No evidence was found for the previously indicated (K^+K^+) resonance, nor for any $I=\frac{3}{2}$ K^*, nor for a positive-strangeness baryon, all of which are inconsistent with such simple compositions. In contrast, we have some confirmatory evidence for a $(K\pi)$ resonance at 1080 MeV and evidence for a new $(K\pi)$ resonance at 1260 MeV. Either of these might well be the $J^P=0^+$ K^* predicted by a quark shell model.

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Search for a Neutral Weak Interaction via $\bar{\nu}_e$ Dissociation of Deuterons*

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An attempt was made to observe the dissociation of the deuteron by electron antineutrinos in order to test the theory of the neutral weak-interaction current. This event could be recognized by the detection of both disintegration products, the neutron and the proton. A deuterated liquid scintillator loaded with gadolinium to provide energetic-neutron-capture γ rays was used in this search. The signature for the event would be a prompt "proton" pulse followed by a coincidence between two crystals which signaled neutron capture. The crystal energy gates were set between 0.75 and 6.25 MeV, and the liquid scintillator was set for a light output equal to that produced by electrons$>$0.20 MeV and $<$0.59 MeV. During 55.5 h of runs near one of the Savannah River Plant reactors, the cross section for this process was determined to be $<(1.7\pm1.4)\times10^{-42}$ cm^2, a limit which is to be compared with a maximum theoretical expectation of 1.3×10^{-44} cm^2 and a previous experimental limit of 10^{-40} cm^2.

INTRODUCTION

An interesting problem in the field of weak interactions is whether neutral weak-interaction currents exist.[1–4] One possible mode of detecting such a current would be via the interaction

$$\nu+N\rightarrow N^*+\nu. \quad (1)$$

If the nucleus were a deuteron and the ν sufficiently energetic, the process would involve the emission of a proton and a neutron, both of which could be easily detected. For $\nu=\bar{\nu}_e$, reaction (1) becomes in this case

$$\bar{\nu}_e+d\rightarrow p+n+\nu_e. \quad (2)$$

According to Gapanov and Tyutin[5] the cross section for (2) is of the order of 10^{-46} cm^2 as a minimum and 10^{-44} cm^2 as a maximum value for fission antineutrinos. The best experimental limit for this cross section prior to the present effort[6] is $<10^{-40}$ cm^2.

In the present experiment we attempted to detect the neutral weak-interaction current via (2) by searching for a delayed coincidence between the prompt pulse produced by the proton and neutron and the subsequent capture of the neutron. The target was a deuterated decalin scintillator[7] ($C_{10}H_8D_{10}$) to which gadolinium was added because it has a high thermal neutron-capture cross section and yields several energetic γ rays per capture.[8] These γ rays were detected by two NaI(Tl)

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[1] R. M. Weiner, Phys. Rev. Letters **20**, 396 (1968).

[2] F. C. Michel, Phys. Rev. **138**, B408 (1965).

[3] E. F. Beall, Phys. Rev. Letters **20**, 947 (1968).

[4] F. C. Michel, Phys. Rev. **16**, 1698 (1967).

[5] Yu. V. Gapanov and I. V. Tyutin, Zh. Eksperim. i Teor. Fiz. **47**, 1826 (1964) [English transl.: Soviet Phys.—JETP **20**, 1231 (1965)].

[6] C. L. Cowan, T. L. Jenkins, and F. Reines, 1965 (unpublished).

[7] T. L. Jenkins and F. Reines, Proc. IEEE **NS-11**, No. 3, 1 (1964).

[8] *The Reactor Handbook* (Wiley-Interscience Publishers, Inc., New York, 1962), Vol. 3, Part B, p. 46.

crystals on opposite sides of the liquid scintillator. The detector arrangement and the imagined occurrence of an event are depicted schematically in Fig. 1.

In our postulated reaction, the scintillation light output from proton and slowing down neutron is summed and amplified resulting in a single pulse one microsecond wide, the "proton pulse." After thermalization, the neutron wanders around until it is captured by the gadolinium, yielding an average of four γ rays with energies totalling 7–8 MeV. These γ rays are then detected by both crystals in coincidence and in delayed coincidence with the "proton" pulse. The crystal pulses are summed and shaped into a single "neutron" pulse. The gate width for the delayed coincidence was chosen to be 30 μsec, time for approximately 90% of the neutrons produced to be captured.

