conspicuous isotope shift anomaly is connected with the completion of the subshell of neutrons with high l value.

Ford [15] and Wilets *et al.*[16] correlated the isotope shift in atomic spectra of heavy elements with the nuclear intrinsic deformation parameter (β) that was introduced by Bohr,[17] in such a way that the actual shift minus the shift predicted by the finite volume theory determines $d\beta/dN$ but not β itself. The above-mentioned shift anomaly would enter as anomalous slope in the β *versus* N curve in even-even nuclei (Fig. 4 of the article of Ford[15]). In this connection it may be remarked that in even-even nuclei the β *versus* N curve is relatively simple, β vanishing only at magic numbers, and the completion of subshell has a minor effect on the general trend of β, according to Ford's Fig. 4. In contrast to this, in even-odd nuclei the completion of subshell has often a marked influence on the form of the β *versus* Z curve (Z=proton number).[18] These facts will probably be connected with the more pronounced importance of the rôle which the alpha-particle model plays in even-even nuclei.

I should like to thank Dr. Ross for his kind cooperation in the work with enriched isotopes. The very pure sample of gadolinium which was used in the present experiment was kindly given to me by Professor Mack to whom my thanks are due.

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[15] K. W. Ford, Phys. Rev. **90**, 29 (1953).

[16] Wilets, Hill, and Ford, Phys. Rev. **91**, 1488 (1953).

[17] A. Bohr, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. *26*, No. 14 (1952).

[18] See, for example, K. Murakawa and T. Kamei, Phys. Rev. **92**, 325 (1935).

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Stern-Gerlach Experiment on Polarized Neutrons

J. E. Sherwood, T. E. Stephenson, and Seymour Bernstein
Oak Ridge National Laboratory, Oak Ridge, Tennessee

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A neutron beam was polarized by total reflection from a magnetized iron mirror. The beam was then analyzed by passing it through an inhomogeneous magnetic field. From the deflection pattern obtained, it is inferred that the resultant neutron spin in the polarized beam was parallel to the magnetic field applied to the mirror. Thus the nuclear and magnetic scattering amplitudes for iron are of the same sign when the neutron spin and electronic spin are oppositely directed, and conversely.

INTRODUCTION

When a beam of neutrons passes through a material body the process may be considered analogous to the passage of light through a refractive medium. Thus we may define an index of refraction $n=[(E-V)/E]^{\frac{1}{2}}$, where E is the energy of a neutron, and V is the average potential energy of the neutron while in the body. If θ is the glancing angle of incidence, it follows that total reflection will occur for $\theta=(V/E)^{\frac{1}{2}}$. In other words, all wavelengths greater than the critical wavelength,

$$\lambda_c=\theta(h^2/2mV)^{\frac{1}{2}},$$

will be totally reflected.

In the case of a magnetized iron mirror, the potential energy is $V=V_n+V_m$, where V_n is that due to the nuclei and $V_m=-\boldsymbol{\mu}\cdot\mathbf{B}$ is the potential energy of the neutron's magnetic moment $\boldsymbol{\mu}$ in the average net field $\mathbf{B}$. Thus, if λ_c^+ and λ_c^- are the critical wavelengths for $\boldsymbol{\mu}$ parallel to $\mathbf{B}$ and $\boldsymbol{\mu}$ antiparallel to $\mathbf{B}$, respectively, we have

$$\lambda_c^+>\lambda_c^- \quad (B\neq 0).$$

The spectrum of reflected neutrons will therefore have the general appearance shown in Fig. 1 (if the spectrum of the incident beam is assumed to be Maxwellian). Thus the spin state with $\boldsymbol{\mu}$ antiparallel to $\mathbf{B}$ is more abundant. Since the gyromagnetic ratio of the neutron is negative,[1] we have the result that the resultant spin of the neutrons in the totally reflected

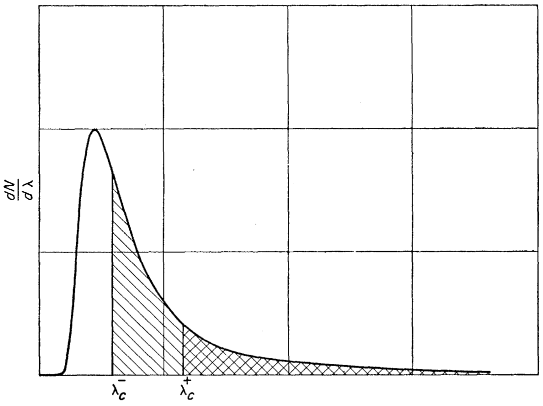

Fig. 1. Intensity distribution of neutrons reflected from magnetized iron mirror. For $\boldsymbol{\mu}$ parallel to $\mathbf{B}$, $\lambda>\lambda_c^+$. For $\boldsymbol{\mu}$ antiparallel to $\mathbf{B}$, $\lambda>\lambda_c^-$.

