The Gyromagnetic Ratios of the Ferromagnetic Elements

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The gyromagnetic ratios for the three ferromagnetic elements have been determined by means of a technique involving a sensitive torsional pendulum. The final values obtained, in terms of the mass-to-charge ratio of the electron, are: iron 1.028±0.001; cobalt 1.068±0.004; and nickel 1.078±0.002.

INTRODUCTION

THE values of the gyromagnetic ratios for the ferromagnetic elements given in this paper are the result of a very extensive investigation undertaken at the General Motors Research Laboratories during the past four years. The results for iron have already been reported, and the reader is referred to that paper[1] for a description of the apparatus and of the experimental techniques used.

The rods used for the three ferromagnetic elements were very nearly of the same dimensions (1.5 cm diameter and 22 cm long). In the case of both iron and nickel, these rods were of very high purity. A cobalt rod of high purity could not be obtained. Measurements for this material were made on two different rods; each of them contained about 1 percent nickel as an impurity.

TABLE I. Condensed data for the determination of the gyromagnetic ratio of nickel.

Date	Double amplitude change per reversal d (cm)	Element current i_e (amp)	Element magnetic moment M_e (amp cm²)	Period P (sec)	Azimuth positions	Gyromagnetic ratio (in terms of m/e for the electron)
1- 9-51	0.03708	0.01601	22289	26.647	XY	1.074
1-10-51	0.03722	0.01601	22284	26.652	XY	1.078
1-11-51	0.03687	0.01600	22272	26.650	RS	1.068
1-17-51	0.03691	0.01600	22237	26.654	RS	1.071
1-18-51	0.03720	0.01600	22265	26.651	RS	1.079
1-19-51	0.03738	0.01600	22255	26.650	XY	1.085
1-24-51	0.03736	0.01601	22268	26.645	XY	1.084
1-25-51	0.03671	0.01600	22263	26.642	XY	1.064
1-26-51	0.03676	0.01601	22247	26.643	RS	1.066
1-29-51	0.03766	0.01600	22241	26.645	RS	1.095
1-31-51	0.03729	0.01600	22261	26.645	XY	1.082
2- 2-51	0.03730	0.01600	22246	26.641	XY	1.083
2- 6-51	0.03751	0.01601	22261	26.647	RS	1.089
2- 7-51	0.03742	0.01601	22199	26.649	RS	1.089
2- 8-51	0.03699	0.01601	22193	26.640	RS	1.076
2- 9-51	0.03651	0.01601	22147	26.638	XY	1.063
2-12-51	0.01571	0.00861	9292	26.618	XY	1.078
2-13-51	0.01601	0.00861	9283	26.616	RS	1.103
2-14-51	0.01543	0.00861	9273	26.613	XY	1.059
					Average	1.078

Area summation of element winding $\Sigma A = 74858$ cm²
Moment of inertia for 16-milliampere runs $I = 206.89$ gram cm²
Moment of inertia for 8.6-milliampere runs $I = 206.75$ gram cm²
Note: 8.6-milliampere values weighted $\frac{1}{2}$ because of the decreased accuracy obtained with this lower value of the element current.

[1] G. G. Scott, Phys. Rev. **82**, 542 (1951).

RESULTS ON NICKEL

The final readings to determine the gyromagnetic ratio of nickel were taken on 19 different days. The work each day consisted of four separate runs taken in two pairs. The first run of a pair would be at one particular azimuth position. The azimuth would then immediately be changed by 180° and the second run of the pair obtained. The second pair would be a repetition of the first pair, except that the small reversing switch located below the pendulum would be reversed. In each run the amplitude was first built up for 30 periods of the torsional pendulum system and then cut down for 30 periods. This was done by synchronously reversing the current in the gyromagnetic pendulum winding. From the amplitude readings taken during these runs the change in angular momentum corresponding to a given change in magnetic moment was computed and the gyromagnetic ratio thereby determined.

Table I gives a day-by-day summary of all the data taken to determine the gyromagnetic ratio of nickel. Table II gives a semiquantitative spectrographic analysis of the nickel rod.

For both nickel and cobalt the magnetic permeability is quite sensitive to temperature. Great care was therefore taken to allow for these temperature effects in determining magnetic moments. With 16 ma flowing in its winding, the nickel rod had a magnetic moment of 22,280 amp cm², and an increase of one degree Fahrenheit would cause an increase of 15 amp cm² in the magnetic moment.

These magnetic moments were ultimately determined by a series of measurements of values of the torque produced by the field of the 8-ft diameter north-south Helmholtz coil system.

RESULTS ON COBALT

In determining angular momentum changes in the cobalt specimens, nonuniformity of magnetization

TABLE II. Semiquantitative spectrographic analysis of impurities in the nickel rod used in gyromagnetic experiments.

Iron	0.003% to 0.03%
Cobalt	0.003 to 0.03
Silicon	0.03 to 0.3
Manganese	0.02 to 0.2
Antimony	0.003 to 0.03
Silver	0.001 to 0.01

TABLE III. Condensed data for the determination of the gyromagnetic ratio of cobalt (IN specimen).

