Neutron Polarization*

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The neutron polarization cross section of iron has been measured as a function of energy from 0.7 to 3.3A by two methods: using the single transmission effect in a block of polycrystalline iron at energies selected by a quartz crystal monochromator; and using a single crystal of magnetized magnetite to analyze the beam emerging from the iron polarizer, the magnetite crystal itself serving as monochromator. The measured values are compared with those of other observers and the theoretically expected values. These are found to agree fairly well within the limits of accuracy of the measurements and existing knowledge of the wave function of the iron *3d* shell. The two techniques were used also to determine the average polarization (32 percent) as seen by a $1/v$ detector in a beam of reactor neutrons emerging from a 4-cm thick polarizing block of iron. Problems and techniques associated with the measurement of the average polarization of a continuous spectrum are discussed. A simplified experimental treatment of the problem of beam "hardening" is described. A description is given of the use of the magnetic resonance method in conjunction with a single-crystal magnetite analyzer for the measurement of neutron polarization.

A. INTRODUCTION

MANY experimental studies[1–12] of the polarization of slow neutrons have been made for the purpose of verifying the theory[13–21] of scattering, polarization, and depolarization of neutrons passing through crystalline magnetic materials. Some of the experiments measure the energy dependence of the change in the total cross section upon magnetization of a polycrystalline sample of iron. The rotating shutter[8] and the pulsed cyclotron[9] time of flight methods have been used for the velocity selection. We have used the higher resolution of the single-crystal spectrometer to measure the polarization cross section as a function of energy from about 0.7 to 3.3A, by two methods: using the single transmission effect in a block of polycrystalline iron at energies selected by a quartz crystal monochromator; and using a single crystal of magnetized magnetite to analyze the beam emerging from the iron polarizer, the magnetite crystal itself serving as monochromator. In the first of these methods the polarization cross section is deduced from the change in the intensity of the beam transmitted by the polarizer on magnetization. We have developed the application of the second method, in which the polarization cross section is deduced from the value of the polarization of the beam emerging from the polarizer, as determined from the known analyzing properties of the magnetite crystal. This method is simpler since the problem of lack of complete magnetic saturation is much less severe. Our results exhibit the discontinuities in the polarization cross section due to crystal structure in greater detail than previous work of other observers. The results are found to agree with the theoretically expected values[20] within the limits of accuracy of the measurements and existing knowledge of the boundary conditions at the atomic radius of the wave function of the *3d* shell of iron in the solid state. This type of experiment can definitely choose between alternate proposed boundary conditions, but our measurements are not considered adequate for this purpose, since the Bragg reflected beam contained considerable higher-order contamination which required appreciable correction to the measurements, and the distribution of crystallite orientations in the sample could not be considered sufficiently close to the completely random distribution required by the theory.

The polarization of a continuous neutron spectrum is difficult to measure with accuracy by use of the single transmission effect because the polarizing block alters the spectrum of the neutron beam. Also, the variation of detector sensitivity with energy may complicate the interpretation of the intensity changes. The two methods described above were used to determine the average polarization (32 percent) seen by a $1/v$ detector in a beam of reactor neutrons emerging from a 4-cm thick polarizing block of iron. This information is per-

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tinent to an associated project[22] on the interaction of polarized neutrons with polarized Mn^{55} nuclei. The problems and techniques associated with the measurement of such an average polarization are discussed below. A simplified experimental treatment of the problem of beam "hardening" is described. A description is also given of the use of the magnetic resonance method in conjunction with a single-crystal magnetite analyzer for the measurement of neutron polarization.

B. SINGLE TRANSMISSION EFFECT *VS* ENERGY

The relationships describing the passage of neutrons through polycrystalline magnetized iron[16] for the case in which the incident beam is unpolarized are given by

$$j=j_0e^{-\frac{1}{2}qd}[\cosh(d/\Delta)+\tfrac{1}{2}q\Delta\sinh(d/\Delta)], \quad (1)$$

$$S=j_0e^{-\frac{1}{2}qd}w\Delta\sinh(d/\Delta), \quad (2)$$

where j is the intensity of neutrons emerging from the magnetized iron block and j_0 is the intensity emerging from the iron block when it is unmagnetized. j_0 is equal to the intensity incident upon the block times the factor $e^{-N\sigma_t d}$, in which N is the number of scatterers per unit volume in the iron, d is the thickness of the iron, and σ_t is the total cross section for unmagnetized iron. The quantity q is called the depolarization coefficient. It takes account of relevant metallurgical properties of the polycrystalline sample and the degree of magnetic saturation. When the iron is completely saturated, $q=0$. The parameter $\Delta=(w^2+\frac{1}{4}q^2)^{-\frac{1}{2}}$, in which $w=Np$, is the polarization cross section per unit volume of iron. The scattering cross section per atom of magnetized iron is given by $\sigma=\sigma_0\pm p$. The term σ_0 is the scattering cross section for unmagnetized iron. It includes the scattering due to nuclear interaction alone and magnetic interaction alone. The quantity p is called the polarization cross section. It arises because of interference between nuclear and magnetic scattering. The scattering due to interference may increase or decrease the cross section depending upon whether the neutron spin is parallel or antiparallel to the atomic spins of the iron. The quantity

$$(j/j_0)-1=E_1 \quad (3)$$

is called the single transmission effect.

