutralizing coils must be mounted on a very solid foundation to prevent small changes in orientation from affecting the compensation. The arrangement used is shown in Fig. 3. A similar foundation is also required for the variometer which follows the N-S field changes.

The laboratory building is L shaped with the variometers at the end of one arm and the main neutralizing coil system at the end of the other. This arrangement makes available long optical paths from the various instruments to a common reading center. The optical paths used with the variometers are 58 ft. long. That used with the main instrument is 54 ft. long and is enclosed in a tunnel to prevent deviations due to thermal air turbulence.

The ferromagnetic sample on which the g-factor measurements are made is suspended as a torsional pendulum in an evacuated chamber which is located at the center of the neutralizing coil array. Some of the construction details of this vacuum chamber are shown in Fig. 4. All nonconducting surfaces on the interior

[8] G. G. Scott, Rev. Sci. Instr. **28**, 270 (1957).

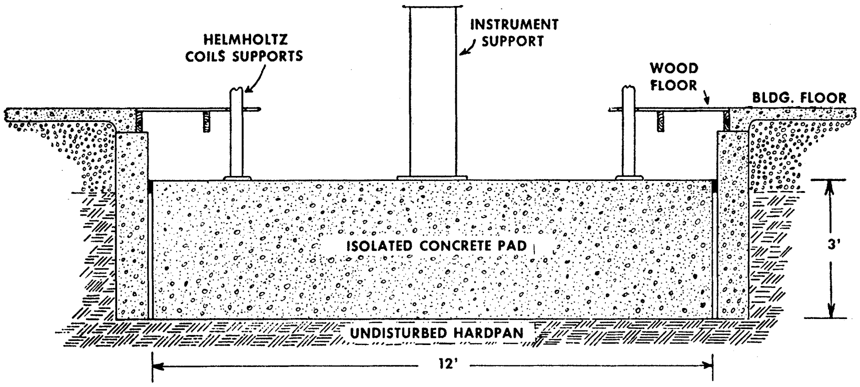

FIG. 3. Supporting foundation for neutralizing coil system.

of this chamber are shielded to prevent electrostatic disturbances. The sample is machined either as a rod or as an ellipsoid and is placed in the hollow winding of the pendulum. Adjusting screws are provided so that all of the pendulum components can be symmetrically placed with respect to the axis of rotation. The supporting suspension also serves as one of the current leads. The other lead consists of a spiral located at the top of a tube which surrounds the suspending filament. This location of the second current lead prevents changes in torsional amplitude which might otherwise be introduced by the microseismic motions which are nearly always present in the earth's crust. The small interchange switch located at the lower end of the pendulum is for the purpose of allowing for asymmetrical torques which can be introduced when current is reversed in a suspension system. This switch is in the circuit between

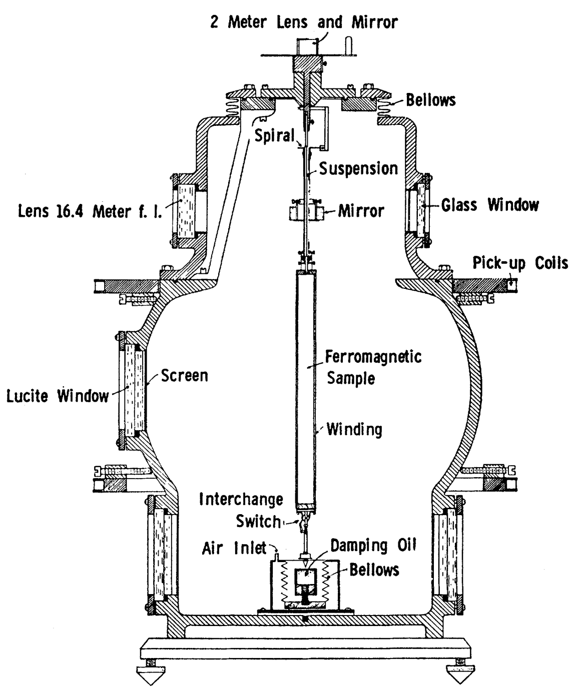

FIG. 4. Sectional diagram of vacuum chamber showing location of torsional pendulum.

the suspension system and the magnetizing winding. It is operated by the bellows located at the bottom of the vacuum chamber. When this bellows is partially raised a small cone is left immersed in an oil reservoir. This quickly damps out the lateral disturbances caused by handling, after which the air is slowly bled from behind the bellows leaving the pendulum completely free. The torsional period of the pendulum is about 25 sec. It takes about one hour for damping to reduce the amplitude to $\frac{1}{2}$.