The data were in the form of photographed traces on a dual beam oscilloscope as depicted in Fig. 2. The "proton" detection efficiency was determined by Monte Carlo calculations,[9] and the "neutron" detection efficiency was determined by using the results from an earlier experiment[10] with a very nearly identical geometry.

EXPERIMENTAL ARRANGEMENT

Detectors

The NaI(Tl) crystals, manufactured by Harshaw, were 29 cm in diameter and 7.6-cm thick, and were viewed by seven RCA three-inch-diameter photomultiplier tubes. The 4.8-liter deuterated liquid scintillator[7] with a concentration of 2 g per liter of gadolinium was contained in an all Lucite system. The container, a

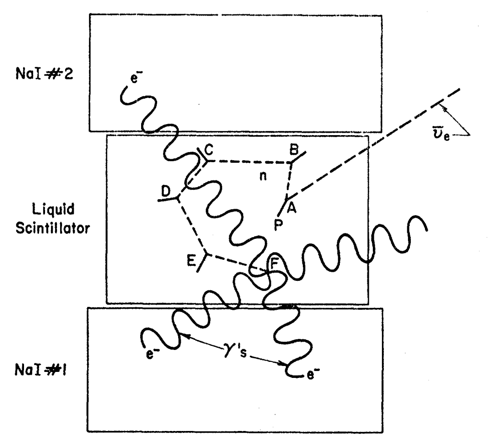

FIG. 1. Hypothetical $\bar{\nu}_e$ disintegration of a deuteron. Reactor neutrino comes from the right and strikes deuteron at A, disintegrating it. The neutron and proton carry off kinetic energy. The neutron strikes nuclei at B, C, D, and E before becoming thermal, after which it wanders around until it is captured at F by a gadolinium nucleus. On the average four γ's are emitted. The γ's then are detected by the NaI crystals.

[9] J. H. Munsee, Ph.D. thesis, Case Western Reserve University, 1968 (unpublished).

[10] F. A. Nezrick and F. Reines, Phys. Rev. **142**, 852 (1966).

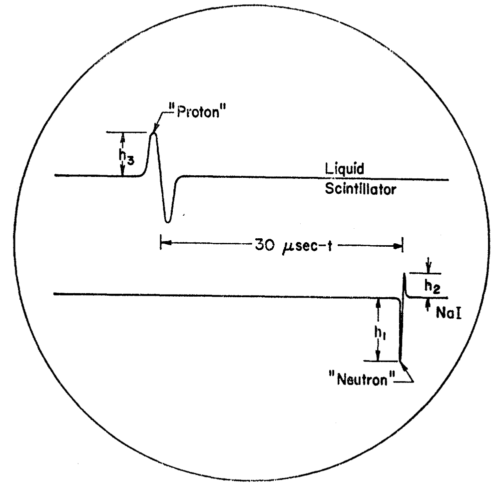

FIG. 2. Oscilloscope trace showing data output. The upper trace is due to the "proton" pulse, the lower to the "neutron" pulse. The pulses from the crystals were coded and mixed to have opposite polarities and be delayed by about 1 μ-sec relative to each other. h_1 and h_2 are the pulse heights produced by crystals 1 and 2 respectively and h_3 is the pulse height produced by the liquid scintillator.

right circular cylinder with interior dimensions 9.5 cm in height and 25.6 cm in diameter, was mounted in a yoke which held the 13 CBS 7817 photomultipliers.

The 9.5-cm depth of the liquid scintillator gives little absorption of the capture γ rays.[10] The diameter of the Lucite container was determined by the width of the detector cavity and the desirability of completely surrounding the circumference with phototubes so as to make the response less sensitive to event location. The phototubes were optically coupled to the walls of the Lucite container with Dow Corning QC2-0057 silicone grease. All surfaces facing the interior of the Lucite container were painted white to enhance light collection.