S is the net spin flux density of the neutron beam emerging from the magnetized iron. If j_1 and j_2 are the intensities of the neutrons with the two possible orientations of the spins with respect to the magnetic field applied to the iron, then the polarization P is given by

$$P=S/j=(j_1-j_2)/(j_1+j_2). \quad (4)$$

In the case of complete saturation the relation between the polarization and the intensities can be expressed by

$$P=[1-(j_0/j)^2]^{\frac{1}{2}}. \quad (5)$$

This relationship is plotted in Fig. 1.

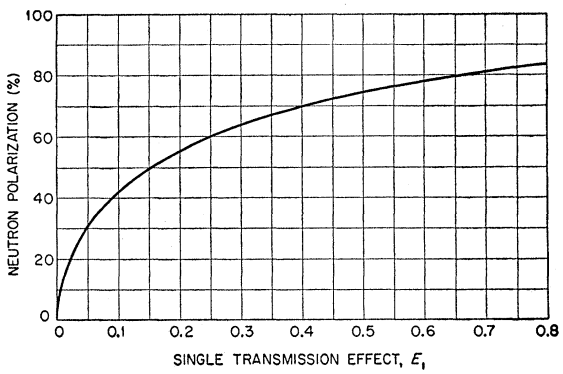

FIG. 1. Polarization *vs* single transmission effect for complete saturation.

TABLE I. Single transmission effect E_1 for 0.0372 ev.

Thickness of block, cm	E_1, measured	E_1, corrected
1	0.020±0.001	0.020
2	0.071±0.001	0.074
3	0.147±0.003	0.157
4	0.253±0.003	0.274

For a single neutron energy, in the absence of complete saturation, measurements of E_1 for two different thicknesses of iron in the same state of magnetization will, in principle, determine the values of q and Δ. From Δ, the value of p, the polarization cross section can be derived. Using these values of q and Δ in (1), (2), and (4), the polarization can be determined. The quantity w, and therefore Δ also, depend upon energy. We have used the method just outlined to determine q and Δ for neutrons of a single energy. The grain size of the iron samples and the neutron spectrum were such that q was taken to be independent of energy. The measured value of Δ was used to fix the scale on the known shape of the curve of polarization cross section *vs* energy. The polarization as a function of energy was then calculated from (1), (2), and (4). The polarization averaged over the spectrum was calculated by weighting the polarization for a given energy in proportion to the abundance of neutrons of that energy in the beam emerging from the polarizing block of iron.

The neutron energy 0.0372 ev was selected by Bragg reflection from a single crystal of quartz following the polarizing block of iron. The single transmission effect was measured for 1, 2, 3, and 4 cm of iron. Care was taken to demagnetize the iron thoroughly before the field-off count. The arrangement was such that small angle scattering effects[23] were not likely to influence the results. The state of magnetization of the blocks was taken to be the same when the magnetic field at the

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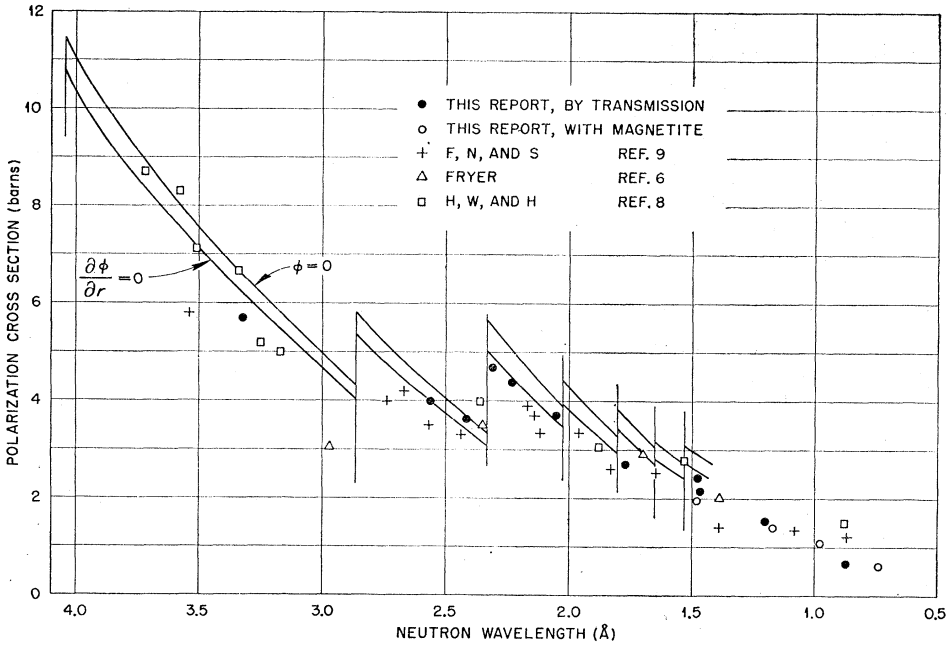

