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The Magnetic Scattering of Neutrons*

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The interaction of neutrons with ferromagnetic materials has been investigated through a number of experiments. Because of the dependence of the interaction upon the spin orientation of the neutron relative to the magnetic field of the atom, and the effect of this spin dependent perturbation on the nuclear scattering, a beam of neutrons transmitted through or scattered from a magnetized iron plate becomes polarized by selective scattering.

This resultant neutron polarization has been studied most thoroughly through the increase in intensity of a neutron beam transmitted through a single iron plate when magnetized. The dependence of observed polarization on thickness of iron has been shown to agree within the limits of error with the theories of Bloch and Schwinger. The dependence of magnetic interaction on neutron energy was studied by the use of an effective "howitzer" for the production of low energy neutrons. The interaction increased rapidly for lower energy neutron energies, as would be expected, since the form factor for the interaction increases for longer neutron wave-lengths. The effective cross sections of iron for neutrons of spin $+\frac{1}{2}$ and $-\frac{1}{2}$ have been determined to be 13.7×10^{-24} cm^2 and 10.3×10^{-24} cm^2 for $\sim300°$K neutrons, and 14.1×10^{-24} cm^2 and 9.9×10^{-24} cm^2 for $\sim120°$K neutrons. Considering the uncertainty in the values to be expected theoretically, these cross sections are probably in reasonable agreement with the theories.

The intensity of neutrons scattered from a single iron plate has been shown to decrease when the plate is magnetized. Neutron polarization has also been studied through the change in neutron intensity when a beam of neutrons partially polarized by transmission through one plate of magnetized iron is scattered from or transmitted through a second iron plate magnetized parallel or antiparallel to the first. (Polarizer-analyzer action.)

These experiments show definitely the existence of nonadiabatic transitions of the magnetic spin quantum numbers of the neutron in rotating or precessing magnetic fields whose frequency is of the same order as the Larmor precession frequency, $g\mu H/h$, for the neutron.

The sign and the approximate magnitude of the neutron's magnetic moment have been determined by an experiment which depended on measuring the probability of nonadiabatic transitions in a controlled precessing magnetic field. This experiment was dependent only on the neutron properties in free space. The neutron magnetic moment has been shown to be negative in sign, and to be 2 ± 1 nuclear magnetons in magnitude.

INTRODUCTION

On the assumption that the neutron has a magnetic moment, Bloch's original investigations[1] showed that there should be an appreciable magnetic interaction between a neutron and an atom of ferromagnetic material. This interaction arises from the atomic magnetic forces which, though small, are of long range in comparison with nuclear forces. Bloch made his calculations treating the atomic magnetic field as that due to an equivalent dipole of the electron currents and showed that the interaction should depend upon the relative orientation of the neutron with respect to the atomic magnetic field; i.e., it should be spin dependent. Schwinger[2] carried out a similar calculation in which he treated the atomic magnetic field as that due to the Dirac electron currents.

The calculations indicate that if σ is the total neutron cross section of demagnetized iron for "slow" (strongly absorbed in Cd) neutrons, then for magnetized iron the cross section becomes $\sigma(1+p)$ and $\sigma(1-p)$ for neutrons which have spin components of $+\frac{1}{2}$ and $-\frac{1}{2}$ in the direction of the field (or vice versa), where p is a constant whose predicted value is of the order of 0.07 to 0.3.[1-4] If a beam of neutrons passes through a magnetized iron sheet of thickness x_1, and atomic density n, the fraction P transmitted (i.e., I/I_0) should be:

$$P=\tfrac{1}{2}e^{-nx_1\sigma(1+p)}+\tfrac{1}{2}e^{-nx_1\sigma(1-p)} \quad (1)$$
$$=e^{-nx_1\sigma}\cosh n\sigma x_1 p \quad \text{—magnetized}$$

$$\text{and}\quad P=e^{-nx_1\sigma} \quad \text{—demagnetized.} \quad (2)$$

For p different from zero, i.e., $\cosh n\sigma x_1 p>1$, a beam of neutrons transmitted through magnetized iron should not only become "polarized,"

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[1] Bloch, Phys. Rev. **50**, 259 (1936).

[2] Schwinger, Phys. Rev. **51**, 544 (1937).

[3] Schwinger, Phys. Rev. **52**, 1250 (1937).

[4] Hoffman, Livingston and Bethe, Phys. Rev. **51**, 214 (1937).

but should also have greater intensity than with the iron demagnetized, since the transmission in that case would be only $e^{-nx_1\sigma}$. This increase in neutron transmission through magnetized iron provides one of the simplest methods for observing neutron polarization. In principle the difference between the two cross sections for the two states arises from the interference between the nuclear scattering and the electronic scattering.

If a partially polarized neutron beam be allowed to pass through a second magnetized plate of thickness x_2, then, depending on whether the magnetization in the second plate is parallel or antiparallel to that in the first plate, the transmitted intensities should be, respectively:

$$P=e^{-n\sigma(x_1+x_2)}\cosh pn\sigma(x_1+x_2) \quad \text{—magnetized parallel} \tag{3}$$

and

$$P=e^{-n\sigma(x_1+x_2)}\cosh pn\sigma(x_1-x_2) \quad \text{—magnetized antiparallel} \tag{4}$$

or

$$P=e^{-n\sigma(x_1+x_2)} \quad \text{—if } x_1=x_2.$$

It is evident that if $x_1=x_2$, the antiparallel case should give the same transmitted intensity as with the iron plates demagnetized. Thus one should expect the maximum intensity when two plates are magnetized in the same direction and the minimum intensity when they are magnetized antiparallel; however, the latter should be the same as if both plates were demagnetized. The second plate may be considered to be an "analyzer."

A variety of configurations are possible in which measurements of intensities may be used to study neutron polarization. These may be grouped into six general types.