Shielding

The shield is depicted schematically in Fig. 3. The paraffin and wood (Southern pine) served as neutron moderators, the cadmium to capture neutrons, and the lead as a γ shield. Earlier measurements[10] indicated that capture γ's from neutrons which penetrated the shield were the predominant source of background. A study[11] showed that equally effective γ shielding could be obtained by reducing the lead thickness by a factor of two on the side farthest from the reactor, allowing room for a neutron shield. The removal cross section for fission neutrons in paraffin[12] is 6.7 cm and a minimum thickness of 10 cm was chosen to provide neutron moderation where paraffin was used. For structural reasons the 30-ton lead shield rested on 41.3 cm of wood which also

[11] J. H. Munsee and F. Reines, Atomic Energy Commission Report No. UCI-10P 19-3, 1968 (unpublished).

[12] J. Rockwell, *Reactor Shielding Design Manual* (D. Van Nostrand, Inc., New York, 1956), p. 7.

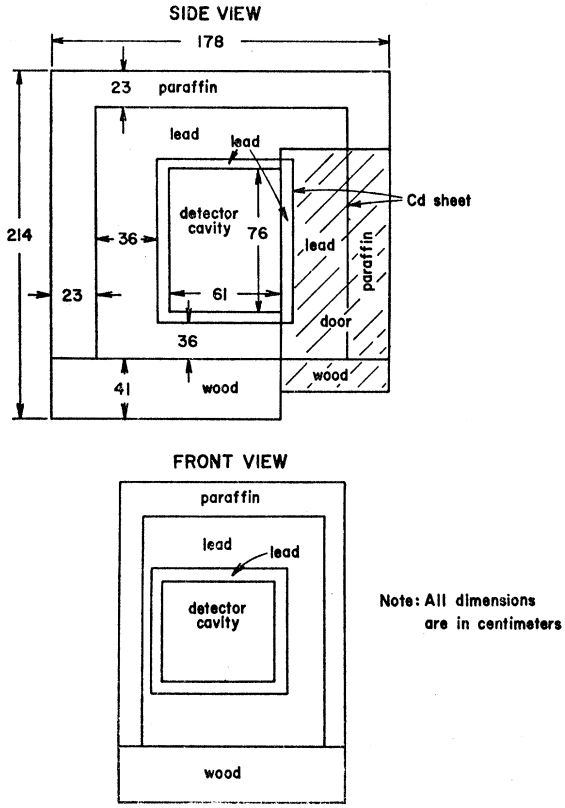

FIG. 3. Shielding.

served as the neutron moderator. A 15-mil layer of cadmium sheet was embedded into the lead 5 cm from the detector cavity to capture neutrons which either penetrated the outer layer of cadmium or were produced in the lead by cosmic rays. To further reduce background the detector cavity was packed with paraffin.

Electronics

The electronics are depicted schematically in Fig. 4. The pulse from the photomultiplier tubes viewing a given scintillator is fed into an A8 preamplifier which drives an A8 amplifier[13] through about 90 m of RG71/U coaxial cable.

The pulse from the center detector amplifier No. 3 is stored in a 35-μsec delay line from which the pulse is fed into a dual-beam oscilloscope for display if the proper set of conditions were met. The pulse from amplifier No. 1 is fed into a mixer which transmits only the negative-going part below a certain cutoff level. The pulse from amplifier No. 2 is fed into a 2-μsec delay line (to give the proper time relationship between the pulses from amplifier Nos. 1 and 2) and then to a mixer which transmits only the positive portion of the pulse above a certain cutoff level. The mixer adds the modified pulses from amplifiers Nos. 1 and 2 and feeds the resultant into a 5-μsec delay line and then to the second input on the dual-beam oscilloscope.

In addition to its normal output each amplifier has a pulse-height selector (PHS) unit which yields a fixed 1-μsec-wide 10-V pulse for each amplified pulse in a given range. The PHS output from amplifier No. 3 was fed into the delayed coincidence unit[14] and the outputs from amplifiers 1 and 2 were sent to a scaler and coincidence unit. If the PHS outputs of 1 and 2 were within 0.55 μsec of each other, the coincidence unit put out a pulse which was inverted, delayed by 2.4 μsec, and then fed to the delayed coincidence unit.