FIG. 2. Polarization cross section *vs* energy. The points give the measured values of this report and those of other observers. The curves are calculated from (7) using σ_{coh} for iron = 11.4 barns.

surface of each of the blocks was measured to be the same with a small flat flip coil which could be placed up against the surface of the block. The field at the surface of each block was 11 000 oersteds. The results of these measurements are given in Table I.

The direct measurements must be corrected for the presence of neutrons of energy 4×0.0372 ev due to the second-order Bragg reflection from the quartz crystal. Orders of reflection higher than the second present in the reflected beam were estimated to have negligible effect upon the measurements because the intensity of neutrons incident upon the crystal is much less for third order, and also because of the decreased reflectivity of the crystal for the higher energy. Corrections for the second order were made by measuring the transmission of a calibrated boron absorber in the beam emerging from each of the blocks. The absorber was calibrated by measuring its transmission at several energies with a mechanical velocity selector. These values were checked by measuring the transmission, also, with a crystal spectrometer arrangement using a single energy so chosen that the second order could be eliminated by means of an appropriate neutron resonance filter. The transmission of the absorber could then be calculated at any energy from the known $1/v$ variation of the boron cross section. The single transmission effect corrected to include first-order neutrons only is given in Table I. The corrected data were fitted using Eqs. (1) and (3) for assumed values of q and w. The values $q=0.204$, $w=0.204$ were found to fit the observations best.

Values of p were measured by the single transmission effect method for several other energies also. In addition, values of p for several energies were derived by a method described below in which the polarization of a single energy in the beam emerging from the iron was measured using a single crystal of magnetite as analyzer. Our measured values of p are shown along with those of other observers in Fig. 2. The polarization cross section is given by the expression[20]

$$p=(\sigma_{coh}/4\pi)^{\frac{1}{2}}(e^2/mc^2)\mu_n\mu_e(\lambda/2a)^2\sum_{l<2a/\lambda}N(l)/l\times(1+\lambda^2l^2/4a^2)F(l), \quad (6)$$

in which σ_{coh} is the coherent nuclear scattering cross section of iron, e, m, and c have their usual meanings, μ_n is the magnetic moment of the neutron in nuclear Bohr magnetons, μ_e is the magnetic moment per iron atom in atomic Bohr magnetons, λ is the neutron wavelength, and a is the dimension of the body-centered-cubic iron unit cell. The quantity $l^2=n_1^2+n_2^2+n_3^2$, where n_1, n_2, and n_3 are the Miller indices of a set of planes. $N(l)$ is twice the value of the usual multiplicity of the set of planes identified by l. $F(l)$ is the magnetic form factor of the iron for the set of planes l. The value of F depends upon the $3d$ electron wave functions of the iron. Values of p have been calculated[20] as a function of energy using the value 10.0 barns for the coherent scattering cross section of iron, on the basis of two assumptions: (1) the wave function ϕ of the $3d$ shell is zero at the atomic radius; and (2) the derivative of the wave function is zero at the atomic radius. We have recalculated p *vs* energy using the more recent value[24] of 11.4 barns for the coherent scattering cross section of iron. The curves are shown in Fig. 2 for comparison with the measured values.

[24] C. G. Shull and E. O. Wollan, Phys. Rev. **81**. 527 (1951).

The measured values fall fairly close to the calculated curve. The accuracy of the measurements is, however, not sufficient to choose between the two assumptions for the magnetic form factor. Equation (6) is based upon the assumption of a random distribution of the orientation of the many small crystallites in the "powder" sample. In the case of our measurements, we used as polarizer, a block of cold-rolled steel, with the magnetic field applied in the direction of rolling. Such an arrangement was chosen because the preferred orientation of the crystallites gives an enhanced effect for a given strength of applied field.[8] It is remarkable that in spite of the known departure of our sample from random orientation, the measured values fall as close as they do to the theoretical curve.