1. *Single transmission.* Change in number of neutrons transmitted through a single plate of iron when magnetized.
2. *Single scattering.* Change in number of neutrons scattered from iron when magnetized.
3. *Double transmission.* Change in number of neutrons transmitted successively through two iron plates when the plates are magnetized parallel and antiparallel to each other.
4. *Transmission scattering.* Change in number of neutrons which are first transmitted through one plate and then scattered from a second iron plate whose directions of magnetization are parallel or antiparallel to that in the first.
5. *Scattering transmission.* Change in number of neutrons which are first scattered from one iron plate and then transmitted through a second iron plate whose magnetization directions are parallel or antiparallel.
6. *Double scattering.* Change in number of neutrons which are scattered successively from two iron plates when they are magnetized parallel or antiparallel to one another.

Quantitative experiments of types 1, 2 and 3 have been performed and will be separately discussed. Types 4 and 5 have been performed with less accuracy because of the low intensity of the scattered neutron beam. Regardless of the intensity of the primary neutron beam, the slow neutrons are always superimposed on an ever-present background of faster neutrons for which Cd does not have a large absorption cross section; i.e., neutrons above the Cd resonance level (above ~0.3 ev) which are also detected by the boron trifluoride ion chamber. Type 6, involving double scattering, has been found impossible to perform satisfactorily with the present neutron sources.

Single Transmission Experiments

Dependence of neutron polarization on (a) thickness of iron, and (b) neutron energy

The most complete investigations of neutron scattering in magnetized iron have been made with experiments of the single transmission type, since they are simpler and involve less possibility of disturbing effects. Fig. 1 shows the essential experimental arrangement used to study the magnitude of the observed neutron polarization as a function of (*a*) thickness of iron, and (*b*) neutron energy. Preliminary results were reported earlier.[5–7]

Neutron source for ~300°K and ~120°K neutrons.—For measurements with neutrons with an energy distribution corresponding to ~300°K, mean energy ~0.037 ev,[8–10] Rn–Be sources of

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[5] Powers, Carroll and Dunning, Phys. Rev. **51**, 371 (1937).

[6] Powers, Carroll and Dunning, Phys. Rev. **51**, 1112 (1937).

[7] Dunning, Powers and Beyer, Phys. Rev. **51**, 382 (1937).

[8] Dunning, Pegram, Fink, Mitchell and Segrè, Phys. Rev. **48**, 704 (1935).

[9] Fink, Dunning, Pegram and Mitchell, Phys. Rev. **49**, 103 (1936).

[10] Fink, Phys. Rev. **50**, 738 (1936).

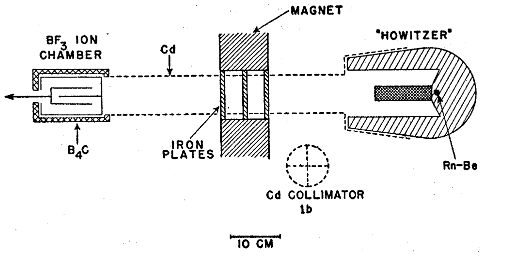

FIG. 1. Schematic arrangement of apparatus for investigation of magnetic scattering in iron as a function of thickness of iron and neutron energy. For measurements with low energy neutrons, the "howitzer" shown in Fig. 2 was used.

300 to 650 mC strength were placed in a paraffin "howitzer" of the usual type, as shown in Fig. 1. For measurements with lower energy neutrons, the special "howitzer" shown in Fig. 2 was constructed in a Dewar flask. The paraffin could be continuously and uniformly cooled by the circulation of liquid nitrogen through the imbedded copper tubing and a minimum amount of material was placed in the neutron beam. The Rn—Be source was placed in a small Dewar with a heater element and thermocouple so that it might be kept at room temperature and thus prevent changes in neutron intensity due to nonuniform condensation of the radon in the various parts of the source.

The temperature of the paraffin was normally maintained at approximately 105°K as measured by two thermocouples imbedded at different points. The "effective temperature" of the neutrons under these conditions was determined by a measurement of the absorption of the neutrons in boron, first with the "howitzer" at ~300°K and then at ~105°K. On the basis of the $1/v$ law for boron,[11] the absorption cross section should increase by $(300/105)^{\frac{1}{2}}$ or 1.70 for the low temperature if complete equilibrium were obtained. The average observed increase for a number of measurements was 1.60, hence from $(300/T_{\text{eff}})^{\frac{1}{2}}=1.60$, $T_{\text{eff}}=\sim 117°\text{K}$. The average energy then corresponds to ~0.015 ev. This approach to equilibrium is the most complete yet obtained.[12]

Detection system.—The sensitivity necessary for these experiments was obtained by a boron-trifluoride pressure ion chamber (see Fig. 3), connected to a linear amplifier system and scale-of-two thyratron recorder.[17]

This chamber represents nearly the maximum feasible size because of the difficulty in achieving sufficiently small collection time and sufficiently small recombination of the ions produced in BF_3 under pressure. The type of collector system shown makes possible the effective collection of ions throughout the large volume, but the increasing capacitance sets an upper limit on the usable size. A pressure of two atmospheres of BF_3 was the maximum which could be used and still give ionization pulses which were sufficiently large and sharp for proper recording with a collection potential of 1650 v. Under these conditions, a maximum of 35 percent of the incident slow neutrons were detected. With quartz insulation, this type of chamber has an indefinite life, some chambers having been in service over two years.

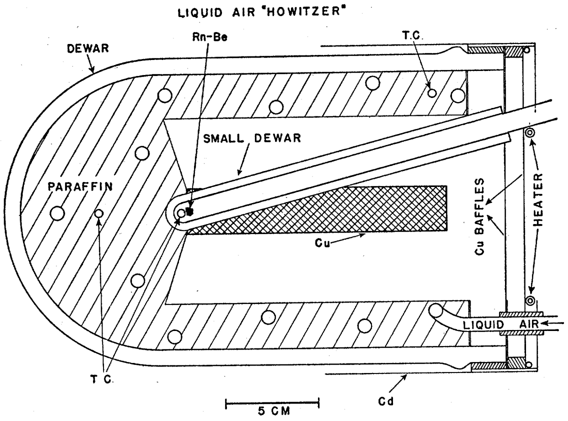

FIG. 2. Neutron source arrangement for lower energy neutrons. The paraffin was cooled by circulating liquid nitrogen through the imbedded copper tubing. An average temperature of ~105°K was maintained, and the "effective temperature" of the neutrons approximated ~120°K, corresponding to an average energy of ~0.015 ev.