If a pulse from the coincidence circuit occurred within 30 μsec after the trigger from PHS 3, the delayed-coincidence unit activated a scaler and the camera control circuit. Pulses entering either of the two input channels were also counted.

A master switch turned on the scalers, a clock, the camera control unit, and a preset counter.

Calibration Procedure

The crystals were calibrated by placing a Cs^{137} source (0.66-MeV photopeak) equidistant from them. A spectrum was run on a 256-channel pulse height analyzer (PHA), the peak channel noted and a 60-Hz mercury pulser matched to the peak. The liquid scintillator was calibrated by running the cosmic ray through peak (16.8 MeV) on the PHA and comparing it with a peak due to the 1.0-MeV conversion electron[15] produced by a Bi^{207} source immersed in it. The system was run with the source bare and then in a β absorber (a sheet of polyethylene). Both runs were made with one crystal set to see the 0.57-MeV cascade γ which accompanies the electron in coincidence with the output of the liquid scintillator. The runs with and without the electron absorber were subtracted to give a peak at 0.97 MeV. The system was calibrated before and after each run.

DETECTION EFFICIENCY

The counting rate to be expected from process 1 is given by

$$R=\eta f\sigma N\,, \tag{3}$$

where η is the detection efficiency, f $(=8\times10^{13}\bar{\nu}_e/\text{cm}^2\,\text{sec})$ is the incident $\bar{\nu}_e$ flux, σ is the cross section for the interaction, and the number of target deuterons $N=1.9\times10^{26}$.

Among the problems relating to the detection efficiency is the light output to expect in the "proton" spectrum with a given incident $\bar{\nu}_e$ flux. There is also the question of neutron detection given a "proton" pulse. This efficiency can be considered in two parts: (1) P_c, the probability that the neutron will remain in the

[13] Oak Ridge National Laboratory Pulse Amplifier Manual, Report No. ORNL-3348 (unpublished).

[14] Designed and built by Mr. Bruce Shoffner, now with Hamner Electronics, Cleveland, Ohio.

[15] R. A. Ricci, Physica 23, 693 (1957).

detector and be captured within 30 μsec and (2) P_γ, the probability that neutron capture γ's will interact in the crystals in the appropriate way.

Therefore

$$\eta = P_1 P_c P_\gamma , \tag{4}$$

where P_1 is the probability that the light output from the "proton" pulse is in the proper range.

A computer program was written[9] to calculate the light expected from the incident neutrino spectrum of Carter *et al.*[16] as given in Ref. 10.

$$N(E_\nu) \propto e^{-0.505E_\nu - 0.0544E_\nu^2} , \tag{5}$$

where E_ν is the energy of the incident neutrino in MeV.

From conservation of energy and momentum the energy E, available for the three resultant particles is very nearly

$$E = E_\nu - 2.2 \text{ MeV}. \tag{6}$$

Phase-space arguments[17] are used to determine the energy distributions (Appendix A).

The efficiency calculation considers the reaction sites to be uniformly distributed throughout the detector and the product neutron to be isotropic.

The calculation of the neutron history proceeds as follows: Three distances are calculated based on the mean free paths of the neutron with energy E_n moving in a medium consisting of protons or deuterons, or carbon using densities found in the liquid scintillator (see Appendix B). The smallest of these three distances is chosen as labelling the struck nucleus and specifying the distance from the previous collision. If the neutron is found to be outside the detector the process starts with a new interaction. If in the detector, new directions are computed and the energy of the struck nucleus determined. The scintillation light output from the recoil nucleus is computed (Appendix C) and the energy of the recoil neutron is noted. We denote the probability that the neutron will thermalize in the detector and that the total prompt pulse associated with the reaction will be in the appropriate gates by P_1 and find that

$$P_1 = 0.024 \pm 0.01 .$$

Once thermalized the neutrons are subject to capture in the liquid.