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[1] P. N. Powers, Phys. Rev. **54**, 827 (1938).

beam is parallel to the applied magnetic field. It may be noted that the direction of the dominant neutron spin in a beam of polarized neutrons is significant in the interpretation of experiments on the interaction of polarized neutron beams with polarized target nuclei.[2,3] However, in no other experiments with polarized neutrons has the direction of the neutron spin been of consequence. Only neutron intensities were involved.

In order to check the results of the above argument in a very direct manner, we have carried out a Stern-Gerlach type of experiment in which a beam of polarized neutrons is deflected magnetically. This experiment is described below.

DESCRIPTION OF THE APPARATUS

The mirror was of soft iron, about $1\frac{3}{4}$ in.$\times$6 in. long, and was magnetized parallel to the face in a direction perpendicular to the length and to the neutron beam. The exit edge of the mirror was rounded off so that the magnetic field in this region would change less abruptly. It was felt that this procedure would partially alleviate the depolarization effects found by early experimenters. The glancing angle of the neutron beam upon the mirror was approximately 3×10^{-3} radian (10 minutes).

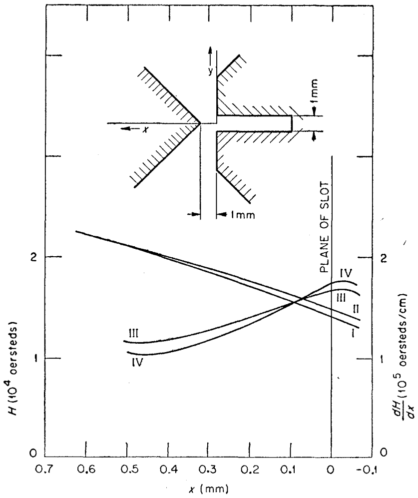

FIG. 2. Field strength and inhomogeneity of magnetic field in gap (reference 5): Curve I: Field strength in the plane of symmetry. Curve II: Field strength 0.2 mm outside plane of symmetry. Curve III: Inhomogeneity in the plane of symmetry. Curve IV: Inhomogeneity 0.2 mm outside plane of symmetry.

The slot-wedge type of deflecting field was felt to give the highest gradient consistent with reasonable cost. Since this arrangement had been thoroughly investigated by the early molecular beam experimenters,[4] the cross section of their magnet gap was copied. Figure 2[5] describes the cross section and magnetic characteristics of the gap; the length chosen was 1 meter. The average field in our magnet gap was found to be about 20 000 oersteds by means of a bismuth wire measurement. The field was maintained by four large solenoids of about 13 000 ampere-turns each.

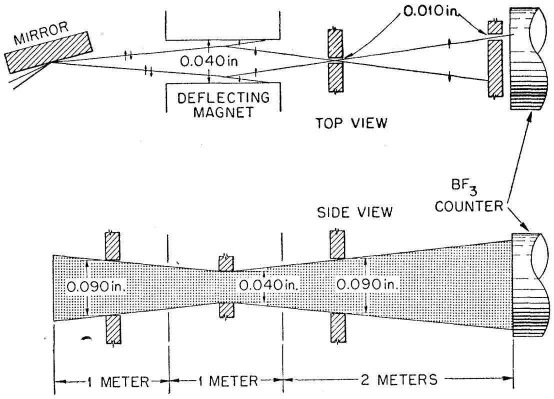

FIG. 3. Schematic diagram of beam collimation system showing typical trajectories and vertical slits (top view) and horizontal slits (side view).

The detector was a conventional arrangement consisting of a well-shielded BF_3 counter about 1 in. in diameter and 8 in. long. Its efficiency was about 90 percent for the reflected neutrons. Standard amplifiers and scale-of-64 registers were used. Background was 1.6 counts/min.

Even with a gradient of the order of 10^5 oersteds/cm extended over a length of a meter, the deflections produced are inconveniently small. This, together with the difficulty of producing such a gradient over a large space, requires a very high degree of collimation, in order to ensure that only those neutrons which spend an appreciable length of time in the region of high gradient will be counted. This was achieved, as shown in Fig. 3, by a combination of cadmium slits and holes. The main collimation was provided by the 0.010-in. vertical slit at the exit end of the deflecting

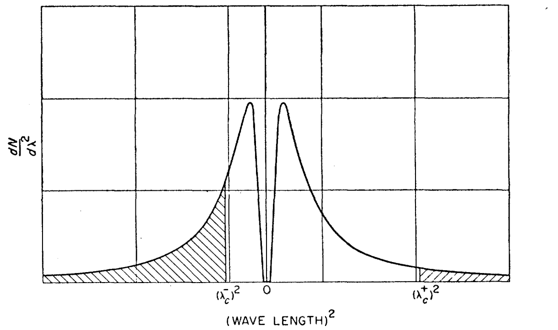

FIG. 4. Expected deflection pattern for infinite resolving power and perfect collimation. Shaded areas are derived from Fig. 1.