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[11] Rasetti, Mitchell, Fink and Pegram, Phys. Rev. **49**, 777 (1936).

[12] A series of measurements of the cross sections of a number of other elements with this "howitzer" has already been reported.[13] The "howitzer" was also used by Dunning, Brickwedde, Manley and Hoge in the experiments on the scattering of neutrons by ortho- and parahydrogen.[14–16]

[13] Powers, Goldsmith, Beyer and Dunning, Phys. Rev. **53**, 947 (1938).

[14] Dunning, Manley, Brickwedde and Hoge, Phys. Rev. **52**, 1076 (1937).

[15] Dunning, Hoge, Manley and Brickwedde, Phys. Rev. **53**, 205 (1938).

[16] Brickwedde, Dunning, Hoge and Manley, Phys. Rev. **54**, 266 (1938).

[17] Dunning, Rev. Sci. Inst. **5**, 387 (1934).

The ionization chamber was magnetically shielded with 0.65 cm iron. Tests showed that under the conditions of the experiments the effects of stray magnetic fields on the detection of the neutrons was not larger than 0±0.20 percent.

The ionization chamber was also shielded by 0.5 cm Cd, and by a 1 cm layer of B_4C, to eliminate the slow neutrons and a large fraction of the faster neutrons just above the Cd absorption limit (i.e., above ~0.3 ev). The neutron beam was well collimated by Cd from source to detector so that the probability of a scattered neutron reaching the chamber was small.

Magnetization of the iron samples.—As shown in Fig. 1, the neutron beam was usually transmitted through one or more plates of unannealled Armco iron, each 10×12.5 cm in area, which were placed between the pole pieces of a large electromagnet.[18] The plates were accurately machined and surface ground so that an excellent magnetic circuit was maintained, and because of the large ratio of core area to plate cross-sectional area, high values of magnetization were attained. The value of the magnetizing field corresponded to approximately 1600 oersteds. The flux density within the iron was measured by a coil which was wrapped around one of the plates and connected to a fluxmeter or ballistic galvanometer. $B-H$ averaged approximately 21,000 to 21,500 gauss for the Armco iron samples.

Procedure and results.—The magnetic interaction was investigated by the change in transmitted neutron intensity first with the plates magnetized and then with the plates carefully demagnetized.

The collected results for a large series of runs are shown in Table I. A series of runs were taken with 0.80, 1.30 and 1.95 cm total thickness of iron for ~300°K neutrons and with 1.30 and 1.95 cm thickness of iron for ~120°K neutrons. The final result for the 1.95 cm thickness and ~300°K neutrons also includes additional data obtained under the same conditions in other experiments in the laboratory and hence has higher precision. A total of about 3,000,000 neutrons were counted in the experiments. The fast neutron background, taken with 0.5 mm Cd interposed in the beam, has been subtracted so that the readings of a number of neutrons per minute refer only to the slow neutrons below the Cd resonance absorption limit.

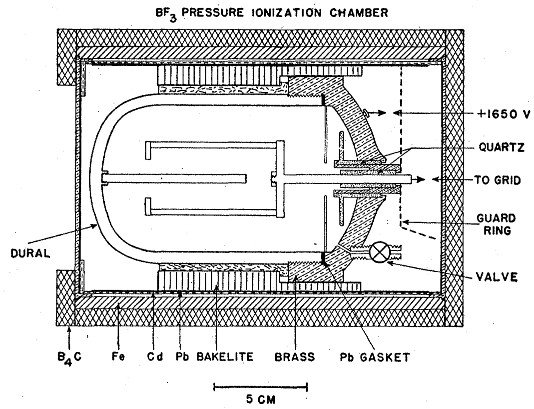

FIG. 3. Boron-trifluoride pressure ionization chamber for detection of slow neutrons. The cage-type collector with a re-entrant high potential electrode minimizes recombination of ions, and reduces ion collection time. Use of quartz insulation (skirt type on high potential) avoids deterioration of insulation in BF_3. Picein is satisfactory as sealing compound.

The last two columns in Table I include calculations of p and the values of $\sigma(1+p)$ and $\sigma(1-p)$, the effective cross section of iron per atom for neutrons of spin $+\frac{1}{2}$ and $-\frac{1}{2}$ in the direction of the field (or vice-versa). The difference between the effective cross sections of the iron for the two spin orientations is actually large: 13.7 as compared to 10.3×10^{-24} cm^2 for ~300°K neutrons and 14.0 as compared to 9.9×10^{-24} cm^2 for ~120°K neutrons.

The total cross section (capture and scattering) for iron has been determined as $12.0\pm0.2\times10^{-24}$ cm^2 for ~300°K neutrons and $12.0\pm0.7\times10^{-24}$ cm^2 ~120°K neutrons;[13, 19] hence there is no change in total cross section for lower energy neutrons beyond experimental error. The capture cross section for iron is probably about 3.5×10^{-24} cm^2 from the measurements of Fink,[10] Goldhaber,[20] and Whittaker and Beyer.[21] The normal scattering cross section is thus approximately 8.5×10^{-24} cm^2, and considered from this basis

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[18] Multiple separated plates with a Cd shielded channel were used in place of one thick plate in order to reduce multiple scattering, since earlier experiments had shown single thicknesses greater than one mean free path to give smaller polarization effects.

[19] Dunning, Pegram, Fink and Mitchell, Phys. Rev. **48**, 265 (1935).

[20] Goldhaber and Briggs, Proc. Roy. Soc. **A162**, 127–143 (1937).

[21] Whittaker and Beyer—in process of publication.

the difference between cross sections for the two spin values is still larger.

Dependence of magnetic scattering on neutron energy.—The change in scattering cross section should be proportional to the form factor, $\int \exp\,(i(\mathbf{k}_0-\mathbf{k})\mathbf{r})m(\mathbf{r})d\tau$, where $\mathbf{k}_0$ and $\mathbf{k}$ are the propagation vectors of the incident and scattered neutrons respectively and $m(\mathbf{r})$ is the magnetization density.[1, 2] Since this expression becomes larger for slower neutrons which have longer wave-length,[22] the percentage increase in transmission should also become larger.