The calculated spatial distribution of thermal neutrons was fitted by the relations (see Fig. 5)

$$N(R) \propto R \sin(\pi R/12.8) \tag{7}$$

and

$$N(Z) \propto 1 + 2 \sin(\pi Z/9.5) . \tag{8}$$

Using these distributions, a program was written to determine P_c. The probability that the neutron will be captured is 0.77 ± 0.02 and the probability that the

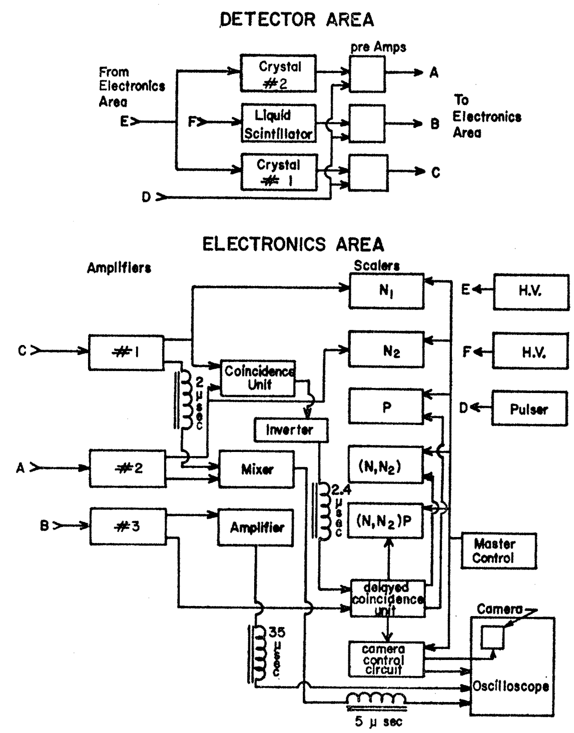

FIG. 4. Electronics block diagram.

capture will occur within 30 μsec is 0.86 ± 0.03 so that

$$P_c = 0.66 \pm 0.04 .$$

The probability that the γ rays from neutron capture in gadolinium will be seen in the proper fashion is[10] (see Appendix D)

$$P_\gamma = 0.32 \pm 0.08 .$$

Therefore

$$\eta = 0.0051 \pm 0.0013 .$$

DATA ANALYSIS AND RESULTS

The oscilloscope was photographed for each event satisfying the electronic constraints (~245/h). Most of the pulses were uninteresting prompt triples and only those delayed-coincidence events with delay times >1 μsec were accepted by the film scanner (~7/h).

The data collected during 55.5 h with the reactor on satisfied the following criteria:

(1) The energy deposited in a crystal, E_{NaI}:

$$6.25 > E_{\mathrm{NaI}} > 0.75 \text{ MeV}.$$

(2) The energy deposited in the liquid scintillator detector, E_{liq},

$$0.59 > E_{\mathrm{liq}} > 0.20 \text{ MeV } (\beta \text{ equivalent}).$$

(3) The pulses 1 and 2 must occur within 0.55 μsec of each other and within 30 μsec after pulse 3.

(4) Acceptable pulses were well defined with no large overloaded pulse preceding them.

[16] R. E. Carter, F. Reines, R. Wagner, and M. E. Wyman, Phys. Rev. **113**, 280 (1959).

[17] M. M. Block, Phys. Rev. **101**, 796 (1956).

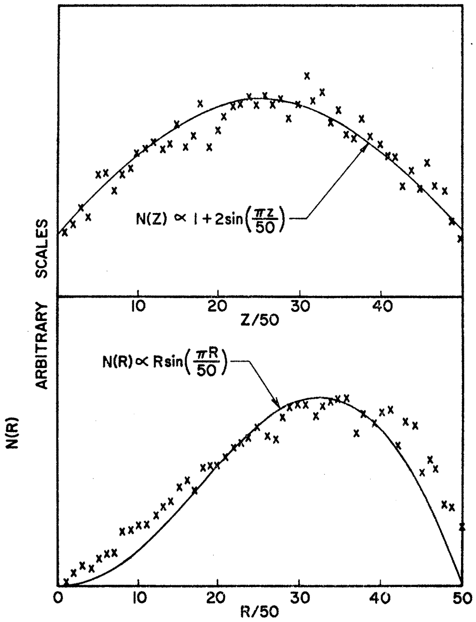

FIG. 5. Spatial distribution for thermal neutrons.