C. TEMPERATURE OF THE INCIDENT NEUTRON BEAM

The assumption was made that the spectrum of neutrons emerging from the reactor from energy zero up to the energy of the Cd cutoff could be represented to a degree of accuracy sufficient for our purposes by a Maxwell distribution. This assumption is known to be only approximately true since the actual spectrum of neutrons emerging from the reactor has fewer neutrons at the very low energies and more neutrons in the 0.5-ev region than does a Maxwell distribution.

We studied the "hardening" of the neutron beam on passage through 1, 2, 3, 4, and 7 cm of iron by measuring the transmission of the calibrated boron absorber in the beam emerging from the iron using a $1/v$ detector. The values of the measured transmissions are given in Table II. The transmission of the absorber rises at first as the thickness of iron is increased, but then falls as thickness is further increased. The measured values were compared to those calculated for the emerging beam, whose spectrum was taken to be the incident Maxwell distribution times the factor $e^{-N\sigma td}$. All integrations were done numerically. The calculated transmissions corresponding to a temperature of 495°K, which were found to come acceptably close to the measured values, are shown in Table II.

The total cross section of iron has not been measured in any great detail for low velocities. In the calculations we have used the curve given by the U. S. Atomic Energy Commission Neutron Cross Section Group[25]

TABLE II. Transmission of boron absorber.

Thickness of iron cm	Measured transmission	Calculated transmission
1	0.370±0.0004	0.370
2	0.377±0.0003	0.374
3	0.372±0.0006	0.3745
4	0.365±0.0009	0.373
7	0.328±0.004	0.300

[25] *Neutron Cross Sections*, Atomic Energy Commission Report AECU-2040 (Technical Information Service, U. S. Department of Commerce, 1952).

as a basis for capture, isotope-disorder, spin-dependent, and inelastic scattering contributions and superimposed upon it the fluctuations due to coherent nuclear and magnetic scattering, calculated from values of the magnetic and coherent nuclear scattering amplitudes furnished by neutron diffraction measurements.[12] The effect of temperature upon the heights of the discontinuities in the coherent scattering was also taken into account.

For an incident Maxwell distribution of 495°K, the spectrum corresponding to filtration through 4 cm of iron is shown in Fig. 3. The average energy of those neutrons of wavelength less than 4.04A, the coherent-scattering cutoff, is increased by passage through the iron, causing a "hardening" of the beam. The filtering action of the iron has the effect also of increasing the relative importance of those neutrons of wavelength greater than 4.04A. For 4 cm of iron, they constitute 8 percent of the neutrons in the emerging beam. The variation in relative importance of these two groups of neutrons as a function of thickness explains the presence of the maximum in the boron absorber transmission data.

D. SINGLE TRANSMISSION EFFECT FOR THE CONTINUOUS SPECTRUM

In order to determine the average polarization seen by a $1/v$ detector in a beam of reactor neutrons emerging from 4 cm of polarizing iron, the single transmission effect for all energies less than the Cd cutoff was measured, using a thin $B^{10}F_3$ proportional counter detector with 1, 2, 3, 4 cm of iron between the poles of

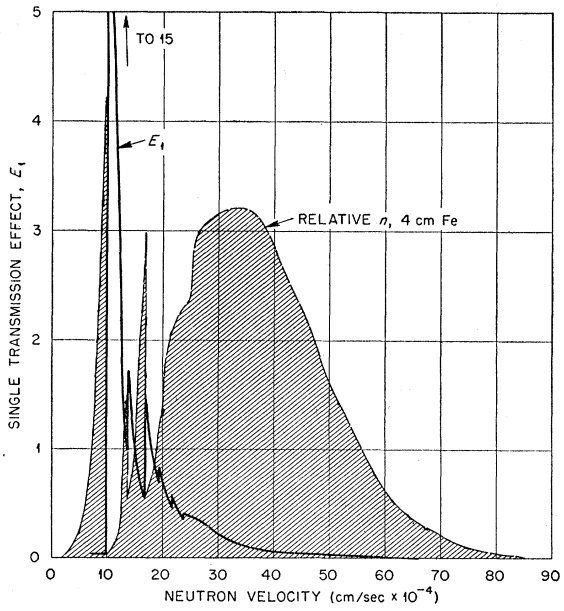

FIG. 3. Single transmission effect *vs* velocity for 4-cm block using measured value of the depolarization coefficient and Eq. (1). The neutron density n emerging from 4 cm of iron is shown by the dashed curve.