The mirror for measuring rotational motion has four 90°-spaced faces so as to facilitate obtaining readings at different angular positions. Allowance can thus be made for any torques caused by small uncompensated magnetic fields.

The objective of these experiments is to determine the change in angular momentum which accompanies a known change in magnetic moment. These angular momentum changes are determined by using a system of resonance in which the magnetizing current is synchronously reversed at the time at which the pendulum is crossing the center of its swing. Accurate phasing is important and is obtained by using a preset electronic timer. The gyromagnetic torque is allowed to both increase and decrease the momentum of the pendulum so that the effect of mechanical damping can be determined. Sixty synchronous reversals of the magnetizing current are used in each direction.

Auxiliary experiments are required to determine the absolute value of the magnetic moment changes involved. These measurements are made by means of a critically damped torsional comparator in which either the sample or a known air core standard is held horizontally and normal to the very uniform field which can be produced by the north-south neutralizing coil array. The unknown magnetic-moment change of the sample is compared with the known change produced in the standard by adjusting the N-S field to obtain equal torsional deflections.

Since angular momentum determinations may extend over a period of several weeks, a secondary system for measuring magnetic moment changes is also used. It is calibrated from the torsional comparator measurements. This secondary system utilizes a pair of pickup coils surrounding the instrument as shown in Fig. 4.

These coils are connected through the secondary of an air core mutual inductance to a ballistic galvanometer. The current pulses induced in these pickup coils are balanced by corresponding pulses generated by synchronously reversing the current in the primary of the inductance.

To calculate angular momentum changes it is necessary to know the pendulum period, its moment of inertia, and the length of the optical arm. To determine g' for the sample it is also necessary to allow for the inertia and the magnetic moment of the electrons flowing in the magnetizing winding.

RESULTS

Values of the magnetomechanical factor g' have been determined for the three ferromagnetic elements and for a variety of ferromagnetic alloys and compounds.

TABLE I. Summary of g' measurements for Fe.

Investigator	Year	g'
Barnett[a]	1944	1.938 ±0.006
Meyer[b]	1951	1.936[h]±0.008
Scott[c]	1951	1.927[i]±0.004
Barnett & Kenny[d]	1952	1.929 ±0.006
Scott[e]	1955	1.919 ±0.006
Meyer & Brown[f]	1957	1.932 ±0.008
Scott (cylinder)[g]	1960	1.917 ±0.002
Scott (ellipsoid)[g]	1960	1.919 ±0.002

[a] See reference 9.
[b] See reference 10.
[c] See reference 11.
[d] See reference 12.
[e] See reference 13.
[f] See reference 14.
[g] See reference 15.
[h] This value originally published as 2.008 has been corrected for an error which was made in determining the length of the optical path.
[i] This value originally published as 1.946 has been corrected for a similar optical error. See reference 16.

These experiments are first reviewed, and then a comparison with ferromagnetic resonance experiments is made.

Iron

Over recent years there have been many elaborate investigations made to determine the gyromagnetic ratio of iron.[9–15] These were conducted independently at General Motors, at the University of California, and at the University of Strasbourg. The results are summarized in Table I. Our most recent experiments were made on two different samples of pure iron. The cylindrical sample was the same as that used in the earlier experiments. The ellipsoidal sample had an eccentricity of about 15 to 1. The values obtained by different investigators have a range of about 1%.

[9] S. J. Barnett, Proc. Am. Acad. Arts Sci. **75**, 109 (1944).
[10] André J. P. Meyer, Ann. phys. **6**, 171 (1951).
[11] G. G. Scott, Phys. Rev. **82**, 542 (1951).
[12] S. J. Barnett and G. S. Kenny, Phys. Rev. **87**, 723 (1952).
[13] G. G. Scott, Phys. Rev. **99**, 1241 (1955).
[14] André J. P. Meyer and Sheldon Brown, J. phys. radium **18**, 161 (1957).
[15] G. G. Scott, Phys. Rev. **119**, 84 (1960).

TABLE II. Magnetic properties of Ni used by different investigators for determining g'. Data by André Meyer, University of Strasbourg.