The crystal lower level was chosen as 0.75 MeV to coincide with that used in the calculation of Nezrick and Reines[10] for the detection efficiency of gadolinium capture gammas. The upper level was chosen to be 6.25 MeV because the maximum γ energy available with any probability from the (n,γ) process in gadolinium is 7 MeV,[8] and a coincidence was required between the two crystals to reduce the accidental background. The lower level on the center detector was set so that the rate corresponded roughly to $\frac{1}{10}$ that at which the scaler jammed. The upper gate was set by the fact that 93% of the incident neutrinos above the 2.2-MeV reaction threshold have energies less than 5 MeV. Guided by the maximum light output from neutrinos <5 MeV, 0.59 MeV was chosen as the upper gate.

The film yielded the time distribution of the "neutron" pulses relative to the "proton" pulses, the pulse height distribution of all those pulses with $1\lesssim t\lesssim 30$ μsec, and a sample pulse-height distribution for all channels for prompt pulses ($t=0$). As can be seen from Fig. 6, most of the pulses were prompt triple coincidences. The "signal" is equal to the total number of pulses in the above time interval minus the number of accidental pulses A, to be expected in that time interval:

$$A=n_1n_2\tau\,, \tag{9}$$

where the "proton" pulse rate $n_1=4.5\times10^5$/h, the "neutron" pulse rate $n_2=1.9\times10^3$/h, and $\tau=29\times10^{-6}$ sec is the period of time over which the accidentals can be observed.

As is shown in Appendix E, ΔA, the uncertainty in A, is

$$\Delta A=0.016A\,. \tag{10}$$

The number of counts in the range $1\lesssim t\lesssim 30$ μsec is 396 (Fig. 6). The number of accidental counts in this interval is 369, where a correction has been made for system dead time. Therefore the number of correlated events collected in the 55.5-h run time with the reactor on is 27 ± 21 and the rate is

$$R=0.49\pm0.38\ \text{h}^{-1}.$$

Inserting these quantities into Eq. (3), the measured limit on the cross section for this process is

$$\sigma<(1.7\pm1.4)\times10^{-42}\ \text{cm}^2.$$

This value is stated as an upper limit because correlated events could be caused by neutrons from cosmic rays[18] as well as from the reactor.[19]

The maximum cross section σ_{th} calculated[20] using the theory of Gapanov and Tyutin for our energy gates is

$$\sigma_{\text{th}}=1.3\times10^{-44}\ \text{cm}^2.$$

Our experimental limit on the rate of reaction (2) can be used to infer a limit on the strength of the neutral current relative to the charged current (which would give $\bar{\nu}_e+d\rightarrow n+n+e^+$). The upper limit so found is <60. This value is smaller than that which can be inferred from the CERN neutrino experiments[21] as they pertain to electron antineutrinos.

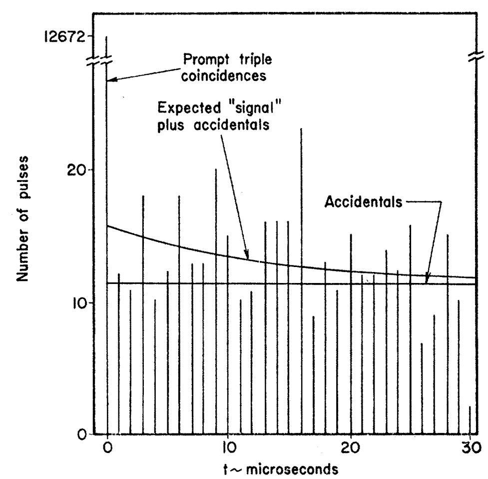

FIG. 6. "Neutron time distribution—number of pulses versus time." The expected "signal" time distribution is determined from the neutron capture time in the Gd solution.

[18] M. F. Crouch and R. D. Sard, Phys. Rev. **85**, 120 (1952).

[19] It is to be noted that this limit is uncertain by at least the statistical fluctuation in the accidental background or by an amount nearly equal to itself. In such a situation, the answer is clearly sensitively dependent on the stability of the system and in our case could be entirely masked by system changes of as little as 5%. Since our system was only stable to ~5%, it was decided that the considerable further effort which would be required in the way of runs with the reactor down was not warranted.

[20] The cross section used from Ref. 5 is σ_1.

