Neutrino Magnetic Moment Upper Limit*

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A giant liquid scintillation detector was employed in a fission-reactor neutrino flux to set an upper limit of 10^{-9} Bohr magneton for the neutrino magnetic moment. The experiment consisted in searching for a count-rate difference associated with the reactor neutrinos.

INTRODUCTION

STIMULATED by the growing body of evidence for the distinction between neutrinos and antineutrinos,[1] one is led to ask on what basis such a distinction arises. The recent two-component theory of Lee and Yang,[2] in which the two kinds of neutrinos are distinguished by a spin angular momentum which is uniquely tied to the linear momentum of the neutrino, provides a theoretical basis on which to make a distinction: a neutrino would be "right handed" and an antineutrino "left handed." Salam[2] points out that according to the two-component theory the neutrino magnetic moment must be identically zero. Another basis for distinguishing between neutrinos and antineutrinos which is made more plausible by the recent discoveries of antinucleons[3] is the possible existence of a neutrino magnetic moment which results from the virtual dissociation of antineutrinos into positron, neutron, and antiproton. (A neutrino virtually dissociates into a negative electron, antineutron, and proton.) The difference between neutrinos and antineutrinos would then consist in opposite spin orientations relative to their magnetic moments. Estimates of the neutrino magnetic moment made on this basis by Houtermans and Thirring[4] give the value

$$f \sim 10^{-10\pm 2} \text{ Bohr magneton.}$$

We have in the present work sought to lower the previous upper limit[5] of 10^{-7} Bohr magneton set in 1954 and have accomplished this aim by using a larger and better-shielded detector with improved energy resolution and a coincidence arrangement to eliminate photomultiplier-tube noise. In addition, greatly improved knowledge of the fission neutrino spectrum made possible less conservative assumptions on that score. As in the previous work, a liquid scintillator provided the reactor-neutrino targets. The counter used was one of the tanks designed for the detection of the free neutrino.[1]

THEORY

Bethe gives a formula for neutrino-electron collisions via a neutrino magnetic moment[6] which relates the cross section $\sigma(W)dW$ for target electrons to appear in a given energy range dW at energy W for a given incident neutrino energy, E. Since the neutrino mass is small (<500 ev)[7] relative to its energy in the energy region of interest to us ($\geq 10^5$ ev) and the target-electron energy is much greater than the ionization potential, Bethe's formula reduces to

$$\sigma(W)dW = Af^2 \frac{1}{1+W}\left(1-\frac{W}{E}\right)\frac{dW}{W}, \tag{1}$$

where A = classical electron area ($=2.5\times 10^{-25}$ cm^2), f = neutrino magnetic moment in Bohr magnetons (1 Bohr magneton $= e\hbar/m_e c$), and all energies are in units of the electron rest energy. Integrating over the fission neutrino spectrum, $n(E)$, the recoil-electron spectrum $N(W)dW$ is given by

$$N(W)dW = dW\int_W^{E_{\max}} \sigma(W,E)n(E)dE$$
$$= \frac{Af^2 dW}{W(1+W)}\left\{\int_W^{E_{\max}} n(E)\left[1-\frac{W}{E}\right]dE\right\}, \tag{2}$$

where

$$\int_0^{E_{\max}} n(E)dE = 1. \tag{3}$$

The reactor-associated count rate $S(W_1,W_2)$ in the energy range $W_1 \rightarrow W_2$ for a detector containing $\mathfrak{N}$ target electrons with a detection efficiency ϵ and in a neutrino flux F neutrinos/cm^2 sec is given by

$$S(W_2,W_1) = F\mathfrak{N}\epsilon \int_{W_1}^{W_2} N(W)dW. \tag{4}$$

Solving (4) for the magnetic moment, f, of the neutrino

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[1] The evidence prior to the recent work on parity nonconservation is reviewed in F. Reines and C. L. Cowan, Jr., Nature **178**, 446 (1956).

[2] T. D. Lee and C. N. Yang, Phys. Rev. **106**, 1671 (1957). We are grateful to Dr. Lee and Dr. Yang for sending us preprints of their work. See also L. Landau, Nuclear Phys. **3**, 127 (1957); A. Salam, Nuovo cimento **5**, 299 (1957).

[3] Chamberlain, Segrè, Wiegand, and Ypsilantis, Phys. Rev. **100**, 947 (1955); Cork, Lambertson, Piccioni, and Wentzel, Phys. Rev. **104**, 1193 (1956).

[4] F. G. Houtermans and W. Thirring, Helv. Phys. Acta **27**, 81 (1954), and private communication from Dr. Thirring.

[5] Cowan, Reines, and Harrison, Phys. Rev. **96**, 1294 (1954).

[6] H. A. Bethe, Proc. Cambridge Phil. Soc. **31**, 108 (1935).