The results in Table I and Fig. 4 show that the change in transmission for ~120°K neutrons is approximately 1.57 times that for ~300°K neutrons, while the average value of p increases by a factor of 1.27 for the lower energy neutrons. The magnetic scattering cross section for lower energy neutrons is thus in accord with the trend expected. The change in magnetic scattering cross section with lower neutron energy is thus appreciable—increasing for one spin orientation, decreasing for the other. Although the total cross section for demagnetized iron changes inappreciably, because of this differential change for the two spin values, and the exponential dependence, the change in transmission for magnetized iron shows a 57 percent increase for the low energy neutron distribution.

Experimentally, however, the neutron polarization is observed only through the differential effect of two exponential curves which decay at different rates, and hence even though the two cross sections for the two spin values differ considerably, the observed changes in transmission are a small fraction of the total number of neutrons transmitted.

Dependence of magnetic scattering on thickness of iron.—Fig. 4 shows a plot of the experimental points, superimposed on the theoretical curves, $\sim\cosh n\sigma x p$, expected from Eq. (1) in which the average of the p values given in Table I for each neutron temperature are used. The change in transmission with thickness does not disagree with the theoretical curves in Fig. 4, beyond the limits of error. However, the systematic trend of the experimental values strongly suggests that increasing thicknesses do not give quite the expected increase in transmission. This departure is what would be expected if there were tendencies for the neutrons to be depolarized within the iron and the possible reasons for such depolarization will be discussed later. Since each cm of iron transmits only about 0.36 of the incident neutrons, it is not practical to increase the thickness much beyond that used in this experiment because the intensity becomes too small in comparison to the fast neutron background.

Comparison with theory.—The magnitude of the magnetic scattering to be expected on the basis of the present theories, is uncertain, primarily because it depends on the value of the form factor for the interaction. The form factor is not accurately known and depends on ques-

TABLE I. *Dependence of magnetic scattering of neutrons on neutron energy and thickness of iron.**

EFFECTIVE NEUTRON TEMPERATURE	IRON THICKNESS IN CM	NUMBER NEUTRONS/MIN. TRANSMITTED**		INCREASE IN NO. TRANSMITTED	% INCREASE IN TRANSMISSION	p	EFFECTIVE CROSS SECTION† FOR SPIN $+\frac{1}{2}$ AND $-\frac{1}{2}$ ($\times 10^{-24}$ CM²)	
		DEMAGNETIZED	MAGNETIZED				$\sigma(1+p)$	$\sigma(1-p)$
~300°K	0.80	719.5±1.0	725.0±1.0	5.5±1.4	0.76±0.19	0.150±0.018	13.8	10.2
~300°K	1.30	440.3±0.6	448.2±0.7	7.9±0.9	1.78±0.20	0.142±0.008	13.7	10.3
~300°K	1.95	221.08±0.24	228.41±0.25	7.33±0.35	3.32±0.16	0.130±0.003	13.6	10.4
						Average: 0.135±0.008		
~120°K	1.30	417.5±1.2	429.2±1.2	11.7±1.6	2.8±0.4	0.178±0.012	14.1	9.9
~120°K	1.95	209.3±0.6	221.0±0.6	11.7±0.8	5.6±0.4	0.158±0.005	14.0	10.0
						Average: 0.171±0.008		

* Unannealed Armco iron. In all of these experiments the precision has been calculated by use of the conventional statistical fluctuation equal to $\pm\sqrt{n}$, where n is the number of neutrons counted for any particular configuration.

** Only the percent increases in transmission are accurately comparable for the ~300°K neutrons and ~120°K neutrons, since the absolute values for the two cases have been calculated separately.

† The total neutron cross section, σ, (scattering and capture) for iron has been taken as 12.0×10^{-24} cm².

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[22] Mitchell and Powers, Phys. Rev. **50**, 486 (1936).

tionable assumptions as to the ratio of the neutron wave-length to the range of the atomic forces, and as to the radius of the 3D-electron shell. The greatly increased magnetic scattering for longer neutron wave-lengths shows the importance of the form factor in determining the magnitude of the observed effects in this region of neutron energies.

The observed results are within the rather wide limits estimated by Bloch. The experimental values should be somewhat less than those based on the more detailed calculations of Schwinger for zero energy (infinite wave-length) neutrons. Bethe's rough approximation of the form factor for iron, by extrapolation from the case for copper, gives values of the same order as those observed. A reasonable value for the form factor can thus be chosen to give good agreement with these experiments, and perhaps the value for the form factor may be most satisfactorily determined through such experiments. On consideration of the elementary state of the present theory and the possibility of disturbing experimental effects pointed out in a later section, the observed magnetic scattering is probably in as good agreement with the present theory as could be expected.

Test for small angle scattering. Dependence of observed magnetic scattering on collimation of the neutron beam.—In the experiments just described the intensity of the *transmitted* neutron beam *increases* when the iron is magnetized, but as will be shown in a later section the intensity of the *scattered* neutron beam *decreases*. There will thus be some compensating effect present in the experiments, but it should be small since the geometrical conditions are quite good and probability of detection of a scattered neutron therefore is small, provided that the scattering is approximately spherical. However, if considerable small-angle scattering were present, this compensation might be appreciable.

In order to test this possibility, the experiments were repeated with a much higher degree of collimation. As indicated in Fig. 1(b), four circular symmetrical cadmium channels were arranged so that neutrons scattered through an angle greater than about 6° could not be detected. Under these conditions, the observed increases in neutron transmission with the iron magnetized were 3.5 percent±0.3 percent for the 1.95 cm thickness iron, and 1.7 percent±0.3 percent for the 1.30 cm thickness. These show no appreciable increase over the previous results, and it must therefore be concluded that the collimation first employed was already sufficiently good so that multiple scattering was not affecting the results markedly, and that within these limits there is no large amount of small angle scattering.