Sample	Curie temp. °C	Saturation magnetization abamp cm²/gram
From Barnett	285	71.04
From Meyer	360	58.89
From Scott	349	58.83
Spectrographically pure Ni	360	58.90

Nickel

The values of the magnetomechanical factor g' for nickel obtained in different investigations have probably caused more concern than those obtained for any other material. Figure 5 summarizes all of the published g' values over the last 10 year period. Not only was there originally a major disagreement with magnetic resonance data, but also there was a wide divergence between the values obtained by the various investigators. The situation is now much improved. Brown[16] pointed out that an optical error existed both in the 1952 work of the author and in the earlier work of Meyer. Meyer[14] also found that his 1954 values were too high because allowance was not made for asymmetries originating from current reversals in the suspension. Meyer checked the purity of the samples used by the different experimenters. This was done by measuring the Curie temperature and the saturation magnetization. Results are shown in Table II. Although Barnett's sample was

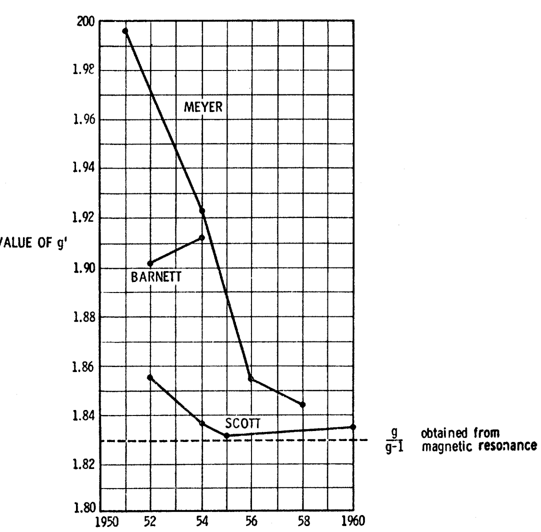

FIG. 5. Variation in published values of g' for Ni over last 10 years.

[16] S. Brown, A. J. P. Meyer, and G. G. Scott, Compt. rend. **238**, 2504 (1954).

TABLE III. Summary of g' experiments on same sample of Ni.

Year	g'
1952[a]	1.837±0.004[d]
1953[b]	1.831±0.004
1955[b]	1.830±0.006
1960[c]	1.837±0.002
Weighted average	1.835±0.002

[a] See reference 17.
[b] See reference 18.
[c] See reference 15.
[d] This value originally published as 1.855 has since been corrected for an error in determining the optical path length.

98.6% pure, the magnetic properties were so much different from pure Ni that it seems difficult to retain his value of g' for this metal.

Four different series of experiments were conducted by the author to determine the g' value for Ni. These results[15,17,18] are summarized in Table III. The 1952 value has been corrected for the optical error mentioned above. All of these experiments were conducted on the same sample. However, the rod was annealed between the 1953 and the 1955 experiments. This annealing process increased the effective permeability of the rod by a factor of about 4 without changing the value of g'.

Cobalt

Table IV is a summary of investigations of the magnetomechanical factor for cobalt.[9,12,17,19] In each of the author's experiments two different samples of cobalt were used. These samples had magnetic impurities of about 1% so that the results were not originally considered to be precise. However, the work on the CoNi alloy series would indicate that these values of g' for cobalt are quite good. There is also excellent agreement with the results obtained by Barnett and Kenny.

Fe-Ni Alloys

Results of experiments on iron nickel alloys are indicated in Fig. 6. The effective g' values for an alloy system such as this can be approximated if it is assumed that the individual g' values and magnetizations per atom are the same as for the constituent metals and

TABLE IV. Summary of g' measurements for Co.

Investigator	Year	g'
Barnett[a]	1944	1.866±0.002
Barnett & Kenny[b]	1952	1.859±0.004
Scott[c]	1952	1.854±0.008[e]
Scott[d]	1956	1.850±0.004

[a] See reference 9. [c] See reference 17.
[b] See reference 12. [d] See reference 19.
[e] This value originally published as 1.873 has since been corrected for an error in determining the optical path length.

[17] G. G. Scott, Phys. Rev. **87**, 697 (1952).
[18] G. G. Scott, Phys. Rev. **99**, 1824 (1955).
[19] G. G. Scott, Phys. Rev. **104**, 1498 (1956).