Date	Double amplitude change per reversal d (cm)	Element current i_e (amp)	Element magnetic moment M_e (amp cm²)	Period P (sec)	Azimuth positions	Element switch positions	Gyromagnetic ratio[a] (in terms of m/e of the electron)
6- 6-51	0.07043	0.01601	42129	26.226	*XY*	AB	1.109
6-11-51	0.06975	0.01601	42252	26.331	*XY*	AB	1.090
6-14-51	0.03474	0.00901	21982	26.255	*RS*	AB	1.042
6-19-51	0.03486	0.00901	21984	26.262	*RS*	AB	1.045
6-20-51	0.02608	0.00701	16386	26.259	*RS*	AB	1.048
6-21-51	0.04937	0.01201	30724	26.270	*RS*	AB	1.061
6-25-51	0.04868	0.01201	30680	26.269	*RS*	AB	1.047
6-26-51	0.06777	0.01601	42256	26.285	*RS*	AB	1.059
6-27-51	0.06663	0.01601	42298	26.283	*RS*	AB	1.039
7- 3-51	0.03619	0.00901	22013	26.257	*XY*	AB	1.086
7- 5-51	0.03655	0.00901	21981	26.253	*XY*	AB	1.099
7- 6-51	0.05017	0.01201	30695	26.268	*XY*	AB	1.080
7- 9-51	0.05058	0.01201	30705	26.271	*XY*	AB	1.089
7-10-51	0.02730	0.00701	16413	26.259	*XY*	AB	1.098
						XYRS four azimuth average	1.071
10- 2-51	0.03584	0.00901	22196	26.821	*VWPQ*	A	1.061
10- 3-51	0.03537	0.00901	21957	26.810	*VWPQ*	B	1.059
10- 4-51	0.03536	0.00901	22054	26.821	*VWPQ*	A	1.053
10- 5-51	0.03489	0.00901	22015	26.808	*VWPQ*	B	1.041
10-10-51	0.03381	0.00901	21972	26.801	*VWPQ*	B	1.009
10-11-51	0.03649	0.00901	21959	26.790	*VWPQ*	A	1.095
						VWPQ four azimuth average	1.053
						Average for all eight azimuth positions	1.062

Area summation of element winding $\Sigma A = 74149$ cm²
Moment of inertia for first set $I = 204.49$ gram cm²
Moment of inertia for second set $I = 208.02$ gram cm²
Note: increase in moment of inertia for second set is caused by a design change in suspension support.

[a] Individual values include magnetic coupling errors.

caused a higher order of magnetic coupling error to become important. Because of this nonuniformity and because of very small magnetic gradients in the neutralized space, two 180° separated azimuth positions were no longer sufficient to eliminate magnetic coupling errors. It was found necessary to take readings at eight 45° spaced azimuth positions in order to eliminate magnetic coupling errors. Also readings at two positions of the small reversing switch located below the element were required in order to eliminate suspension effects.

TABLE IV. Condensed data for the determination of the gyromagnetic ratio of cobalt (GM specimen).

Date	Double amplitude change per reversal d (cm)	Element current i_e (amp)	Element magnetic moment M_e (amp cm²)	Period P (sec)	Azimuth positions	Element switch positions	Gyromagnetic ratio[a] (in terms of m/e of the electron)
7-18-51	0.04174	0.00901	23201	26.123	*RS*	AB	1.189
7-19-51	0.03547	0.00901	23191	26.121	*XY*	AB	1.001
7-24-51	0.03831	0.00902	23211	26.117	*XYRS*	A	1.085
7-26-51	0.03853	0.00901	23233	26.115	*XYRS*	B	1.091
						XYRS four azimuth average	1.092
9- 6-51	0.03635	0.00901	23125	26.045	*VWPQ*	A	1.063
9- 7-51	0.03605	0.00901	23095	26.037	*VWPQ*	B	1.056
9-11-51	0.03615	0.00901	23154	26.050	*VWPQ*	B	1.055
9-13-51	0.03622	0.00901	23165	26.046	*VWPQ*	A	1.057
						VWPQ four azimuth average	1.058
						Average for all eight azimuth positions	1.075

Area summation of element winding $\Sigma A = 84458$ cm²
Moment of inertia for first set $I = 202.90$ gram cm²
Moment of inertia for second set $I = 208.38$ gram cm²
Note: increase in moment of inertia for second set is caused by a design change in suspension support.

[a] Individual values include magnetic coupling errors.

TABLE V. Chemical analysis of impurities in the cobalt rods used in gyromagnetic experiments.

	International Nickel Company specimen	General Motors Research Laboratories specimen
Nickel	0.87%	0.93%
Iron	0.12	0.10
Silicon	0.26	0.10
Manganese	0.22	0.03
Aluminum	0.11	...
Carbon	0.02	...
Sulfur	0.01	...
Chromium	...	0.08
Cadmium	...	0.05

The mirror on the gyromagnetic pendulum system had four 90° spaced faces so that readings at four 90° azimuth positions could be readily obtained. To obtain readings at eight azimuth positions, the data were taken in two sets. In the second set this four-sided mirror was rotated 45° from the position it occupied for the first set. In the Tables azimuth positions X and Y are 180° apart. Positions R and S are likewise 180° apart and 90° removed from X and Y. In the second set, V and W are 180° apart, and P and Q are likewise 180° apart and 90° removed from V and W.