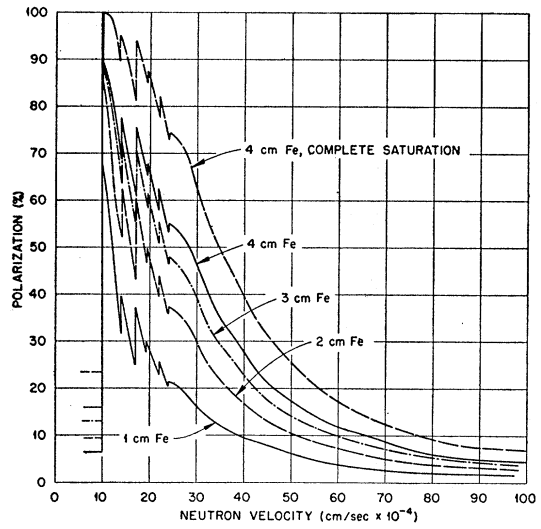

FIG. 4. Polarization *vs* velocity for 1, 2, 3, and 4 cm of iron.

the magnet. In order to keep the spectrum incident upon the detector always the same, a total of 4 cm of iron was always kept in the path of the beam. The single transmission effect is the ratio of the counting rate with d cm of magnetized iron, and $(4d)$ cm of unmagnetized iron in the beam, to that with 4 cm of unmagnetized iron in the beam. [The magnetic field at the surface of the magnetized iron was always kept at the value used in the nuclear polarization experiment[22] (11 000 oersteds).]

The measured values of the single transmission effect for the entire spectrum as a function of block thickness were compared to calculated values. The calculated average single transmission effect was obtained by weighting the value for a single energy by the density of neutrons in the beam emerging from 4 cm of iron. The integrations were performed numerically. The value for the depolarization coefficient determined previously was used. It so happened that a good fit to the data was obtained using the boundary condition that the slope of the $3d$ wave function is zero at the atomic radius with the value 12.3 barns for the coherent scattering cross section of iron. This choice is obviously not unique. The value 10.0 barns and the alternate boundary condition would do as well. For wavelengths greater than about 1.5A the values of the form factor given in reference 20 were used. Reference 20 gives no values of $F(l)$ for $l^2>14$, which are needed in addition to those for $l^2<14$ in calculating the polarization cross section for wavelengths less than 1.5A. These were estimated from a brief approximate analytical expression[26] giving F for a free iron atom. The error involved in using these rough values of F for $l^2>14$ is small, since a large fraction of the polarization cross section at the short wavelengths is contributed by planes for which $l^2<14$.

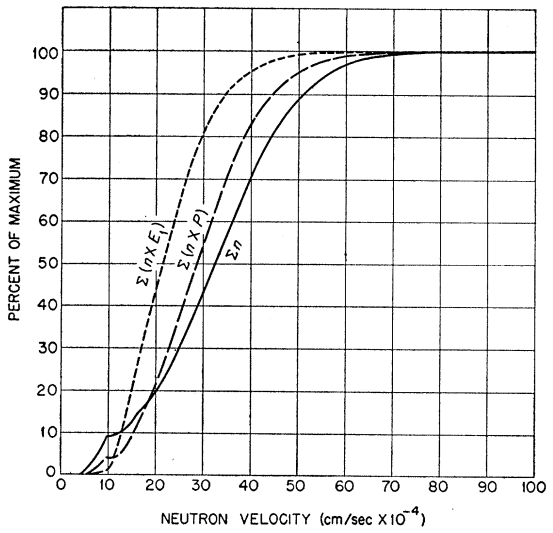

FIG. 5. Cumulative plots of neutron density, neutron density$\times E_1$, and neutron density$\times$polarization for 4 cm of Fe.

Those neutrons of wavelength greater than $\lambda=2d_{110}$ or 4.04A are not scattered coherently from iron. Those neutrons of this energy region which are scattered inelastically from magnetized iron may be polarized.[27] We have used measured values of the single transmission effect in this region[28] to calculate the contribution to the polarization of these low-energy neutrons. For 4 cm of iron, 8 percent of the neutrons emerging are below 4.04A. These neutrons have a polarization of about 16 percent.

The single transmission effect for 4 cm of iron is shown as a function of velocity in Fig. 3. These values were calculated using (1). The large values of the single transmission effect at velocities slightly greater than that of the coherent scattering cutoff of iron emphasize the possible importance of these neutrons in a weighted average.

The polarization as a function of velocity calculated from (1), (2), and (4) is shown in Fig. 4 for 1-, 2-, 3-, and 4-cm thicknesses of iron. The polarization *vs* velocity for 4 cm with complete saturation is shown for comparison. Cumulative plots against velocity of neutron density$\times$single transmission effect and neutron density$\times$polarization for 4 cm are shown in Fig. 5 along with the cumulative neutrun density as a function of velocity. From these plots the relative contributions of selected portions of the spectrum can be taken. The curve $\sum(n\times E_1)$ rises more quickly than the curve $\sum(n\times P)$, because to a first approximation, the single transmission effect is proportional to p^2, while the polarization is proportional to p.