[21] G. Bernardini, *Proceedings of the International School of Physics Enrico Fermi Course XXXII, Weak Interactions and High-Energy Neutrino Physics* (Academic Press Inc., New York, 1966). The CERN experiments can be used to infer a limit for electron antineutrinos only if it is assumed that the strengths of the neutral current for ν_e and $\bar{\nu}_e$ interactions with protons are the same.

POSSIBLE IMPROVEMENTS

Several improvements could be made to lower the limit obtained in the present experiment. A more complete anticoincidence shield for muons would enable rejection of pulses from neutrons produced by muon capture in the vicinity of the detector.

Under present conditions the maximum theoretically predicted signal rate is one event per 230 h. This is to be compared with the observable signal rate $s_0=1/20$ per hour assuming a running time t of 100 days, the present accidental rate A of 6.87 per hour, and a significant increase in stability of the electronics. The criterion of observability chosen is equality of the signal and the fluctuation in the accidental background:

$$s_0 t=(At)^{1/2}. \qquad (11)$$

The system sensitivity could be enhanced by increasing the detection efficiency and the number of deuteron targets. The volume of the liquid scintillator could be increased with very little additional loss due to absorption of the capture gammas by the liquid and it is conceivable that the volume could be enlarged by a factor of nine and still satisfy the geometrical constraints. By replacing the present detection system with one in which the liquid is entirely contained by NaI, the neutron capture γ detection efficiency P_γ could be raised towards unity, gaining an additional factor of three.

Taking the above factors into account, we can increase the present expected signal rate by a factor of >30. If the background also increases by the same factor, the maximum predicted signal could be seen in ~ 1 year. Some background reduction might be achieved by using radioactively cleaner materials for the center detector and by more effective shielding.

One of the backgrounds which must be considered in an experiment sufficiently sensitive to detect a 10^{-44} cm^2 cross section is that due to the reaction $\bar{\nu}_e+p\rightarrow n+e^+$ which has a cross section of 10^{-43} cm^2 for fission $\bar{\nu}_e$. Although the precise rejection ratio depends on the detailed design of the experiment the essential features which can be used to discriminate are the e^+ annihilation γ rays and the high first pulse energy characteristic of the proton reaction.

ACKNOWLEDGMENTS

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APPENDIX A: PHASE-SPACE CALCULATION

The density of allowed states[22] per unit energy interval for a particle emitted as the result of an interaction is

$$\rho_n=\frac{d}{dE}\prod_{i=1}^{n-1}\int d\mathbf{p}_i \qquad (12)$$

and the momentum spectrum for the jth particle is

$$d\rho_n/dp_j=4\pi p_j dp_j \rho_n. \qquad (13)$$

The solution of (2) in the center-of-mass system for a three-body problem is given by Block.[17] Particularizing his solution to the case at hand and noting that the particle energies are <10 MeV, we find to a good approximation (about 1% error)

$$d\rho_3/dK_i\propto(\sqrt{K_i})(E_0-2K_i), \qquad (14)$$

where

$$E=2M+E_0. \qquad (15)$$

E_0 is the energy available for the products of the reaction, K_i= kinetic energy of the proton ($i=1$) or neutron ($i=2$), and M= proton (or neutron) rest energy.

If we measure the kinetic energy K_i in terms of the available energy E_0 (i.e., let $K_i=\alpha_i E_0$), then

$$d\rho_3/dE\sim(\sqrt{\alpha_i})(1-2\alpha_i)^2. \qquad (16)$$

Now consider the neutrino spectrum. Again particularizing the Block solution to the present case, we find

$$d\rho_3/dE\sim\lambda^2(1-\lambda)^{1/2}, \qquad (17)$$

where $\lambda=E_3/E_0$ and E_3 is the neutrino energy.

It is reasonable in view of the large mass of the target nucleus relative to the small momentum carried by the incident neutrino that the difference between the center-of-mass and laboratory distributions is small.[23] In consequence the energy distributions given in Eqs. (16) and (17) are appropriate to the laboratory system. Also it is clear that $\lambda=1-2\alpha$ so that the spectra of the product neutrino and nucleons are simply related.