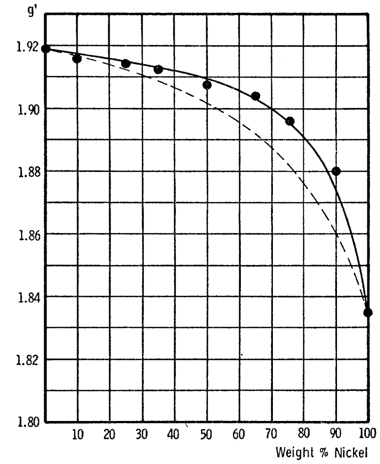

FIG. 6. g' vs % Ni for the Fe-Ni alloys. The solid circles indicate experimental values determined by Scott from measurements of the Einstein-de Haas effect. The dashed curve was obtained using the Tsuya-Wangsness relation, with a magnetization ratio of 4.0 which is the ratio of the saturation intensities for Fe and Ni. The solid curve was obtained using a magnetization ratio of 8.2.

that the component atoms have their magnetic moments parallel throughout each domain.

An expression is thus obtained which is similar to that developed by Tsuya[20] and Wangsness.[21] The ratio of the saturation intensities for Fe and Ni is about 4. Using this value for the ratio of the individual magnetic moments the dashed curve results. Arbitrary use of a magnetic moment ratio of 8.2 gives the solid curve which fits the experimental points. This difference, of course, merely points out the oversimplification of the above assumptions.

These alloy values were originally published in 1956.[22] The original paper reported an apparent decrease in the values of g' for very weakly magnetized specimens of Fe, Ni, and the Fe-Ni alloys. This has since been shown to be the result of a systematic error in the measurement of magnetic moment. This error did not affect the g' values obtained at the higher values of magnetic induction. Appropriate corrections have been applied to three of the points in Fig. 6 which were obtained at low magnetizations. For a discussion of the error see reference 15.

The Fe-Ni alloys were also investigated by Barnett and Kenny[12] but the precision was not great enough to determine the shape of the g' vs concentration curve.

Co-Ni Alloys

Gyromagnetic experiments are currently being conducted by the author on the cobalt-nickel alloy series and thus far only two rods have been completed.

[20] N. Tsuya, Progr. Theoret. Phys. (Kyoto) **7**, 263 (1952).
[21] R. K. Wangsness, Phys. Rev. **91**, 1085 (1953).
[22] G. G. Scott, Phys. Rev. **103**, 561 (1956).

Figure 7 summarizes these results. The dashed curve was calculated by using the Tsuya, Wangsness formula.

Supermalloy

Supermalloy, which consists of 79% Ni, 16% Fe, and 5% Mn, produces quite sharp peaks in ferromagnetic resonance experiments. It should consequently be a good material to check the Kittel-Van Vleck relation between g' and the spectroscopic splitting factor g.

Two separate series of experiments have been conducted by the author on this alloy. The value[23] obtained in 1953 after correction for the optical error previously mentioned was 1.910 ± 0.002. These experiments were repeated[24] in 1960 and resulted in a g' value of 1.905 ± 0.002.

Ferromagnetic Alloys of Manganese

Recently experiments have also been conducted by the author on two ferromagnetic alloys of manganese.[25] The g' value for the Heussler alloy Cu_2MnAl was given by Barnett[9] as 2.00 indicating complete orbital quenching. It was thought that more precise experiments to determine whether orbital quenching is complete to one lower order of magnitude might be of interest. Two different rods of Cu_2MnAl were used in these experiments and there was no significant difference between them. The average of all the experiments on Cu_2MnAl gave a g' value of 1.993 ± 0.002. Although this value departs only 0.35% from the spin only value for g', the precision of these experiments is such that it is thought unlikely that orbital quenching is complete.

Experiments were also conducted on a rod of manganese antimonide (MnSb). The value obtained for g' of 1.978 ± 0.002 indicates a considerably larger orbital contribution to the net magnetization for this alloy.

Nickel Ferrite

Magnetomechanical experiments on ferrites should furnish very direct evidence as to the source of the net magnetization in these materials. The torsional pendulum which is now being used utilizes a rod having a length to diameter ratio of about 15 to 1. For rods of this shape many ferrites can be magnetized to the same order of intensity as the ferromagnetic metals on which previous experiments have been conducted.