The curves described above were used in calculating the single transmission effect for a $1/v$ detector weighted over the emerging spectrum through 1, 2, 3, and 4 cm

[26] Hoffman, Livingston, and Bethe, Phys. Rev. **55**, 924 (1939).
[27] O. Halpern, Phys. Rev. **72**, 261 (1947).
[28] Hughes, Burgy, and Woolf, Phys. Rev. **80**, 481 (1950).

of iron for all velocities from zero up to the Cd cutoff. The calculated values are compared with the measured values of Table III. The measured and calculated values agree to about 0.5 percent.

The measured values of single transmission effect having been acceptably accounted for, the curves were then used to calculate a polarization weighted with neutron density over the spectrum. The average polarization for energies greater than the iron cutoff and less than the Cd cutoff (0.5 ev) was 37 percent. The average polarization from zero energy up to the Cd cutoff is 35 percent.

The epi-cadmium neutrons are polarized only to a small degree. Their effect upon the average polarization is small because only about 10 percent of the activity of the sample used in the nuclear polarization experiment was due to epi-cadmium neutrons. We estimate that the 35 percent average polarization of all those neutrons below 0.5 ev becomes 32 percent when the averaging is done over the entire spectrum.

The polarization cross section corresponding to the average single transmission effect 0.221 for all energies less than 0.5 ev for the magnetic state of saturation of

TABLE III. Single transmission of continuous spectrum with $1/v$ detector.

Thickness cm	(j/j_0), measured	(j/j_0), calculated
1	1.022±0.001	1.016
2	1.063±0.001	1.059
3	1.136±0.001	1.130
4	1.221±0.001	1.231

our experiment in which $q=0.2$, is 2.2 barns. This value of p corresponds to a polarization of 45 percent under the same conditions of magnetization. The average polarization for all neutrons in this energy range is actually 35 percent. These numbers illustrate the degree of accuracy to be expected in deducing the average polarization from the average single transmission effect without taking into account the details of the spectrum.

E. MEASUREMENT OF POLARIZATION USING MAGNETITE

The polarization of a beam of neutrons of a single energy produced by a given polarizer can easily be measured if the polarization produced by a second polarizer from the same incident unpolarized beam is known. A schematic arrangement of the apparatus is shown in Fig. 6. The incident beam of unpolarized neutrons is passed through the polarizer A and analyzer B. The counting rate C is measured with A and B in parallel so that they both discriminate against neutrons of the same orientation. The counting rate C_2 obtained when the polarization of the beam between A and B is brought to zero by passing it through a shim of iron placed in zero field, is also measured. It can be

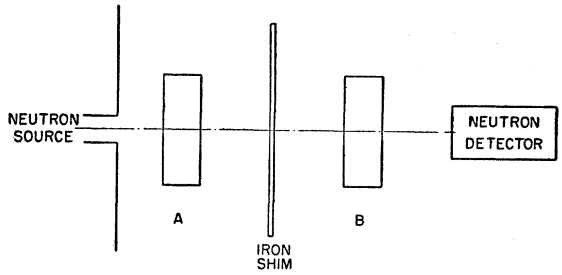

FIG. 6. Schematic arrangement for measuring polarization. A and B are polarizing regions. The shim reduces the polarization to zero.

shown that

$$G=C_1/C_2=1+P_1P_2, \tag{7}$$

where P_i is the polarization produced by polarizer i alone from the incident unpolarized beam of neutrons. We call G the "shim effect." This method has the advantage that $(G-1)$ is linear with the unknown polarization. It is equally sensitive for small and large polarizations. Measurements of small values of the polarization by the single transmission method are very difficult to make with accuracy as can be seen from Fig. 1. A polarization of 10 percent gives a single transmission effect of only 0.005.

We have attempted to measure unknown polarizations by using the polarization properties of the (220) reflection from a single crystal of magnetite. The polarization produced by a given set of planes of Miller indices (hkl), can be calculated[12] from the known chemical and magnetic structure of magnetite, the known values of the relevant nuclear and magnetic scattering amplitudes, and the direction of the applied magnetic field with respect to the scattering vector. For the applied field perpendicular to the scattering plane, the polarization of the (220) reflection is calculated to be close to 100 percent. The polarization of the second order (440) is calculated to be about minus 10 percent, the negative sign denoting polarization in the direction opposite to that of the first order (220). For the (220) reflection of the 56 atoms per unit cell, only the eight Fe^{+++} ions in the tetrahedral positions contribute to the coherent scattering. All 56 atoms contribute to the (440) reflection. Consequently, a crystal set to reflect a 100 percent polarized beam in the first order from the (220) planes, will reflect also in the same direction an appreciable intensity of second-order neutrons polarized slightly in the opposite direction.

