Some Direct Evidence on the Magnetic Moment of the Neutron

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(Received December 3, 1936)

An attempt has been made to observe the magnetic moment of the neutron through its selective scattering from magnetized iron. An experimental effect of 3.3 times the mean error has been observed. This effect agrees with that obtained from an evaluation of Bloch's theory.

Introduction

Bloch[1] has suggested that the magnetic moment of the neutron might be observed through its interaction with the fields of ferromagnets. There should be a difference in the number of slow neutrons scattered by an iron atom according to whether the spin of the atom is parallel or antiparallel to that of the neutron. This can be observed by "polarizing" the neutron beam by passing it through a magnetized iron bar, and "analyzing" this polarized beam by a second iron bar. Then the number of transmitted neutrons should be larger if the magnetizations of polarizer and analyzer are parallel than if they are antiparallel.

Experimental Procedure and Results

In the experimental arrangement these iron bars were made of transformer-core laminae of 0.9 cm total thickness for each bar, magnetized to approximately 15,000 gauss by electrical coils. The two iron bars reduced the slow neutron counts (neutrons absorbable in Cd) by a factor 3.18. A beam of slow neutrons from a Be-Rn source of approximately 500 mc strength located in a "howitzer" was collimated by apertures in Cd shields so as to traverse the two iron bars at right angles to the magnetization. (See Fig. 1.) The detecting apparatus consisted of a BF_3 ionization chamber in which the B disintegrations were registered, and a linear amplifier operating a thyratron "scale-of-eight" counter. The average solid angle subtended by the BF_3 chamber as viewed from a point midway between the iron bars was 0.14 radian.

In two runs with slightly differing geometrical arrangements the effects observed agreed within the rather large experimental error. The total counts were:

Fields parallel	218,868	
Fields antiparallel		216,695
Background (Cd penetrating neutrons)	96,580	96,580
Transmitted Intensity, I	122,288	120,115

The difference between the two directions of magnetization is 2173 counts. The mean error is the square root of the overall count of 435,563, or 660 counts. Expressed in percent the effect is therefore:

$$\frac{I(\text{parallel})-I(\text{antiparallel})}{I(\text{average})}=1.8\pm0.54 \quad \text{percent.}$$

Theoretical Calculations

If the incident neutron beam is perpendicular to the magnetization the cross sections for the two directions of neutron spin per unit solid angle are, according to Bloch:

$$\sigma=\sigma_\omega\pm\gamma_n\gamma_e\sigma_\omega^{\frac{1}{2}}(e^2/mc^2)\cos^2\tfrac{1}{2}\theta F(q). \qquad (1)$$

Here γ_n is the magnetic moment of the neutron in nuclear magnetons (-2.0 as deduced from the moments of proton and deuteron); γ_e is

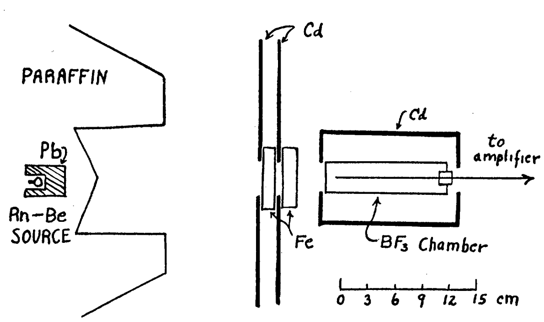

Fig. 1. Experimental arrangement for observing the magnetic moment of the neutron through its selective scattering in magnetized iron.

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

the average moment per atom in the iron (γ_e is equal to magnetization divided by 9800 gauss, which is 1.53 for our case); σ_ω is equal to[2] the total scattering cross section[3] divided by 4π, i.e.: $12.0\times10^{-24}/4\pi=0.96\times10^{-24}$ cm^2; θ is the angle of scattering of the neutron;

$$q=2\sin\tfrac{1}{2}\theta/\lambda \qquad (2)$$

where λ is the de Broglie wave-length of the neutron divided by 2π; and $F(q)=\int e^{i(\mathbf{q}\cdot\mathbf{r})}g(\mathbf{r})d\tau$ is the form factor for the electrons responsible for the magnetic moment of the iron.