The rod used in these experiments[26] was made in the Physics Department of the General Motors Research Laboratories. Considerable care was used to assure the stoichiometry of $NiOFe_2O_3$. Correlation between individual daily experiments was better for this nickel ferrite than for any other material measured thus far

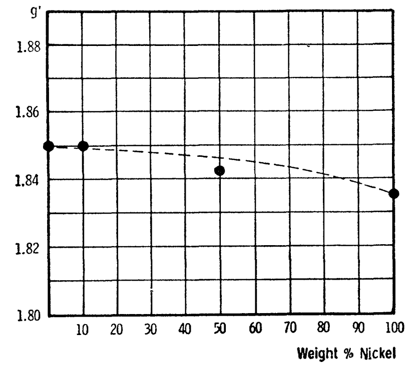

FIG. 7. g' vs % Ni for the Co-Ni alloys. The solid circles represent experimental values determined from measurements of the Einstein-de Haas effect. The dashed curve was obtained using a magnetization ratio of 3.0 which is the ratio of the saturation intensities for Co and Ni.

at this laboratory. The g' value of 1.849 ± 0.002 indicates that the net magnetization in this material is largely due to the Ni^{++} ions as in the Néel model.

Pyrrhotite

The gyromagnetic ratio of pyrrhotite (Fe_7S_8) was measured in 1935 by Coeterier[27] who obtained a g' value of 0.63. This extraordinary value is unexplainable on the basis of recent models[28] for the ferrimagnetism of this material.

Pyrrhotite is an extremely difficult material on which to make gyromagnetic measurements. Not only is it very weakly ferromagnetic, but it is also subject to relatively large field coupling torques because of its highly anisotropic nature.

These gyromagnetic ratio experiments on pyrrhotite were conducted at the laboratory described in this paper.[29] The sample was fabricated at the University of Strasbourg under the direction of Dr. André J. P. Meyer. Natural crystals were crushed into particles having grain sizes between 0.25 mm and 0.70 mm and a magnetic method of selecting those grains having the highest possible permeability was used. These grains were placed in a thin walled brass tube and fixed in paraffin with random orientation. Originally, favorable orientation of the individual grains was attempted. However, this led to excessive field coupling due to difficulty in making the easy magnetization directions coincide exactly with the axis of rotation of the cylinder. As used, this pyrrhotite sample produced a net gyromagnetic torque about 1/400 of that which was obtained for Fe. It was therefore necessary to utilize a diffracting slit and microscope arranged so that angular displacements could be estimated to 1/100 mm at the end of the 16 meter optical arm.

[23] G. G. Scott, Phys. Rev. **89**, 618 (1953).
[24] G. G. Scott, Phys. Rev. **120**, 331 (1960).
[25] G. G. Scott, Phys. Rev. **121**, 104 (1961).
[26] G. G. Scott, Phys. Rev. **123**, 434 (1961).
[27] F. Coeterier, Helv. Phys. Act. **8**, 522 (1935).
[28] L. Néel, Revs. Modern Phys. **25**, 58 (1953).
[29] G. G. Scott and André J. P. Meyer, Phys. Rev. **123**, 1269 (1961).

TABLE V. Experimental verification of the Kittel-Van Vleck relation between g and g'.

Material	Ferromagnetic resonance experiments: Investigators	Year	g	$g/(g-1)$	Magneto-mechanical experiments g'
	Bagguley[a]	1953	2.16	1.86	
Fe	Barlow, Standley[b]	1956	2.09	1.92	
	Asch[c]	1959	2.09	1.92	
	Rodbell[d]	1959	2.05	1.95	
		Average		1.91	1.92
Co	Bagguley[a]	1953	2.23	1.81	
	Asch[e]	1959	2.18	1.85	
		Average		1.83	1.85
	Bloembergen[f]	1950	2.20	1.83	
	Young, Uehling[g]	1954	2.28	1.78	
	Bagguley, Herrick[h]	1954	2.22	1.82	
Ni	Standley, Reich[i]	1955	2.19	1.84	
	Reich[j]	1956	2.21	1.83	
	Meyer[k]	1958	2.17	1.84	
	Asch[e]	1959	2.17	1.85	
		Average		1.83	1.84
	Hoskins, Wiener[l]	1954	2.13	1.88	
FeNi	Asch[e]	1959	2.10	1.91	
		Average		1.90	1.91
CoNi	Meyer, Asch[m]	1959	2.18	1.85	1.84
Supermalloy	Bloembergen[f]	1950	2.12	1.89	
	Young, Uehling[g]	1954	2.07	1.93	
		Average		1.91	1.91
Cu_2MnAl	Yager, Merritt[n]	1949	2.01	1.99	1.99
MnSb	Adam, Standley[o]	1952	2.10	1.91	1.98
$NiOFe_2O_3$	Yager *et al.*[p]	1950	2.19	1.84	
	Yager, Galt, Merritt[q]	1955	2.19	1.84	
		Average		1.84	1.85

