

MAGNETIC NEUTRALITY OF THE NEUTRON

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Present interest in the possible existence of isolated magnetic charges has raised questions about the degree of magnetic neutrality in magnetic dipole systems. For the free neutron case, past experiments dealing with the spatial deflection of neutron beams in extended magnetic fields have been analyzed by Ramsey to set an upper limit of 10^{-12} for the fractional unbalance of poles separated by the neutron radius. This limit has been lowered by about *six orders of magnitude* in present experiments of deflection effects in crystals of silicon wherein the anomalously small effective mass of neutrons provides greatly enhanced sensitivity.

1. Introduction

The search for magnetic monopoles began in 1951 with the Malkus [1] experiment and continues today. Monopoles of extremely large mass play a critical role in GUTS [2] theories of cosmology. With the known magnetic dipole moment of the neutron, it is interesting to set an upper limit on the possible fractional unbalance of pole strength of the neutron. Ramsey [3] analyzed an early neutron beam experiment to set a limit on the monopole charge of $q_m < 1.8 \times 10^{-15}$ Dirac charges ($e/2\alpha$).

In the present experiment we take advantage of the very small effective mass of neutrons as they diffract through perfect crystals to explore this limit on a scale lower by about six orders of magnitude. The effective mass concept for neutrons, predicted by dynamical diffraction theory, is analogous to the dynamical effective mass description of the electron in the nearly free electron model of charge transport in semiconductors. Horne [4] has derived an expression for the effective mass (m^*) in terms of the normal mass (m). In the special case where an external force is applied along a direction parallel to the reciprocal lattice vector $G(\text{hkl})$ the effective mass is:

$$\frac{1}{m^*} = \frac{1}{m} \left\{ 1 \pm (1 - \Gamma^2)^{3/2} \frac{\Delta_0}{d_{(\text{hkl})}} \right\}. \quad (1)$$

Here $d_{(\text{hkl})}$ = lattice spacing for (hkl) planes,

Δ_0 = the pendellosung length, a characteristic length for diffraction in perfect crystals.

$\Gamma = \tan \Omega / \tan \Theta_B$, with Ω the angle between the neutron propagation direction and the (hkl) planes, while Θ_B is the Bragg angle for this reflection.

The ratio in the second term is of order 10^{+5} which implies that $m^* = \pm m \times 10^{-5}$. The +, – sign indicates that the neutron can have either a positive or negative mass. These two signs are associated with two wave fields in the crystal β , α respectively.

These wave fields are produced when an incoming plane wave enters a crystal (in symmetric Laue geometry) within its Darwin acceptance range. When an incident wave approaches the crystal at the exact Bragg angle, the β , α fields flow parallel to the (hkl) planes. Thus a crystal, along with slits placed symmetrically opposite to each other (fig. 1) can serve as a crystal collimator passing only exact Bragg radiation. If the neutron possesses a monopole charge, application of a uniform, transverse magnetic field is expected to deflect the beam trajectory inside the crystal. A small effective mass inside the crystal would result in a correspondingly large deflection.

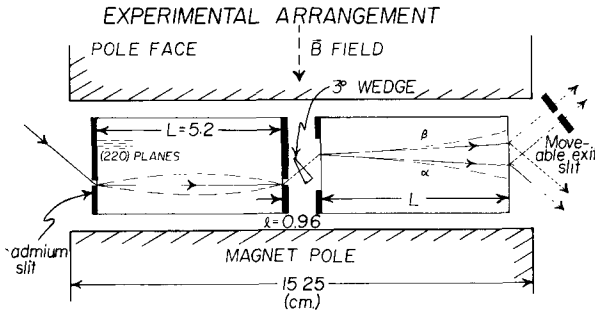


Fig. 1. Top view of the experimental arrangement showing the double crystal placed in the most uniform field region between the oversized, flat iron pole faces of an electromagnet. There is, in addition, a moveable slit which travels perpendicular to the beam exiting the second crystal in the forward direction. The dashed lines illustrate the effect of a force on the neutron trajectories inside the crystal.

2. Experiment

Two connected silicon crystals are used in this experiment, the first acts as crystal collimator while the second is a sensitive deflection analyzer. Each crystal is 52.2 mm thick. It is necessary to separate the β , α wave fields (positive & negative m^*) in the analyzing crystal. This is accomplished by insertion of a small angle aluminum wedge between the two crystals as shown in fig. 1. Monochromatic radiation (2.46 \AA with angular divergence 0.4° and $\Delta\lambda/\lambda$ of 1%) from a graphite monochromator was filtered through graphite to reduce order contamination before it passed to the front face of the crystal collimator.

To optimize sensitivity to intensity changes in the β , α peaks at the back face of the analyzing crystal due to deflections, the aluminum wedge angle is chosen to separate the β , α wave fields by a distance equal to their individual widths. Fig. 2 shows intensity obtained through a scanning exit slit for two different wedge angles. The 3° wedge was used in this experiment.