TABLE IV. Shim effect for magnetite crystals.

Crystal in position A	Crystal in position B	Shim effect
III	I	1.430
III	II	1.437
I	II	1.547
I	III	1.385
I	IV	1.353

TABLE V. Shim effect *vs* energy.

Energy in ev	$(G_{obs}-1)$	$(G_{corr}-1)$
0.0372	0.138	0.369
0.0600	0.192	0.277
0.0858	0.177	0.215
0.149	0.103	0.132

Our first problem was to measure the polarization produced by the (220) reflection from a magnetite crystal. We procured several large natural crystals, and cut out several slabs $\frac{1}{8}$ in. thick and of area about 2 square in. in the (220) plane. The polarizations produced by the slabs were compared by measuring the shim effect with one of the slabs in position A, and with each of the other slabs in turn in position B. The results as shown in Table IV.

As can be seen from the data, the polarizations produced by the crystals were in general not the same. Crystal slabs I and II which were cut from the same crystal gave closely the same shim effect. If $P_1=P_2$, then $G-1=P^2$. The measured shim effect of 1.55 using crystals I and II together was corrected for higher-order content to give a value for first order only of 1.81. The polarization produced by each of these crystals alone is, therefore, about 90 percent. The polarization produced by crystal slabs III or IV alone would have been less than 90 percent, as indicated by their lower values for the shim effect using I in position A. Ordered impurities in the spinel structure of our large crystals are perhaps responsible for the values of the polarization being less than that expected on the basis of measured scattering amplitudes and the crystal structure.

We have used the value of 90 percent for the polarization produced by crystal I alone, to measure the values for the polarization in the beam coming through 4 cm of magnetized iron as a function of energy using expression (7). The shim effect was measured and corrected for the presence of second order by use of the boron transmission measurements. Values for the polarization cross section p were then derived for these energies from the polarization of the beam from the iron, using the previously measured depolarization coefficient in expressions (1), (2), and (4). These values of p are shown in Fig. 2.

The great disadvantage of the use of magnetite as analyzer is the large second-order correction required

TABLE VI. Polarization *vs* energy.

Energy in ev	Polarization as measured by transmission, percent	Polarization as measured with magnetite, percent
0.0372	49	41
0.0600	35	31
0.0858	26	24
0.149	13	15

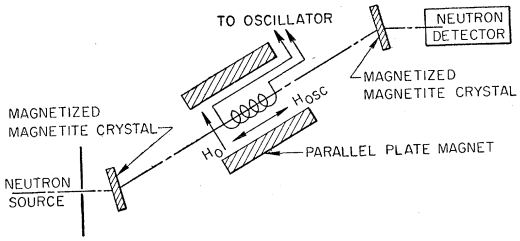

FIG. 7. Arrangement for measuring polarization using two magnetite crystals and magnetic resonance method.

in the measured value of $(G-1)$. The observed and corrected values for the quantity $(G-1)$ are given in Table V.

Values of the polarization at four energies deduced from the single transmission and magnetite methods are compared in Table VI. The agreement is quite good for all but the lowest energy 0.0372 ev, where the correction for higher order in the magnetite method is unacceptably large. For this energy, we take the transmission method to give more reliable results. The method described for measuring unknown polarization using a magnetic crystal of known properties as analyzer would be more practical if a crystal giving small higher-order content along with high neutron polarization were available.

It was pointed out above that the shim effect $G=1+P_1P_2$ is a more sensitive measure of polarization than the single transmission effect. An even more sensitive measure is the double transmission effect,[10,16] the ratio of the intensity with polarizer and analyzer aiding to that with polarizer and analyzer opposing, which is given by

$$K=(1+P_1P_2)/(1-P_1P_2). \quad (8)$$

We have used the arrangement of Fig. 7 to obtain values of K. The reversal of P_1 was achieved in the region between crystals I and II by the magnetic resonance method,[29] in which the steady field H_0 was perpendicular to the direction of the beam, and an oscillating field H_{osc} was along the beam direction. Polarizer, I, and analyzer, II, are again our magnetized magnetite crystals, in which $P_1=P_2=0.9$. Intensity measurements were taken under the four sets of conditions listed in Table VII. The shim referred to in Table VII is a depolarizing sheet of iron in zero field. Turning the oscillator on, changes the intensity from 100 to 30.2. BF_3 absorption measurements indicate that a large

TABLE VII. Intensity measurements using oscillator.