According to present ideas,[4] the electrons responsible for ferromagnetism are those in the $3d$ shell. The form factor for these electrons was calculated using the Hartree wave functions for Cu^+. It was found by numerical integration that the form factor could be represented fairly accurately by:

$$F(q)=(1+0.182a^2q^2)^{-1.5}, \qquad (3)$$

where a is the Bohr radius. Since $3d$ shell is more contracted in Cu^+ than in Fe this form factor will be slightly too large, especially for large scattering angles. In order to take this effect roughly into account, we may multiply a in (3) by the ratio of the "effective nuclear charges" acting on the $3d$ electrons in Cu and Fe. From Hartree's paper, this ratio may be estimated to be about 917. Then we have for Fe:

$$F(q)=(1+0.30a^2q^2)^{-\frac{3}{2}}. \qquad (3a)$$

Denoting the total scattering cross section for neutron spin parallel to the magnetization by $\sigma_0(1+p)$, we have by integrating (1):

$$p=\frac{\gamma_n\gamma_e}{\sigma_\omega^{\frac{1}{2}}}\frac{e^2}{mc^2}\frac{1}{2}\int\sin\theta d\theta\cos^2\tfrac{1}{2}\theta F(q)$$
$$=\frac{\gamma_n\gamma_e}{\sigma_\omega^{\frac{1}{2}}}\frac{e^2}{mc^2}\frac{1}{K^2}[K+1-(1+2K)^{\frac{1}{2}}], \qquad (4)$$

where $$K=2\times0.30a^2/\lambda^2. \qquad (5)$$

For values of the wave-length λ in question the p is approximately proportional to λ. Therefore we insert for λ the average wave-length for neutrons of thermal velocities, which is the wave-length of a neutron of energy $\pi kT/4$. This gives $\lambda=3.2\times10^{-9}$ cm, and $K=1.64$. With the values of the constants given above we obtain:

$$p=0.178. \qquad (6)$$

Let us assume that one of our iron bars reduces the intensity of a neutron beam to $e^{-\mu}$ if unmagnetized. Then the transmitted intensity will be $e^{-\mu(1+p)}$ for one direction of polarization and $e^{-\mu(1-p)}$ for the other direction. With parallel magnetization of the two bars the transmitted intensity will therefore be:

$$\tfrac{1}{2}e^{-2\mu(1+p)}+\tfrac{1}{2}e^{-2\mu(1-p)}\backsimeq e^{-2\mu}(1+2p^2\mu^2). \qquad (7)$$

In the case of antiparallel magnetization the transmission will be simply: $e^{-2\mu}$. Thus the relative difference in transmission is:

$$\frac{I(\text{parallel})-I(\text{antiparallel})}{I(\text{average})}=2p^2\mu^2. \qquad (8)$$

In our experiment the transmission coefficient was $e^{-2\mu}=1/3.18$ corresponding to $\mu=0.58$. With the value of p calculated in (6) this gives from (8):

$$\frac{I(\text{parallel})-I(\text{antiparallel})}{I(\text{average})}=2.3\text{ percent.}$$

This is in satisfactory agreement with the experimental results.

It is a pleasure to acknowledge the assistance of a grant in support of these investigations from the National Research Council through its Committee on Radiation.

[2] The measured cross section is an average of the scattering cross sections for the various iron isotopes. In calculating the ratio of the magnetic scattering (second term in (1)) to the nuclear scattering (first term) we should insert $(\sigma_\omega^{-\frac{1}{2}})_{\text{av}}$ rather than $(\sigma_{\omega\text{av}})^{-\frac{1}{2}}$ which will tend to increase the magnetic effect.

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

[4] Slater, Phys. Rev. **49**, 537 (1936).