[7] L. M. Langer and R. J. D. Moffat, Phys. Rev. **88**, 689 (1952); Hamilton, Alford, and Gross, Phys. Rev. **92**, 1521 (1953).

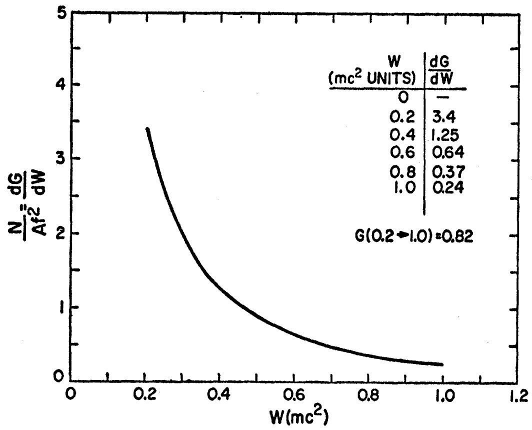

FIG. 1. Dimensionless neutrino spectrum factor.

we find

$$f=\left[\frac{S(W_2,W_1)}{AF\mathfrak{N}\epsilon G(W_2,W_1)}\right]^{\frac{1}{2}}, \qquad (5)$$

where

$$G(W_2,W_1)$$
$$=\int_{W_1}^{W_2}\frac{dW}{W(1+W)}\left\{\int_{W}^{E_{\max}}n(E)\left[1-\frac{W}{E}\right]dE\right\}. \qquad (6)$$

For the purposes of the present calculation we take Muehlhause and Oleksa's measured beta spectrum from fission[8] as the antineutrino (ν_-) spectrum. Since the antineutrino spectrum is in fact slightly more energetic than the β spectrum from fission fragments, we predict on this count a slightly lower-lying recoil spectrum than we should predict and hence fewer recoil electrons in a given energy range because the recoil spectrum decreases monotonically with increasing energy. This means that the denominator of Eq. (5) is calculated to be a trifle too small and hence we obtain from this assumption too large a number for the magnetic moment limit. It follows from Eq. (6) that the value of G in the energy range <0.5 Mev is not sensitive to the precise shape of the spectrum above 2 Mev. Calculating $N(W)/Af^2$ from the spectrum of Muehlhause and Oleksa, we obtain Fig. 1. Inserting numerical values for A, $\epsilon(\approx 1)$, $\mathfrak{N}(=4\times 10^{29})$ target electrons, ν_- flux $F=1.3\times 10^{+13}/\text{cm}^2$ sec, we find, for f, the expression

$$f=9\times 10^{-10}[S(W_2,W_1)/G(W_2,W_1)]^{\frac{1}{2}} \text{ Bohr magnetons.} \qquad (7)$$

EXPERIMENTAL ARRANGEMENT

Figure 2 shows a schematic diagram of the experimental arrangement.[9]

[8] C. O. Muehlhause and S. Oleksa, Phys. Rev. **105**, 1332 (1957). We are grateful to Dr. Muehlhause who kindly communicated these results to us in advance of publication.

[9] Some details of the detector construction are given in reference 1.

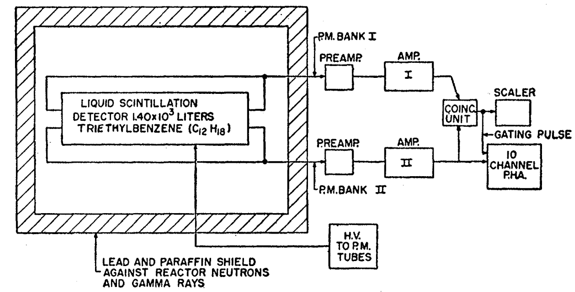

FIG. 2. Schematic diagram of the experimental arrangement.

The experiment was performed as follows: first an energy scale for minimum-ionizing particles was set for each bank of 55 5-inch DuMont photomultiplier tubes which viewed the scintillator by employing the peak in the counting rate *versus* energy curve for cosmic-ray μ mesons passing through the detector. Since the system is linear, the through-peak energy of about 100 Mev determines the calibration for all minimum-ionizing particles. In addition, the scintillator response to electrons is linear over the range considered, i.e., 0.1 to 0.5 Mev. The pulses from each photomultiplier bank were sent into a coincidence unit which in turn pulsed a scaler when the pulses were coincident in time. The resolving time of the system was about 0.2 microsecond. A 10-channel pulse-height analyzer, gated by the coincidence circuit, measured the pulse-height spectrum. A standardized pulser was used to set all energy gates relative to the μ meson through peak.