One of the two different rods used in working with cobalt was furnished by the International Nickel Company and is labeled IN in the Tables. The other rod was cast by the Metallurgical Department at the General Motors Research Laboratories. This second rod is labeled GM in the Tables.

A summary of all the data obtained on the IN cobalt rod is given in Table III. This information is tabulated in the order in which it was taken. Each azimuth set is averaged and the average of the two sets taken to determine the final value for the rod. A similar tabulation for the GM cobalt rod is given in Table IV, and a chemical analysis of the two rods is shown in Table V.

The difference between the two rods is probably caused by accidental error rather than to the effect of different amounts of impurities. In obtaining the average value for cobalt, the IN rod is weighted 3 to 2 for the GM rod because of the larger number of readings taken on the IN rod.

TABLE VI. Final values for the gyromagnetic ratios of the ferromagnetic elements expressed in terms of the mass-charge ratio of the electron (ρ) along with the corresponding Landé factors (g').

	ρ	g'
Iron	1.028±0.001	1.946
Cobalt	1.068±0.004	1.873
Nickel	1.078±0.002	1.855

The final value for cobalt is, therefore, $1.068m/e \pm 0.004$.

SUMMARY

In Table VI we have the final tabulation of the values measured in these experiments for the gyromagnetic ratios of the ferromagnetic elements, in terms of the mass-charge ratio of the electron. The corresponding Landé factors are also given in this table.

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Proton-Proton Scattering at 5 Mev by a Coincidence Method*

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The scattering of 5-Mev protons by protons was examined by a coincidence method. Particular attention was given to the absolute value of the differential cross section at 45° in the laboratory system. The differential cross sections at other angles were determined relative to the cross section at 45°. The S-wave phase shift calculated from the observed cross section at 45° agrees, within the experimental error, with that from other experiments in this energy range. No indication of a P-wave effect was observed.

INTRODUCTION

PROTON–PROTON scattering at 5 Mev has been reported by two other workers,[1,2] one of them from this laboratory. In view of the fact that both of these results were obtained by the photographic plate technique, it appears to be desirable to report the results obtained by a totally different method. The method employed in the present work is similar to that described by Wilson and co-workers,[3] which uses two proportional counters placed at 90° with respect to one another and a hydrogenous foil used as a scattering medium. True scattering events are recorded by coincidence pulses between the two counters. Knowing the angle between the scattered and recoil particles makes it possible to predetermine the geometrical factors involved, except for the effect of multiple scattering.

APPARATUS

The apparatus used in the present experiment is basically the same as that described by Karr *et al.*[4] Minor circuit improvements were made and an oscillating foil holder was added. The purpose of the latter was to provide an automatic method of averaging over variations in foil thickness. The same definitions of defining and conjugate counter apply, i.e., the defining counter and defining slit are to be associated with the solid angle definition and resolution of the experiment. The conjugate counter and conjugate slit are to be associated with the particles conjugate to those entering the defining counter.

PROCEDURE AND CALCULATIONS

The only measurement of absolute cross section was made at an angle $\Theta = 45°$ in the laboratory frame of reference. The scattering yield from seven foils was measured by observing no less than 10,000 scattering events from any one foil.[5] Variations in foil thickness

TABLE I. The letter in column 1 designates the foil. A, B, C, and E_2 were Nylon foils. B_2, D, and E were polyethylene-terephthalate foils. Column 2 shows the average number of hydrogen atoms per cm² and column 3 lists the laboratory cross section as determined from that foil. The correction for multiple scattering is not included in these figures.

Foil	$N \times 10^{-19}$	$\sigma(45°) \times 10^{24}$ cm² steradian^{-1}
A	3.293	0.268
B	2.785	0.259
B_2	1.921	0.262
C	2.907	0.261
D	1.816	0.274
E	1.682	0.273
E_2	2.957	0.262

$\sigma(45°)_{Av} = 0.266 \pm 0.002 \times 10^{-24}$ cm² steradian^{-1}.

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† Now at Los Alamos Scientific Laboratory, Los Alamos, New Mexico.
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[1] R. E. Meagher, Phys. Rev. 78, 667 (1950).
[2] K. B. Mather, Phys. Rev. 82, 133 (1951).
[3] R. R. Wilson and E. C. Creutz, Phys. Rev. 71, 339 (1947); R. R. Wilson, Phys. Rev. 71, 384 (1947); and Wilson, Lofgran, Richardson, Wright, and Shankland, Phys. Rev. 72, 1131 (1947).
[4] Karr, Bondelid, and Mather, Phys. Rev. 81, 37 (1951).

[5] It was found that prolonged bombardment caused changes to occur in the foil. Hence, the seven foils used to determine the absolute cross section were not subjected to any previous bombardment and only the first observation of Y on any one foil was used to determine the absolute cross section. The relative cross sections were determined by making successive measurements at different angles during a period of foil stability. A foil was considered to be stable when no change was observed in the yield at a given angle as a function of bombardment time.