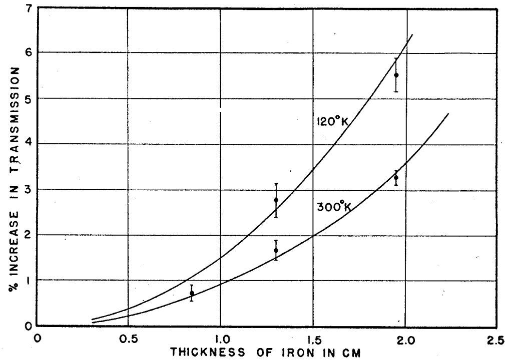

Fig. 4. Dependence of magnetic scattering on thickness of iron and neutron energy. The points represent the observed changes in neutron transmission. The curves represent the theoretical trend expected from Eq. (1), $\sim \cosh n\sigma x p$, in which the average p values from Table I for the two neutron temperatures are used.

Single transmission experiments with a small magnet.—The measurements for magnetic scattering made with a small magnet constructed by Dr. J. H. Manley and kindly loaned for this experiment are of interest, since magnets of this type were used in the experiment on the sign of the neutron magnetic moment to be described later. The design of the magnet is shown in Fig. 5. Instead of solid Armco iron plate, seven strips of Swedish iron, each of 0.65 cm×1.30 cm cross section were placed side by side on the yoke with Cd strips interposed. The neutron beam, 7.5×4.5 cm in area, thus passed normally through 1.3 cm of iron while the Cd strips served both to reduce multiple scattering and to make the direction of the field in the iron parallel to the strips. In such a design, with only one thickness of iron for the neutrons to traverse, depolarization effects due to non-uniform fields outside the iron cannot affect the results. An excellent magnetic circuit was produced by careful surface grinding of all contact surfaces, and as a result a value of $B-H$ in the iron strips of approximately 20,000 gauss

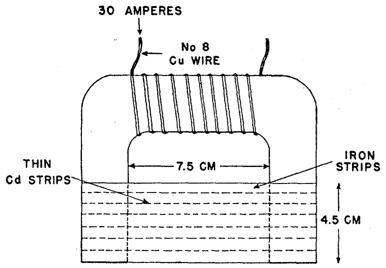

FIG. 5. Small type magnet designed by Dr. J. H. Manley. Swedish iron strips 0.65 cm×1.30 cm are placed side by side on the yoke, with Cd strips interposed. The Cd reduces multiple scattering and makes direction of field definitely parallel to strips.

was attained with relatively small power dissipation.

The observed increase in neutron transmission for the small magnet with 1.30 cm Swedish iron was 1.7 percent±0.3 percent. This is in good agreement with the value of 1.78 percent±0.2 percent previously observed, with the Armco iron of the same thickness. (See Table I.) Thus the single transmission experiments give consistent polarization effects.

Dependence of magnetic scattering on intensity of magnetization of iron.—Beyer, Carroll, Witcher and Dunning[23] have shown that the Armco iron samples do not show appreciable neutron polarization until a sharp threshold is reached which is very near complete saturation. Above this field value the observed polarization is practically constant. The measurements described here on Armco iron were all made with fields above this critical value.

Swedish iron, however, was shown to have a broader threshold. The observed polarization was appreciable with much lower magnetizing fields and approached its maximum more gradually. Thus the small magnets which were used in the experiments described here are able to produce practically the maximum polarization for the Swedish iron samples, but they were not effective with Armco iron.

The maximum polarization observed for the two types of iron, however, is seen to be practically the same. Theoretically, the observed polarization should vary approximately as the square of the intensity of magnetization. That the polarization depends on the composition and nature of the iron and does not follow such a simple function is additional evidence of the complexity of the phenomena.

This points again to the conclusion mentioned previously in connection with Fig. 4 and Table I, that neutrons may be depolarized through nonadiabatic transitions in domains within the ferromagnetic material. See next section for further discussion.

Double Transmission Experiments

A number of experiments[5, 24] have been performed to investigate the neutron polarization phenomena through the use of two iron plates which could be magnetized parallel or antiparallel by two separate magnets and in order to secure the "polarizer-analyzer" action discussed in the introduction.

The essential arrangement is shown in Fig. 6 Two types of variations have been made: (a) Two different thicknesses of iron plates, totalling 1.30 and 1.95 cm, respectively, have been used and (b) first one and then both iron plates have been inclined at an angle of about 60° to the neutron beam in order to test the variation of polarization with the angle between neutron direction and the field direction. The thicknesses of iron used for oblique incidence were chosen so that the effective thickness was also approximately 1.30 or 1.95 cm.

The procedure used in making the observations was to take successive runs with (A) "polarizer" plate magnetized parallel to "analyzer" plate; (B) "polarizer" magnetized antiparallel to "analyzer," and (C) demagnetized.

TABLE II. *Observation of magnetic scattering of neutrons through double transmission experiments.—i.e., "polarizer-analyzer" action. Averaged results.**

EFFECTIVE THICKNESS OF IRON	MAGNETIZATION OF IRON PLATES	NUMBER OF NEUTRONS/MIN. TRANSMITTED	DIFFERENCE IN TRANSMISSION	PERCENT INCREASE IN TRANSMISSION
(a) 1.30 cm	Parallel	358.0±0.8	6.4±1.1	1.8±0.3
	Antiparallel	354.8±0.7	3.2±1.0	0.9±0.3
	Zero	351.6±0.7	0	0
(b) 1.95 cm	Parallel	181.11±0.40	6.01±0.56	3.44±0.32
	Antiparallel	178.82±0.40	3.72±0.56	2.12±0.32
	Zero	175.10±0.39	0	0

* The fast neutron background obtained by interposing Cd in the beam has been subtracted.

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[23] Beyer, Carroll, Witcher and Dunning, Phys. Rev. **53**, 947 (1938).

[24] Dunning, Powers and Beyer, Phys. Rev. **51**, 51 (1937).

No significant variations outside experimental error were found between oblique incidence and normal incidence for the same effective thickness of iron, so the results have all been reduced to the same basis and averaged together. Table II shows the collected results. With both plates magnetized parallel, the experiment corresponds to those of single transmission types described previously; and the percentage increases in transmission agree very well with those in Table I.