Conditions	Relative intensity
1. Oscillator off	100
2. Oscillator on	30.2
3. Oscillator on, with shim	64.8
4. Oscillator off, with shim	64.8

[29] L. W. Alvarez and F. Bloch, Phys. Rev. **57**, 111 (1939).

fraction of the residual 30.2 is due to the presence of second-order neutrons. The oscillating field affects the second-order neutrons very little for two reasons: K will be close to one because their polarization is low (-10 percent); when the strength of the oscillating field is such that the probability of flipping first-order neutrons is a maximum, the probability of flipping second-order neutrons is considerably less than maximum. The symmetry of the intensities in cases (3) and (1) with respect to (2) indicates strongly that all first-order neutrons are being flipped. The fact that the intensities in cases (3) and (4) are equal indicates that the depolarizing shim is removing completely the polarization of the beam passing through it. This method could be used, also, if I and II were transmitting blocks of iron. The use of magnetite crystals is advantageous because the high polarization of the first order of reflection from the (220) planes gives large intensity changes, and the polarization is independent of energy.

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The Alpha- and Gamma-Ray Spectra of Pu^{238}†

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The alpha and gamma spectra of Pu^{238} have been studied with an alpha-particle spectrograph and gamma-ray scintillation and proportional counters. Alpha groups of 5.495 (72 percent), 5.452 (28 percent), and 5.352 Mev (0.09 percent) and electromagnetic radiations of 17 (13 percent), 43.8±0.5 (0.038 percent), 99±2 (0.008 percent), and 150±2 kev (0.001 percent) were observed. Spins and parities are assigned to the energy levels, and the results are evaluated with respect to the developing theory and systematics of complex alpha spectra and excited states of even-even nuclei.

I. INTRODUCTION

MARKED regularities have been observed in the alpha spectra of different *even-even* nuclei indicating strongly that corresponding spectroscopic states are involved in the decay processes. Among the heaviest nuclei the low-lying excited states are spaced in such a fashion as to suggest that they constitute a rotational band[1] interpreted according to the Bohr and Mottelson[2] theory which unifies independent particle and collective aspects of nuclear states.

In another publication[3] the details of the alpha spectrum and gamma spectrum of Cm^{242} were reported and discussed in terms of the excited states of Pu^{238}. The present communication deals with Pu^{238} and the energy levels of U^{234}. The close similarity between Cm^{242} and Pu^{238} spectra can be seen from the decay schemes shown in Fig. 1, and it will be seen that the gamma-ray conversion coefficient data also show that comparable spectroscopic states are involved.

II. METHODS

The samples of Pu^{238} used in the present measurements[4] were made by the prolonged neutron irradiation of Am^{241} through the following series of reactions:

$$Am^{241}(n,\gamma)\, Am^{242m} \xrightarrow[16\text{ hr}]{\beta} Cm^{242},$$

$$Cm^{242} \xrightarrow[162\text{ day}]{\alpha} Pu^{238}.$$

The primary objective of the irradiations was to make Pu^{242} through the electron capture branching of 16-hour Am^{242m} so sizable amounts of this isotope were present. Also in a long irradiation the Pu^{238} captures neutrons to give successively Pu^{239}, Pu^{240}, and Pu^{241}, all of which were also present in small quantities. Mass spectrometric analyses[5] were made on two of the preparations

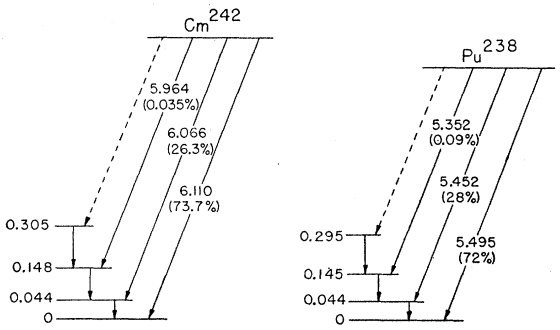

FIG. 1. Comparison of alpha spectra of Cm^{242} and Pu^{238}.

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[1] F. Asaro and I. Perlman, Phys. Rev. **91**, 763 (1953).

[2] A. Bohr and B. R. Mottelson, Phys. Rev. **89**, 316 (1953); **90**, 717 (1953); Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **27**, No. 16 (1953).

[3] Asaro, Thompson, and Perlman, Phys. Rev. **92**, 694 (1953).

[4] We are indebted to Dr. S. G. Thompson of this laboratory and to the personnel of the Atomic Energy of Canada, Ltd., Chalk River, Ontario, Canada, for making some of these preparations available to us.

[5] The analyses were made by Mr. F. L. Reynolds of this laboratory.