Neutral-Current Limit and Future Prospect at a Fission Reactor*

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(Received 22 April 1974)

Data are presented which yield a new upper limit for the weak neutral- current reaction $\bar{\nu}_e+d\rightarrow n+p+\bar{\nu}_e$ in the MeV range of 6 times theoretical expectation at a 3-standard-deviation level. These data also demonstrate the feasibility of a test which is an order of magnitude more sensitive.

The possible existence of neutral currents in the weak interaction has aroused intense interest recently with the reported observations at CERN[1] and the National Accelerator Laboratory.[2] Measurements at our Savannah River Plant fission-reactor neutrino facility have resulted in an improved upper limit for a neutral-current $\bar{\nu}_e$ reaction and also indicate the feasibility of a neutral-current test at the level of theoretical expectation in the well-shielded environment which we have constructed in connection with our $\bar{\nu}_e$-e^- scattering search.[3] The reaction under discussion,

$$\bar{\nu}_e+d\rightarrow n+p+\bar{\nu}_e, \tag{1}$$

was studied in an energy range (2.2 to ~5 MeV) which differs greatly from that explored at high-energy accelerators (>1 GeV), and $\bar{\nu}_e$ is involved instead of ν_μ ($\bar{\nu}_\mu$). Further, according to the Weinberg theory, the rate of (1) is independent of the Weinberg angle since at these low energies only the axial vector (Gamow-Teller) contributes to this reaction,[4] leaving no arbitrary parameters. These widely differing conditions motivate the study of (1).

In an earlier attempt[5] the deuteron target was contained in a deuterated scintillator to which gadolinium was added. The object there was to identify the reaction by the distinctive delayed-coincidence signal provided by the product proton and the γ rays associated with neutron capture in gadolinium. The experimental sensitivity was limited, primarily because of the small (~2%) probability of the proton receiving enough energy to appear above random background. Clearly the detection efficiency would be greatly enhanced if the product neutron alone provided a sufficiently distinctive signature. The experiment under discussion is based on the fact that we have succeeded in drastically reducing the neutron background.

The measurements were made with H_2O or pure D_2O and a large BF_3 neutron counter as indicated in Fig. 1. Not shown in the schematic is the massive Pb, water, and concrete shield in which the liquid scintillation anticoincidence detector is enclosed. Table I summarizes the results obtained for a variety of target and shielding configurations in the inner region with the reactor on and off. A Pu-Be neutron source was used for energy calibration, for system stability checks, and in the determination of neutron detection efficiency. The dead-time-corrected (~40%) BF_3 rates tabulated refer to the main α-particle peak (~81% of the neutron-capture spectrum). The time referred to in the "Liquid scintillator" column is the duration of the system block following the penetration of the scintillator by a cosmic-ray muon.[6] We use these data and neutron detection efficiencies together with reaction cross sections for fis-

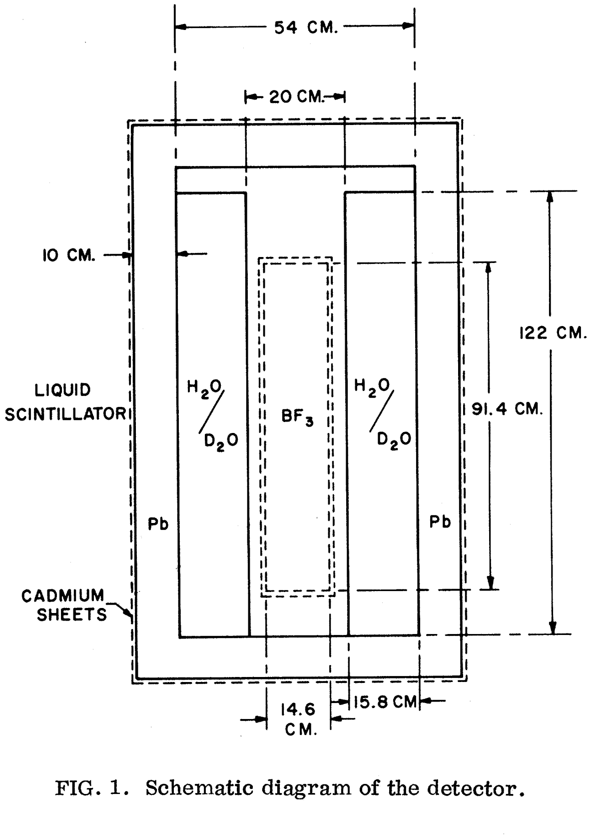

FIG. 1. Schematic diagram of the detector.