The results for the antiparallel case, however, disagree seriously with what is to be expected. As pointed out in the introduction (Eq. (4)), if the thicknesses are equal, the transmission when antiparallel should be the same as when demagnetized. Instead, the antiparallel readings lie between the parallel and demagnetized readings.

Nonadiabatic transitions between the neutron states.—These experiments show quite conclusively that nonadiabatic transitions between the neutron states occur between the iron plates in the antiparallel case. The neutron beam is partially polarized after leaving the first plate; i.e., the number of neutrons having spin components $+\frac{1}{2}$ is different from the number having $-\frac{1}{2}$ in the direction of the field. However, with respect to a moving neutron between the plates, the magnetic field must effectively rotate, since at some point the value is zero. The frequency of this rotation under the conditions here is of the same order of magnitude as the Larmor precession frequency of the neutron, $g\mu H/h$, and transitions would be expected to occur between the neutron states.[25–27] This amounts to a reorientation of the partially polarized beams parallel to the second plate. The antiparallel case thus becomes similar to the parallel case and an increase in neutron transmission is to be expected compared to the demagnetized case. The magnitude of this increase depends on the transition probability which must be reasonably high, since of the order of 50 percent of the neutrons are reoriented. Evidence that such transitions occur has been confirmed by Frisch, von Halban and Koch.[28, 29]

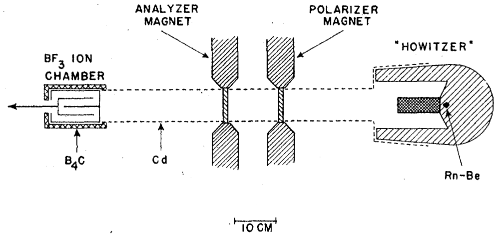

FIG. 6. Schematic arrangement of apparatus for study of neutron polarization by transmission through two successive iron plates which can be magnetized either parallel or antiparallel to each other by means of separate magnets. Measurements were made with two thicknesses of iron. Studies were also made with one and with both plates inclined at an angle of 60° with respect to the neutron beam.

A double transmission experiment was also performed by Hoffman, Livingston and Bethe[4] in which measurements were taken for the parallel and antiparallel cases, but not of the demagnetized case. They reported an increase in transmission of 1.8 percent$\pm$0.54 percent for the parallel case, which is probably consistent with our results. A comparison of the parallel and antiparallel cases given in Table II (b) shows a difference of only 1.32 percent$\pm$0.32 percent. Since their results did not include the demagnetized case the amount of reorientation cannot be established.

Nonadiabatic transitions within the iron.—The possibility of depolarization of the neutron within the iron has already been pointed out in connection with the systematic trend of the results on polarization as a function of thickness of iron, and the results of Beyer, Carroll, Witcher and Dunning[23] on the polarization as a function of magnetization intensity of the iron. Multiple scattering will, of course, account for some depolarization within the iron, but in view of the experiments described previously, testing this point, and of the excellent geometrical conditions prevailing in all experiments, is does not seem likely that multiple scattering plays a large role.

The microscopic field which the neutron "sees" as it passes through the iron atoms, the iron crystal structure, the crystal boundary regions and the atoms of the impurities present is by no means certain. However, in regions where B is high, the Larmor precession frequency is high, and transitions (i.e., depolarization) should occur

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[25] Güttinger, Zeits. f. Physik **73**, 169 (1931).
[26] Majorana, Nuovo Cim. **9**, 43 (1932).
[27] Rabi, Phys. Rev. **51**, 652 (1937).
[28] Frisch, von Halban and Koch, Nature **139**, 756 (1937).
[29] Frisch, von Halban and Koch, Phys. Rev. **53**, 719 (1938).

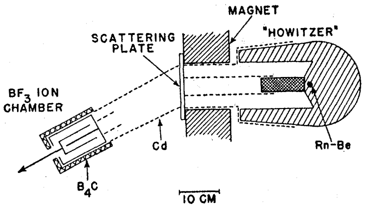

FIG. 7. Arrangement for investigating neutron polarization by scattering through a mean angle of approximately 23°. The ion chamber is shielded from the direct neutron beam by the pole pieces and by Cd.

within very small regions.[30] The passage of polarized neutrons through incompletely oriented "domains" (whose number becomes less as the magnetization approaches saturation as determined by temperature as well as magnetizing field), may thus give rise to nonadiabatic transitions, and hence depolarization. Disturbing effects may also occur at crystal boundary regions, and the presence of impurities may also complicate the phenomena. Especially in regions below saturation, one might well expect polarization effects to depend considerably on the type of iron used.

It has not been the purpose of these experiments to investigate this phase of the phenomena, and the Armco iron and Swedish iron samples used have been magnetized to as high values as feasible with the various magnets. Strictly speaking, however, the results given apply only to these iron samples, under these conditions of magnetization, and the results are in general very consistent.

POLARIZATION OF NEUTRONS BY SCATTERING

As shown in the previous experiments, the direct neutron beam transmitted through a plate of iron increases when the iron is magnetized. Conversely, the *scattered* neutrons should *decrease* in intensity when the iron is magnetized. Two methods utilized for measuring the changes in scattered neutron intensity are shown in Figs. 7 and 8. In Fig. 7, the ionization chamber was placed outside the direct transmitted neutron beam at an angle of approximately 23° so that neutrons scattered through small angles could be detected. In Fig. 8, a small magnet was arranged so that the back scattering at an angle of 90° could be measured. The beam was inclined at 45° to the iron. Both the "howitzer" and the ionization chamber were in the plane of the magnetized strips.

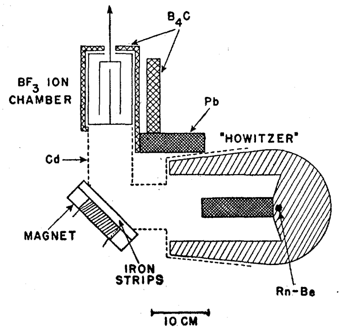

FIG. 8. Arrangement for studying amount of neutron polarization by scattering through a mean angle of approximately 90°.