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[2] Bernstein, Roberts, Stanford, Dabbs, and Stephenson, Phys. Rev. **94**, 1243 (1954).

[3] Roberts, Bernstein, Dabbs, and Stanford, Phys. Rev. **95**, 105 (1954).

[4] I. Estermann and O. Stern, Z. Physik **85**, 17 (1933).

[5] Reference 4, p. 18.

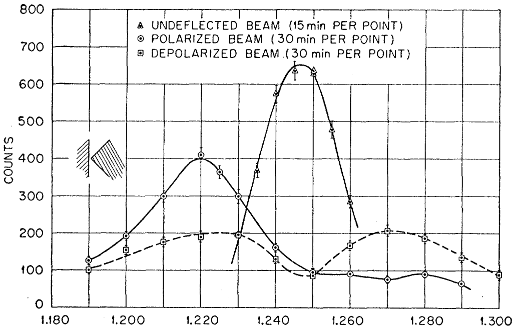

FIG. 5. Experimentally observed deflection patterns. Inset shows orientation of pole pieces with respect to the intensity pattern.

magnet. It is easily seen that this location of the slit does not complicate the interpretation of the results and leads to much better collimation than is obtained with the slit preceding the deflecting magnet.

PROCEDURE

Neutrons in the two spin states will suffer opposite forces in the deflecting magnet so that, with perfect collimation and infinitely good resolution, one should obtain an intensity distribution in the beam as shown in Fig. 4. (Displacement is proportional to λ^2.)

In practice, however, a 0.010-in. slit is translated across the face of the detector and yields the result shown in Fig. 5. For comparative purposes, undeflected and deflected-depolarized beams are shown there also. The depolarization was accomplished by interposing a soft iron shim in the beam between the mirror and the deflecting magnet, at a place where the magnetic field was small. For these data, the field between mirror and deflecting magnet was such as to permit only adiabatic transitions.

The experiment was repeated under conditions in which the neutron spins were "flipped" relative to the magnetic field, during their passage from the mirror to the deflecting magnet. This spin reversal was brought about by means of an arrangement of permanent magnets and pole pieces which caused the field to reverse its direction in a distance short compared with the Larmor precession distance. An intensity-displacement run then yielded the result shown in Fig. 6, in which it is seen that the main portion of the beam is now deflected to the right, instead of to the left.

INTERPRETATION OF RESULTS

If we consider only the normal pattern, Fig. 5, and agree to take the positive x axis to the right, the following argument applies: The energy of the dipole is $W=-\boldsymbol{\mu}\cdot\mathbf{H}=-(\boldsymbol{\mu}\cdot\mathbf{h})H$, where $\mathbf{h}$ is a unit vector in the direction of the magnetic field $\mathbf{H}$, and H is the magnitude of the field. Then, along the x axis, $F_x=-\partial W/\partial x=(\boldsymbol{\mu}\cdot\mathbf{h})\partial H/\partial x$. By inspection of Fig. 5, it is seen that $F_x<0$ and $\partial H/\partial x>0$. It follows that $\boldsymbol{\mu}\cdot\mathbf{h}<0$. Thus, since the gyromagnetic ratio of the neutron is negative, the experiment shows directly that the resultant spin in a neutron beam polarized by reflection from magnetized iron is parallel to the magnetic field applied to the mirror.

From this it can be shown that the nuclear and magnetic scattering amplitudes (for iron) are of the same sign when the neutron spin and electronic spin are oppositely directed, and conversely.

By means of double-transmission experiments, the resultant spin direction in the totally reflected beam from a magnetized iron mirror was compared with the resultant spin direction produced by transmission through magnetized polycrystalline iron. We find that for a sample magnetized perpendicular to the neutron velocity, the resultant neutron spins in the transmitted beam are directed opposite to the applied magnetic field. In the case of a single crystal of magnetite, in which the magnetic field was applied perpendicular to the scattering plane, the resultant spin in a beam reflected from the 220 planes is opposite to the applied magnetic field also.

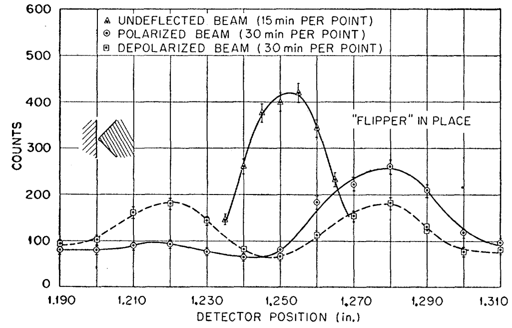

FIG. 6. Deflection pattern for "flipped" beam.

ACKNOWLEDGMENT

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