The energy resolution of the detector itself is of some concern in the evaluation of the results. The point here is that the background as well as the expected signal decreases monotonically with increasing energy in the range of interest. Consequently the effect of finite resolution is to "throw" the more abundant low-energy signals into the higher energy range and so give more counts in the energy range selected than are really there. To estimate the effect of finite energy resolution, we consider a 0.1-Mev energy deposition and obtain a figure for the spread due to statistical fluctuations in the number of photoelectrons, n_e, ejected from the photomultiplier cathodes. The number n_e is given by the product of several factors: the energy deposited in the scintillator, the number of photons produced per electron volt absorbed ($\sim 1/150$), the number of photoelectrons produced per photon reaching the photocathode ($\sim 1/10$), the fraction of light emitted which reaches the photocathode (~ 0.15). Using the values here listed, we find that $n_e=10\pm 3$ photoelectrons are collected in each bank for 0.1 Mev deposited in the scintillator solution. If we allow in addition several percent of variation in the signal because of the nonuniformity of collection of light originating throughout the scintillator, we obtain as a more reasonable figure an energy resolution at 0.1 Mev of $\pm 35\%$. It is felt that the rapid rise of the background with energy shows that this energy resolution would enable one to account for as much as $\frac{1}{3}$ of the counts in the 0.1- to 0.5-Mev range as due to spillover from the lower energies.

EXPERIMENT

The counting rate in the range 0.1 to 0.5 Mev was observed for a sequence of 100-second runs as the reactor went from full to zero power. The scaler rate at full reactor power was observed to be 404 ± 2 sec^{-1}, and that with the reactor at zero power was 388 ± 2 sec^{-1}, the difference being 16 ± 3 sec^{-1}. Since the likely cause of the reactor-associated signal was gamma rays and neutrons, an experiment was performed in which additional shielding was provided against these radiations in the form of water-soaked sawdust. Measurements with an Am-Be neutron source showed this shield to cut the source neutrons by about a factor of twenty. The sawdust shield cut the counting rate by 13 counts per second, i.e., from 476 to 463 counts per second. The difference in absolute counting rate in the two experiments cited is attributed to equipment drift over the weeks which elapsed between the two sets of measurements. Correcting the residual reactor-associated count rate by subtracting the counting-rate drop due to the sawdust, we find, after normalizing the total absolute rate to that occurring during the reactor "up-down" experiment,

$$\Delta_{\text{reactor}}=(16\pm3)-13\times(400/470)=5\pm3\ \text{sec}^{-1}.$$

A source of drift in the equipment was its sensitivity to the ambient temperature at the discriminator circuits. Although we did not make a precise determination of this dependence, it appeared that a coefficient of something like -2 counts/sec °F was applicable to our system. Using the above and the observation that temperature rises from 3 to 4°F occurred in the equipment during the time of day appropriate to the reactor shutdown under consideration, we arrive at a net reactor associated signal of -1 ± 3 counts per second in the energy range 0.1 to 0.5 Mev. Taking the count rate 2 sec^{-1} as the largest which could reasonably be due to a neutrino magnetic moment and $W_1=0.2\ mc^2$, $W_2=1.0\ mc^2$, we find

$$f<1.4\times10^{-9}\ \text{Bohr magneton.}$$

Allowing for the spillover from energies below $0.2\ mc^2$ because of the finite energy resolution and the generally conservative treatment of the various factors involved, we quote

$$f<10^{-9}\ \text{Bohr magneton.}$$

This calculation assumes that all the neutrinos which follow a fission have been emitted between the "reactor up" and the "reactor down" measurements. The best information on this point is the work of Muehlhause and Oleksa[8] which indicates, in conjunction with the work of Way and Wigner,[10] that in our experiment more than half of the 6.1 antineutrinos per fission were emitted. The effect on our limit is however less than $\sqrt{2}$ because the more energetic neutrinos are emitted promptly, i.e., between our two sets of measurements, and so are accounted for. Indeed it can be seen from an integration of Eq. (1) that a 2-Mev neutrino is twice as effective in producing a 0.1-Mev recoil electron as is a 0.5-Mev neutrino. The cross section corresponding to the production in the scintillator of 2 counts per second for electrons in the energy range 0.1 to 0.5 Mev is 4×10^{-43} cm^2.

It is interesting to contemplate how much further down one might hope to push this limit. We guess that by careful stabilization of the equipment against temperature changes and a redesign of the detector with the use of low-background materials and improved shielding against local backgrounds as well as better energy resolution through the use of cylindrical geometry, an improvement of two or so in the limit on f might be attained.

It has been pointed out by Houtermans and Thirring[4] and Feynman[11] that if one assumes a universal Fermi interaction as discussed by Konopinski and Mahmoud,[12] a direct interaction can be calculated between electron and neutrino and should give rise to a neutrino-induced recoil-electron spectrum. The total cross section for this direct interaction is variously estimated to be from two[11] to four[4] orders of magnitude below the limit we have been able to set.

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[10] K. Way and E. P. Wigner, Phys. Rev. **73**, 1318 (1948).
[11] R. P. Feynman (private communication).
[12] E. J. Konopinski and H. M. Mahmoud, Phys. Rev. **92**, 1045 (1953).