APPENDIX B: CROSS SECTIONS

In order to compute the distance d the neutron travels between collisions, it is necessary to know the cross section for interaction since

$$d_i=(\ln 2/N_i\sigma_i)\ln R, \qquad (18)$$

[22] See for example W. S. C. Williams, *An Introduction to Elementary Particles* (Academic Press Inc., New York, 1961), Ch. 5 and Appendix B. See also Leon Heller, Report No. LAMS-3013, 1964 (unpublished).

[23] A detailed argument may be found in Ref. 11.

where the index indicates the type of particle with which the neutron will collide, d_i is the distance from the last collision to this collision, N_i is the number of particles per unit volume, σ_i is the cross section, and R is a random number between 0 and 1. For our liquid scintillator

$$N_p=3.22\times10^{22}/\text{cm}^3,\quad N_d=3.90\times10^{22}/\text{cm}^3,\quad N_c=3.90\times10^{22}/\text{cm}^3.$$

Fitting the cross sections[24] by empirical formulas, we find

$$d_p=-7.07\ \ln R\Bigg/\left[\frac{3}{1.206E+(-1.86+0.09415E)^2}+\frac{1}{1.206E+(0.4223+0.13E)^2}\right], \tag{19}$$

$$d_d=\frac{-17.8\ \ln R}{0.0208E^2-0.4647E+3.446}, \tag{20}$$

$$d_c=\frac{-17.8\ \ln R}{-0.049E^3+0.738E^2-2.79E+4.72}, \tag{21}$$

where the distances are in centimeters and the energies are in MeV.

APPENDIX C: LIGHT OUTPUT OF LIQUID SCINTILLATOR

In order to compute the light output of the scintillator for the interactions of interest we must evaluate the contributions from protons, deuterons, and carbon atoms in the liquid scintillator. We used the following empirical expressions for light output[25]:

$$L_p=0.03E^2+0.26E \tag{22}$$

$$L_d=-0.00098E^3+0.036E^2+0.14E \tag{23}$$

$$L_c=0.017E, \tag{24}$$

where E is expressed in MeV and the L's in β-equivalent light output.

APPENDIX D: P_γ CALCULATION

If a single γ ray is emitted isotropically the probability that it will be detected by a crystal in our geometry is

$$P=0.409\pm0.027.$$

Let P_i represent the probability that i γ's will be detected by the crystals,

$$P_4=P^4$$
$$P_3=4P^3(1-P)$$
$$P_2=6P^2(1-P)^2.$$

If n γ's are detected, the probability that both crystals are involved is $1-2(\frac{1}{2})^n$. Therefore

$$P_\gamma=\tfrac{7}{8}P_4+\tfrac{3}{4}P_3+P_2=0.32\pm0.08. \tag{25}$$

APPENDIX E: SAMPLE DATA

TABLE I. Typical run data.

$t=8.7$ hours	
Scaler	Total count
n	1.64×10^4
s	2.14×10^3
p	3.61×10^6
n_1	6.90×10^5
n_2	6.28×10^5

Table I gives typical run data. n is the number of coincidences between the two crystals, i.e., counts in the neutron channel, s the number of coincidences between the proton channel and n, p the number of counts in the proton channel, n_1 the number of counts in crystal 1, and n_2 the number of counts in crystal 2.

The accidental rate is given by

$$A=(pn/t^2)\tau, \tag{26}$$

where t is the time over which these counts are accumulated, and τ (29±0.5 μsec) is the length of the coincidence time gate. The primary uncertainty ΔA in the accidental background, A, is seen to be due to the uncertainty in the time gate τ and $\Delta A=\pm0.016$.

[24] Brookhaven National Laboratory BNL Supplement #2, 2nd ed. (unpublished).

[25] C. Joseph, J. C. Alder, G. A. Grin, J. F. Lounde, and B. Vaucher, Helv. Phys. Acta **35**, 296 (1962). Computed from data given by T. J. Gooding and H. G. Pugh, Nuc. Inst. Meth. **7**, 189 (1960); R. Batchelor, W. B. Gilboy, J. B. Parker, and J. H. Towle, *ibid.* **13**, 70 (1961). It is assumed that the light output of all hydrocarbon-based scintillators for protons, deuterons, and carbon relative to that for electrons is very nearly the same.