[a] See reference 30.
[b] See reference 31.
[c] See reference 32.
[d] See reference 33.
[e] See reference 34.
[f] See reference 35.
[g] See reference 36.
[h] See reference 37.
[i] See reference 38.
[j] See reference 39.
[k] See reference 40.
[l] See reference 41.
[m] See reference 42.
[n] See reference 43.
[o] See reference 44.
[p] See reference 45.
[q] See reference 46.

These experiments on pyrrhotite resulted in a g' value of $1.9\pm15\%$.

Comparison with Ferromagnetic Resonance Experiments

Table V compares g' values with the results of various ferromagnetic resonance experiments.[30–46] The resonance g values have been converted to their magnetomechanical equivalent by using the Kittel-Van Vleck relation. With the exception of MnSb the agreement existing between magnetomechanical experiments and ferromagnetic resonance experiments is very good.

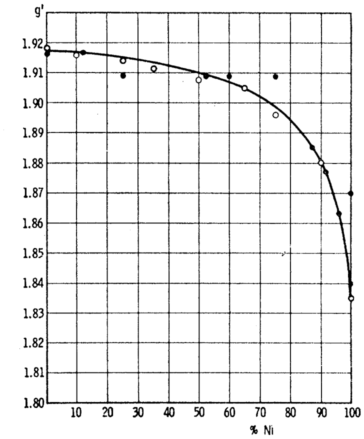

FIG. 8. g and g' values for the Fe-Ni alloys. The open circles as points obtained by Scott using the Einstein-de Haas effect. The solid circles represent the factor $g/(g-1)$ from g values obtained by Georges Asch using ferromagnetic resonance.[32]

Further confirmation of the Kittel-Van Vleck relation is obtained from recent ferromagnetic resonance experiments on a series of FeNi alloys made by Asch[32] at the University of Strasbourg. In Fig. 8 the factor $g/(g-1)$ derived from these experiments is plotted along with the curve of g' vs percentage Ni obtained by the author. Asch used two samples of 100% Ni in this series. It is the sample of highest purity which checks the g' determinations.

Electron Inertia Experiments

Since the g' value associated with the magnetic moment generated by a current-carrying loop of wire is exactly one, the techniques which have been developed for gyromagnetic work can be used to determine the sign and specific charge of the carrier of electricity in the metal which forms the conducting loop.

Such experiments may seem to be relatively unimportant since it is tacitly assumed that electrons are the electric carriers in all metallic conductors. However, because of their basic nature such experiments do have some interest. Electron inertia experiments by the author[47] on three copper coils and one aluminum coil resulted in an m/e value of $-5.69\pm0.03\times10^{-9}$ grams/coulomb. The accepted value for the electron is -5.68×10^{-9} grams/coulomb. An experiment was also conducted on a coil of cadmium wire[48] the result being $-5.5\pm0.2\times10^{-9}$ grams/coulomb.

[30] D. M. S. Bagguley, Proc. Phys. Soc. (London) **A66**, 765 (1953).
[31] G. S. Barlow and K. J. Standley, Proc. Phys. Soc. (London) **B69**, 1052 (1956).
[32] George Asch, Compt. rend. **249**, 1483 (1959).
[33] D. S. Rodbell, J. Appl. Phys. **30**, 1875 (1959).
[34] George Asch, Compt. rend. **248**, 781 (1959).
[35] N. Bloembergen, Phys. Rev. **78**, 572 (1950).
[36] J. A. Young and E. A. Uehling, Phys. Rev. **94**, 544 (1954).
[37] D. M. S. Bagguley and N. J. Herrick, Proc. Phys. Soc. (London) **A67**, 648 (1954).
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TABLE VI. Summary of g' values obtained by G. G. Scott using Einstein-de Haas effect.