If the neutron has a magnetic charge (q_m), application of a magnetic field B will pull the α , β peaks apart; reversing B will push them closer. The intensity of neutron radiation leaving the crystal through the centered exit slit will change accordingly.

Allowing for the effect of B in both crystals and in

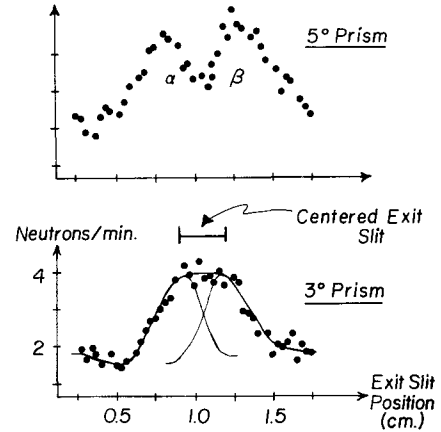


Fig. 2. Intensity pattern vs. the position of exit slit seen in fig. 1 for two intercrystal-prism angles. The 3° prism was used in the search for a magnetic charge because it displaces the α , β peaks ($-$, $+$ masses) so their inner half intensity positions coincide. This is suggested by the component curves in the lower portion of the figure. By placing the exit slit over this central region one doubles the sensitivity for measuring intensity changes due to a change in peak separation.

the gap between them, one finds an expression for q_m :

$$q_m = \frac{\text{Force}}{|B|} = \frac{\sqrt{\ln 2}}{2} \frac{R}{S} \frac{V_0^2}{|B|} m_0 \times \frac{d_{(hkl)}}{\Delta_0} \frac{\cos^2 \theta_B}{\tan \theta_B} \frac{1}{L^2(3/2 + l/L)}, \quad (2)$$

where R is the fractional difference in intensity upon field reversal,

S = average slope of peaks at the $1/2$ intensity point,

V_0 = free space neutron speed,

$m_0 \frac{d(220)}{\Delta_0}$ = effective mass of neutron for (220) reflection.

Neutron intensity fluctuations caused by changes in reactor power, temperature, and background occur with a characteristic time of a few hours. To minimize their influence, the counting interval between field reversals was 5 minutes. In fig. 3 we plot R for 16 counting periods each representing about

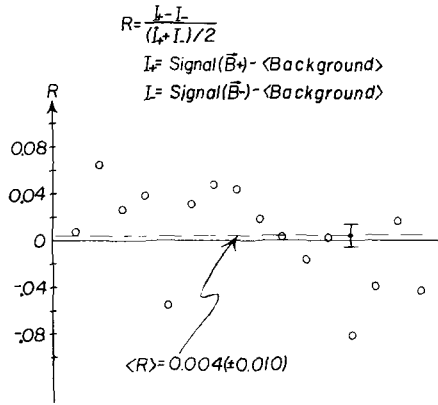


Fig. 3. Compilation of data taken over a seven week period. Each data point represents about 19 hours of 5 minute counting intervals. Background data were obtained by covering the exit slit with cadmium and counting as above. The dashed line represents the average R after counting about 40 000 neutrons with each field direction.

230 field reversal pairs. The uncertainty in $\langle R \rangle$ is obtained by considering the statistical error δI (the square root of the total number of counts divided by the number of counting intervals) independent for each field direction, and calculating a $\langle \delta R \rangle$ from these two numbers.

3. Results

Using the results of fig. 3 in (2) we establish an upper limit on the neutron magnetic monopole charge to be $0.28 (\mp 0.72) \times 10^{-27}$ cgs units or $0.85 (\mp 2.2) \times 10^{-20}$ Dirac charges. The previous limit set by Ramsey [3] was $q_m < 0.14 \times 10^{-21}$ cgs units, thus the present experiment implies a lowering of the Ramsey limit by a factor of about 2×10^5 . This new value would be useful in a "Amperian currents" model for the neutron electric dipole moment. From the measured neutron magnetic dipole moment and a neutron size (in a simple picture, the separation between poles) of 2×10^{-13} cm one calculates a dipole charge of 0.5×10^{-10} cgs units.

Then the fractional unbalance (monopole charge/dipole charge) is 1.2×10^{-17} . This monopole charge limit for the neutron may be compared to the nucleon charge limit of Vant-Hull [5] who used a Squid detector to measure the net magnetic charge of bulk materials. He found a limit of 10^{-26} Dirac charges/nucleon, not being able to distinguish protons and neutrons.

One question worth addressing is the effect of gradients in the magnetic field on the experiment since their presence would also produce deflection forces. The maximum field gradients occur at the front and back faces of the double crystal arising from the finite size of the magnet pole pieces. The gradient at the front of the crystal (the region of greatest influence on the experiment) is 100 gauss/cm at 5000 gauss mean field and decreases rapidly with increasing depth in the crystal. Careful analysis indicates that a stationary gradient (in space) will cause only a broadening of the α , β peaks; it will not introduce any peak shifting effect upon field reversal.

Acknowledgment

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