The results obtained are shown in Table III. Both experiments show definitely that the scattered neutron intensity *decreases* when the iron is magnetized. Because of the low intensity of the scattered neutron beam compared to the residual fast neutron background, the probable error is necessarily large, but in both cases it is less than one-third the observed change.

The difference between the observed magnetic scattering for the two angles is not considered significant.

THE SIGN AND MAGNITUDE OF THE MAGNETIC MOMENT OF THE NEUTRON

The investigations of the scattering of neutrons by ferromagnetic materials under various conditions are in reasonable agreement with the simple theories. However, the theories are only

TABLE III. *Scattering of neutrons from magnetized iron.*

ARRANGEMENT	READINGS	NUMBER OF NEUTRONS/MIN. RECORDED	DIFFERENCES DUE TO SCATTERING	PERCENTAGE DECREASE WITH IRON MAGNETIZED
Fig. 7	Magnetized	123.4 ± 0.2	−1.0 ± 0.3	4.0 ± 1.2%
	Demagnetized	124.4 ± 0.2		
~23° Scattering	Background with Cd	99.6	(24.8 Slow neutrons)	
Fig. 8	Magnetized	111.61 ± 0.18	−0.80 ± 0.25	2.5 ± 0.8%
	Demagnetized	112.41 ± 0.18		
~90° Scattering	Background with Cd	80.3	(32.1 Slow neutrons)	

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[30] Frisch, von Halban and Koch (Nature **140**, 360 (1937)) have shown that transitions may be made to occur in very thin strips of magnetized iron where the B value is high.

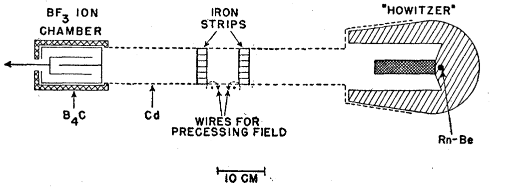

FIG. 9. Arrangement of apparatus for determination of sign and approximate magnitude of the neutron magnetic moment.

approximate, and in order to measure the magnitude of the neutron magnetic moment it is therefore important to use methods which are free from doubtful assumptions as to the exact nature of the complicated processes occurring within the ferromagnetic material. Furthermore, the sign of the neutron moment is not uniquely determined by the scattering in magnetized materials.

In order to determine the sign and magnitude of the neutron moment, it is therefore intrinsically desirable to perform experiments dependent only on the properties of the neutron in free space. Since slow neutrons have been shown to make nonadiabatic transitions in a rotating magnetic field,[6, 25, 26] this is clearly possible.

Rabi[31] has suggested a method through which these transitions may be controlled by a precessing magnetic field. A preliminary report of an experiment in which this method was used has already been published.[32] Rabi[27, 31] and Schwinger[33] have made calculations of the transition probability for a neutral atom in a precessing field which show that the probability depends upon the sign of rotation of the rotating component of the magnetic field, relative to the Larmor precession.

Thus a method is given which is applicable to the neutron for determining the sign of its magnetic moment (direction of the magnetic moment relative to the spin) as well as its magnitude. The transition probability is given by:

$$P_{-\frac{1}{2}}{}^{\frac{1}{2}}=\left(\frac{\hbar^2\omega^2\sin^2\theta}{\mu_n{}^2H_1{}^2+(\mu_nH_2+\hbar\omega/2)^2}\right)\times\sin^2\left(\frac{t}{2\hbar}\right)[\mu_n{}^2H_1{}^2+(\mu_nH_2+\hbar\omega/2)^2]^{\frac{1}{2}},$$

where H_1 is the rotating component of the precessing field; H_2 the constant component of the field; θ the angle between the resultant field and H_2; ω the angular velocity of the rotating component; t the time the neutron spends in the field, and μ_n the neutron magnetic moment. Since the transition probability depends on the relative signs of μ_n and ω, the sign of the neutron moment is determined by the direction of ω which produces maximum transitions. Furthermore, since this expression depends on the magnitude of the precessing field, i.e., H_1 and H_2, the magnitude of the neutron moment is in principle determined by the optimum values of H_1 and H_2 for a given configuration.

The arrangement of apparatus finally adopted for the experiment is shown in Fig. 9. The two sets of iron strips were magnetized in a direction parallel to a normal drawn outward from the paper, by means of two separate small magnets of the type shown in Fig. 5. The neutron beam was partially polarized after passing through the first set of magnetized strips. The precessing field in the region between the two magnets was formed by the resultant of the constant component H_2 produced by the stray field of the two magnets, and H_1, the rotating field (with respect to the moving neutron) caused by the two parallel wires carrying current in opposite directions. Fig. 10 shows diagrammatically the

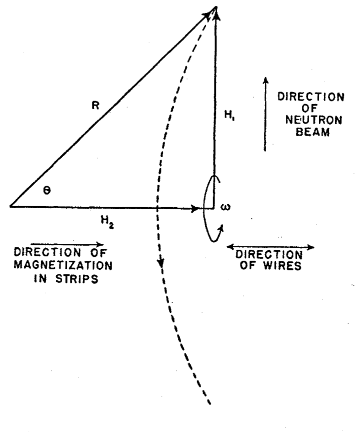

FIG. 10. Schematic diagram showing how the constant component, H_2 (the stray field) is combined with a rotating component, H_1, due to the field from the two parallel wires carrying current in opposite directions, in order to approximate a precessing field (with respect to the moving neutron), of the proper direction to induce the maximum amount of transitions.

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[31] Rabi, Phys. Rev. **51**, 683 (1937).

[32] Powers, Carroll, Beyer and Dunning, Phys. Rev. **52**, 38 (1937).

[33] Schwinger, Phys. Rev. **51**, 648 (1937).

way in which the resultant precessing field is produced. The nonadiabatic transitions between the neutron states induced by this precessing field between the two sets of magnetized strips are in the end observed through testing the subsequent polarization of the neutron beam, i.e., by the change in transmitted neutron intensity through the second set of magnetized strips. The transitions produced in the partially polarized neutron beam by the controlled precessing field may thus be determined, and hence the sign and approximate magnitude of the neutron moment, without the specific interaction of the neutron with the iron coming into consideration.