Material	Year obtained	g'
Fe	1959	1.919±0.002
Co	1956	1.850±0.004
Ni	1959[a]	1.835±0.002
$Fe_{0.90}Ni_{0.10}$	1954	1.915±0.004
$Fe_{0.75}Ni_{0.25}$	1954	1.914±0.004
$Fe_{0.65}Ni_{0.35}$	1955	1.912±0.002
$Fe_{0.50}Ni_{0.50}$	1954	1.908±0.004
$Fe_{0.35}Ni_{0.65}$	1955	1.904±0.004
$Fe_{0.25}Ni_{0.75}$	1955	1.895±0.004
$Fe_{0.10}Ni_{0.90}$	1955	1.880±0.006
$Co_{0.90}Ni_{0.10}$	1960	1.850±0.002
$Co_{0.50}Ni_{0.50}$	1960	1.843±0.002
Supermalloy	1960	1.905±0.002
$NiOFe_2O_3$	1961	1.849±0.002
Cu_2MnAl	1960	1.993±0.002
MnSb	1960	1.978±0.002
Pyrrhotite	1960	1.9 ±15%

[a] Average of four experiments—1951, 1953, 1955, 1959. Subscripts used with alloys refer to weight percentages.

Similar experiments were conducted by Barnett[49,50] on Cu, Mo, and Zn.

Summary

Table VI summarizes g' values obtained by the author which are reviewed in this paper. The largest measured g' value is 1.993 for the Heussler alloy Cu_2MnAl. The smallest is 1.835 for nickel. Hence there exists what might be called a range of interest which covers only about 8%. This reemphasizes the necessity for precision in making these measurements if the results are to have theoretical significance.

The experimental techniques which have been used to obtain these results were developed over a period of about 18 years. During this time many control experiments were conducted using toroidal samples having a zero net magnetic moment. Such samples, of course, also have zero gyromagnetic torque, but they do have all of the possibilities of coupling with extraneous magnetic fields which are exhibited by the cylindrical samples used in the gyromagnetic work. Also torques incident to reversing current directions on suspended systems can be observed in such control experiments.

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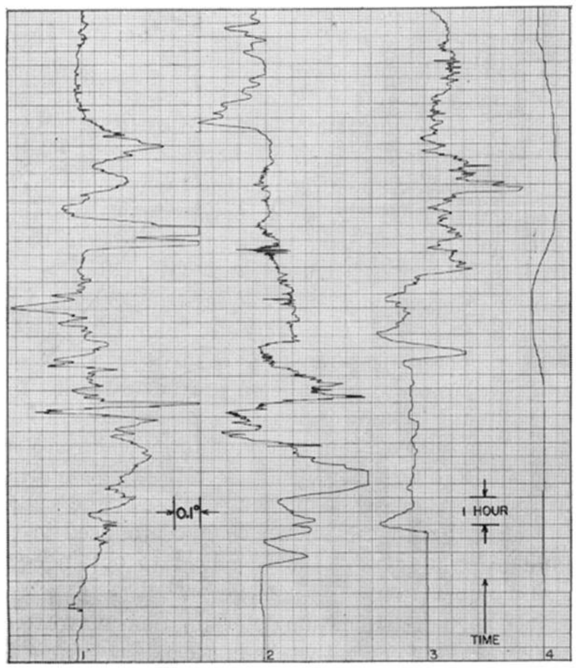

FIG. 1. Variation in magnetic declination for four different 24-hour periods.

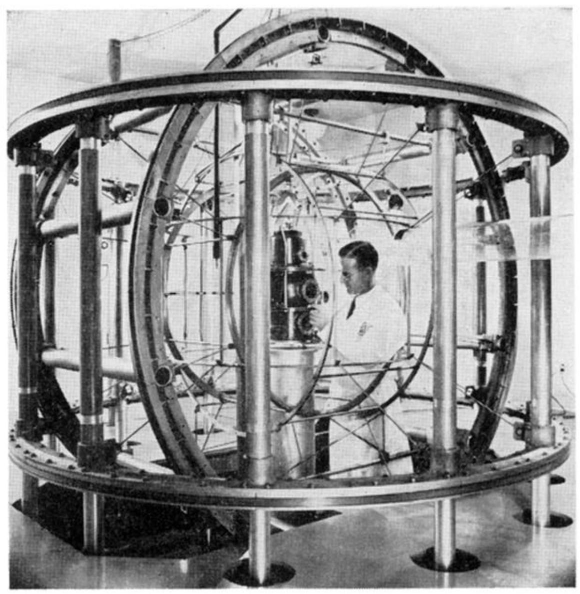

FIG. 2. Coil system used for neutralizing the earth's magnetic field.