sion $\bar{\nu}_e$ for the processes

$$\bar{\nu}_e + p \to n + e^+ \; (1.0\times10^{-43}\ \mathrm{cm}^2/\bar{\nu}_e,\ \text{experimental}), \tag{2}$$

$$\bar{\nu}_e + d \to n + n + e^+ \; [(2.4\pm0.4)\times10^{-45}\ \mathrm{cm}^2/\bar{\nu}_e,\ \text{theoretical}^7], \tag{3}$$

and

$$\bar{\nu}_e + d \to n + p + \bar{\nu}_e \; (4.4\times10^{-45}\ \mathrm{cm}^2/\bar{\nu}_e,\ \text{theoretical}^4),$$

and together with the $\bar{\nu}_e$ flux at our detector, $2.4\times10^{13}\ \bar{\nu}_e/\mathrm{cm}^2\ \mathrm{sec}$, to set a new upper limit on (1).

To test our system we filled it with H_2O and measured the reactor-associated neutron rate (runs I and II). The resultant difference, $52\pm24\ \mathrm{day}^{-1}$, compared with the predicted rate, $\sim39\ \mathrm{day}^{-1}$, indicates that we were probably observing Reaction (2) via the product neutron[8] without benefit of the delayed coincidence between e^+ and n pulses previously required.[9] According to runs III and IV, reactor-associated neutrons originating external to the detector contribute a small part ($<15\ \mathrm{day}^{-1}$, at 1 standard deviation) of the observed signal[10] and increase the statistical uncertainty from $\pm24\ \mathrm{day}^{-1}$ to $\pm35\ \mathrm{day}^{-1}$.

The D_2O data are used to set an upper limit on the neutral-current reaction (1). Runs III and IV yield a reactor-associated neutron rate of $1.4\pm7.2\ \mathrm{day}^{-1}$. To obtain a more restrictive limit we subtract the calculated[11] charged-current contribution of Reaction (3),

$$(0.30\ \mathrm{kg}^{-1}\ \mathrm{day}^{-1})\times(178\ \mathrm{kg})\times0.082 = 4.3\ \mathrm{day}^{-1},$$

and obtain $-2.9\pm7.2\ \mathrm{day}^{-1}$. This number is to be compared with that predicted for the neutral-current reaction, 4.0×0.81. From these numbers we obtain a 3-standard-deviation upper limit on the ratio,

$$\frac{\sigma_{\mathrm{expt}}}{\sigma_{\mathrm{neutral\ theory}}} < \frac{-2.9+3(7.2)}{4.0\times0.81} < 6.$$

This limit is a factor >100 lower than the previous attempt.[5]

TABLE I. BF_3 counting rate for various experimental configurations.

Run	Reactor condition	H_2O/D_2O	Liquid scintillator[a] anti condition	BF_3 rate (day^{-1})
I	Down	H_2O	700-μsec block	63.4 ± 7.2
II	Up	H_2O	700	115 ± 23
III	Down	D_2O	3000-μsec block and 1000 μsec	54.7 ± 5.8
IV	Up	D_2O	3000 and 1000 μsec	56.2 ± 4.3

[a] Ref. 6.

The neutron counter envisaged in an improved experiment would be filled with ^3He to a pressure of 3.7 atm. As shown in Fig. 2 it would surround a 130-liter D_2O target. The anticipated overall neutron detection efficiency of the system is ~75%.

The $\bar{\nu}_e$ signals anticipated are as follows: neutral-current reaction, $\cong 60\ \mathrm{day}^{-1}$; charged-current reaction, $\cong 16\ \mathrm{day}^{-1}$ (single detected neutron), $\cong 24\ \mathrm{day}^{-1}$ (two detected neutrons).[12]

The reactor-independent background arises from a variety of causes: α activity in the counter, external neutrons, and photoneutrons. Scaling the background as seen in the BF_3 experiment we predict[13] a value of ~900/day. The reactor-dependent background arises from two sources: neutrons which penetrate the liquid anticoincidence shield and photoneutrons. Scaling the data from the present experiment (Table I) yields a prediction $-40\pm100\ \mathrm{day}^{-1}$ in the absence of a neu-