Such an experiment may be in principle as accurate as desired. At the present stage of development, the sign may be determined unequivocally, but compromises must be made which greatly reduce the accuracy of measurement of the magnitude of the moment. Unfortunately, with the present neutron sources and detection methods, a wide aperture is necessary to secure sufficient intensity compared to the background, and it is not possible to secure uniform optimum conditions for complete reorientation of spins over such a large region. The approximate Maxwellian velocity distribution of the neutrons further complicates the situation. However, assuming $\mu_n \sim 2$ n.m., as might be expected from the values of the proton and deuteron magnetic moments, Mr. Julian Schwinger showed that the conditions could be made reasonably suitable over a large part of the region. By adjusting the distance between the magnets, introducing strips of iron just outside the beam, and shielding the coils, the stray field parallel to the strips was made to range from 8 to 14 gauss, and over the greater part of the region it averaged from 10 to 12 gauss. This field provided the constant component, H_2. The distance between the plates was 7 cm. For a Maxwellian velocity distribution of the neutrons, the average value of t was then approximately 3×10^{-5} sec.

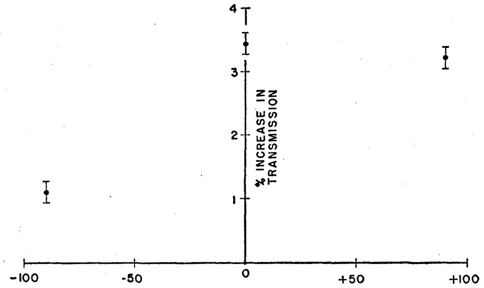

FIG. 11. Plot showing experimental points—Determination of sign and approximate magnitude of neutron magnetic moment. With the precessing field in the proper direction for a negative moment, the observed transmission is greatly reduced, but a precessing field in the opposite direction produces no observable change.

TABLE IV. *Experimental data—sign and magnitude of neutron magnetic moment.*

POLARIZING FIELD (MAGNETS)	CURRENT IN ROTATING FIELD (WIRES)	NUMBER OF NEUTRONS/ MIN. TRANSMITTED	% INCREASE IN TRANSMISSION
(a) Demagnetized	Zero	439.3 ±0.9	0 ±0.30
(b) Magnetized +	Zero	447.0 ±0.9	3.43 ±0.30
(c) Magnetized +	−90 Amperes	441.8 ±0.9	1.08 ±0.30
(d) Magnetized +	+90 Amperes	446.5 ±0.9	3.21 ±0.30
Background with Cd		213.3	

On the basis of a neutron moment of 2 n.m., under these conditions a current of 90 amperes in each wire should result in optimum values of H_1 (and H_2) in the center of the beam; i.e., a component is produced, rotating through approximately 180° with respect to the neutron, of very nearly constant magnitude (~ 10 gauss) and constant angular velocity. (See Fig. 10.) From the average neutron velocity, ω can be calculated.

Runs were taken successively with (a) both magnets demagnetized and zero wire field; (b) both magnets magnetized and with zero wire field—thus (a) and (b) correspond to the parallel double transmission case; (c) both magnets magnetized and wire current in the direction to give transitions for a negative neutron moment; (d) the same as (c) but with the current in the wire reversed so that transitions should not occur. Approximately 2,500,000 neutrons were counted in the course of the experiment. The averaged results for a series of 60 runs are given in Table IV.

The change in transmitted intensity from (a) to (b) in Table IV with no precessing field agrees fairly well with that in the earlier experiments of the parallel double transmission type and the single transmission type for approximately the same iron thickness.

The sign of the neutron moment.—The effect of the precessing transition field on the probability of transition, and hence of the observed neutron transmission through the two sets of magnetized strips, is clearly shown in Fig. 11.

With zero current in the wires, i.e., no precessing field, the maximum polarization is observed, with an increase in transmission over the completely demagnetized case of 3.43±0.30 percent.

With the direction of current in the wires negative (see (c) in Table IV), the percentage change in transmission decreases to about one-third the value with no precessing field, showing that a considerable fraction of the neutrons made transitions, and were in effect reoriented. With the direction of the current in the wires reversed (see (d) in Table IV), the precessing field clearly has little effect on the neutrons.

Hence the results prove that the neutrons are reoriented when the angular velocity of the precessing field has the proper sign. The sign of the neutron moment is therefore definitely *negative.*

The magnitude of the neutron magnetic moment.—As pointed out, this experiment cannot be expected to yield a highly accurate value for the magnitude of neutron moment, because of the lack of uniformity in magnetic field conditions over the large beam area necessary for intensity, and because of the velocity distribution of the neutrons. However, since a large fraction of the neutrons were reoriented, the average magnetic field conditions, i.e., H_1 and H_2 must have been very near the optimum values. A rough numerical integration has been made taking into account the magnetic field values over the region of the beam, and it shows that the results are consistent with a value of -2 nuclear magnetons for the neutron moment. Considering the averaging involved, and the probable errors, the neutron moment must be within -2 ± 1 n.m., and is probably within -2 ± 0.5 n.m.

An experiment performed by Frisch, von Halban and Koch,[20] is in good agreement. With the use of a solenoid they produced a small field, H, between the "polarizer" and "analyzer," parallel to the direction of the neutron beam. The neutrons precessed about this field with an angular velocity proportional to H. Thus, with varying values of H, the depolarization of the neutron beam varied in the direction indicating the neutron moment to be negative. The conditions for complete depolarization (precessing through 90°) was reasonably consistent with the assumed magnitude of 2 n.m. The percentage changes which they observed were smaller than those observed here, although this would be expected from the configurations used.

The author wishes to express his appreciation to Professor John R. Dunning for suggesting the problem and for invaluable advice. I am much indebted to Professor I. I. Rabi and Mr. Julian Schwinger for interesting and helpful discussions, and for assistance in some of the calculations. Mr. Henry Carroll and Mr. H. G. Beyer were of great assistance in the laboratory. The Norton Company has been very generous in supplying quantities of Norton Boron Carbide for use as a shield from slow and fast neutrons.