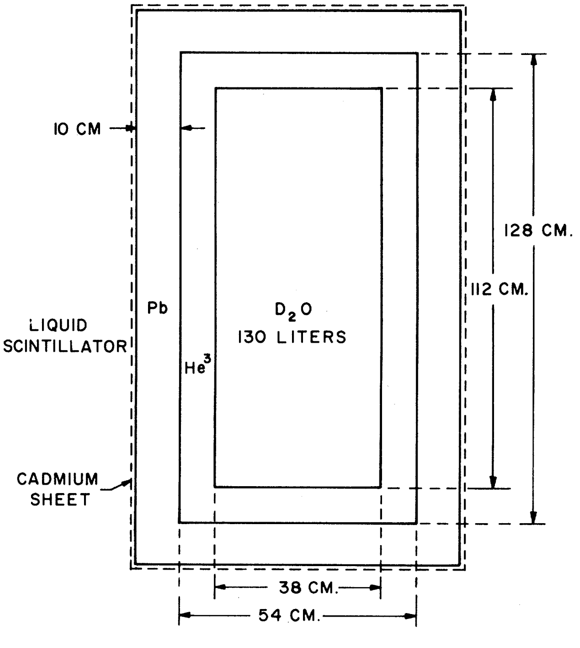

FIG. 2. Schematic diagram of the proposed experimental configuration.

tral-current signal or -100 ± 100 day^{-1} if a neutral current exists. The photoneutron component calculated from a measurement of the γ-ray spectrum *in situ* yields an acceptable upper limit of a few counts per day.

If a signal is observed it can be tested by use of of neutron differential shielding techniques and by observation of the effect of a neutron source. The sensitivity of the system to neutrinos can also be tested by observation of the two neutrons from the charged-current reaction (2), and by use of an H_2O filling and observation of Reaction (3).

We now estimate the statistical precision expected from a modest run sequence with the reactor on for 30 days and off for 10 days. The reactor-dependent neutron background is taken to be negligible since on the basis of present neutron limits there appears to be no obstacle to achieving this condition. Then

$$\frac{\Delta S}{S} = \pm \frac{1}{S}\left(\frac{S+B}{t_{\mathrm{on}}} + \frac{B}{t_{\mathrm{off}}}\right)^{1/2}, \qquad (4)$$

where $S = 76$ day^{-1} is the total $\bar{\nu}_e$ signal, $B = 900$ day^{-1} is the background, and $\Delta S/S = \pm 0.15$. If we allow for the statistical accuracy of the charged-current portion of the signal, S_c, in this period of time, $\Delta S_c/S_c = \pm 0.04$, and the neutral current would be determined in terms of the theoretical prediction S_n to an accuracy of $\Delta S_n/S_n = \pm 0.19$.

We wish to thank H. H. Chen and J. Lathrop for helpful discussions, and A. A. Hruschka for help in the design and installation of the equipment. We would also like to thank the Harshaw Chemical Company for the loan of the BF_3 counter and associated electronics and in particular B. M. Shoffner for his advice in setting up this apparatus. The continuing hospitality and assistance of the E. I. Dupont de Nemours Company which operates the Savannah River Plant for the U.S. Atomic Energy Commission is gratefully acknowledged.

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*Work supported by the U. S. Atomic Energy Commission.

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[6] In the D_2O runs an extra (1000 μsec, low threshold) anticoincidence condition was imposed to identify and reduce the background due to knock-on protons from neutron collision. This reduced the measured BF_3 rate by about a factor of 2. The cosmic-ray muon anticoincidence time for the D_2O runs was increased from 700 to 3000 μsec to take into account the increased neutron diffusion time in this medium.

[7] This reaction has been detected, but in view of the large experimental uncertainty $[(3.0 \pm 1.5) \times 10^{-45}$ cm$^2]$, we use the theoretically predicted value. T. L. Jenkins, F. E. Kinard, and F. Reines, Phys. Rev. 185, 1599 (1969).

[8] The neutron detection efficiency in this case is estimated to be about 15%.

[9] F. Reines and C. L. Cowan, Jr., Phys. Rev. 113, 273 (1959); F. A. Nezrick and F. Reines, Phys. Rev. 142, 852 (1966).

[10] This limit on the reactor-associated neutron background is derived from the rate -2.9 ± 7.2 day^{-1} (see following paragraph) by applying the ratio of the neutron detection efficiences for H_2O and D_2O (0.15/0.043).

[11] The overall neutron detection efficiency (η_n) with a D_2O target has been conservatively estimated as 0.043. The contributing factors are neutron absorption in D_2O, 0.87; solid-angle considerations, 0.29; BF_3 efficiency (counter filled to a pressure of 20 cm Hg), 0.19; Fe-wall attenuation factor, 0.9. The efficiency, 0.082, that enters in this calculation is the probability of seeing at least one neutron, $\sim 2\eta_n(1-\eta_n)$.

[12] The background for such a distinctive signal—two neutron pulses in delayed coincidence with a time interval of ~1 msec—is negligible under the conditions envisaged.

[13] Further neutron shielding and pulse-shape discrimination against α contamination in the counter walls can be expected to reduce this background.