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Neutrino Experiments at Reactors*

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A description is given of the $\bar{\nu}_e$ program using a large fission reactor. A search has been made for a neutral weak interaction via the reaction $\bar{\nu}_e + d \rightarrow p + n + \bar{\nu}_e$, the reaction $\bar{\nu}_e + d \rightarrow n + n + e^+$ has now been detected, and an effort is underway to observe the elastic scattering reaction $\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$ as well as to measure more precisely the reaction $\bar{\nu}_e + p \rightarrow n + e^+$. The upper limit on the elastic scattering reaction which we have obtained with our large composite NaI, plastic, liquid scintillation detector is now about 50 times the predicted value.

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* Under the auspices of the U. S. Atomic Energy Commission

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I. Search for Neutral Weak Interaction via $\bar{\nu}_e + d \rightarrow n + p + \bar{\nu}_e$

(Munsee and Reines)

Introduction

It is problematical whether a neutral current exists. The experimental test described here gives an upper limit on the cross-section using reactor antineutrino of

$$< 1.7 \pm 1.4 \times 10^{-43}\ \text{cm}^2$$

an improvement of approximately two orders of magnitude over the best previous experiment which gave $< 10^{-40}\ \text{cm}^2$. The process sought $\bar{\nu}_e + d \rightarrow n + p + \bar{\nu}_e$ is a special case of neutrino induced nuclear excitation

$$\nu + N \rightarrow N^* + V$$

A theory of the deuteron case proposed by Gapanov and Tyutin* predicts 10^{-46} to $10^{-44}\ \text{cm}^2$ as the cross-section. High energy experiments done at CERN are not directly comparable because they deal primarily with muon neutrinos or require assumptions to be made regarding the equality of $\bar{\nu}_e + p \rightarrow \bar{\nu}_e + p$ and $\nu_e + p \rightarrow \nu_e + p$.

The Experiment

The detector used in this experiment is shown schematically in Figure 1.

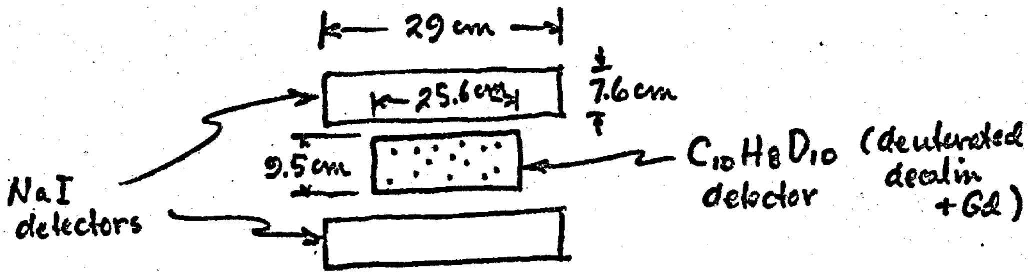

Figure 1. Scintillation Detector

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* Yu. V. Gapanov and I. V. Tyutin, Sov. Phys.--JETP20, 1231 (1965).

The experiment consisted of seeking a delayed coincidence between a prompt pulse (produced by the initial proton and neutron recoils) and the neutron capture pulse. The gadolinium concentration was chosen so that 90% of the neutron captures occurred within 30 microseconds. The energy gates selected were:

prompt pulse: > 0.20, < 0.59 Mev electron equivalent.
(liquid scintillator
only. No NaI pulse)

delayed pulse: > 0.75, < 6.25 Mev
(the two NaI pulses
in coincidence)

The detector was enclosed in a composite shield of Cd, Pb, wood and paraffin near a reactor at the Savannah River Plant of the U. S. Atomic Energy Commission with the following results. In a run of 55.5 hours, we observed an accidental rate of 6.9/hr. and a correlated rate $R = 0.49 \pm 0.38$/hr. Since the flux $f = 8 \times 10^{13}\ \overline{\nu}_e/\mathrm{cm}^2$ sec, the number of deuteron targets $N_0 = 1.9 \times 10^{26}$, and the detection efficiency $\eta = 0.0051 \pm 0.0013$ the resultant cross-section $\sigma = \frac{R}{f N_0 \eta} < 1.7 \pm 1.4 \times 10^{-42}\ \mathrm{cm}^2$. This σ derived from these numbers cross-section is an upper limit because it includes cosmic ray associated correlated events as well as the effects of reactor neutrons which penetrated the shield.

It is interesting to compare strength of the neutral coupling deduced from the above result with that associated with the charge changing coupling. Eliminating phase space factors and taking into account the difference in the two reaction thresholds we find

$$\frac{[\bar{\nu}_e + d \rightarrow n + p + \bar{\nu}_e]}{[\bar{\nu}_e + d \rightarrow n + n + e^+]} < 60.$$

A full paper describing this experiment has been submitted to the Physical Review.

II. Observation of $\bar{\nu}_e + d \rightarrow n + n + e^+$

(Jenkins and Reines)

Introduction

This reaction is interesting to observe for several reasons:

Although completely specified by weak interaction theory and the structure of the deuteron its inverse, unlike the reaction $\bar{\nu}_e + p \rightarrow n + e^+$ for example, is not accessible to direct experimental check. The coupling is pure Gamow Teller (axial vector) as opposed to mixed Gamow Teller plus Fermi (axial vector + vector) as in the proton reaction. Nevertheless, the factor of two enhancement in the cross-section due to parity non-conservation should be in evidence here. As a matter of taste, it would be nice to see a second interaction involving reactor antineutrinos.

The expected cross-section for fission $\bar{\nu}_e$ is $\sim 4 \times 10^{-45}$ cm^2. This result is based on theoretical calculations of J. Weneser (Phys. Rev. 105, 1335, 1957), and private communication 1963.

The present experiment is a first crude but positive observation of the reaction. The idea is to see the e^+ (+ neutron recoil pulses) followed by the double delayed coincidence provided by the neutron capture pulses. This is a very distinctive sequence of events.

The Experiment

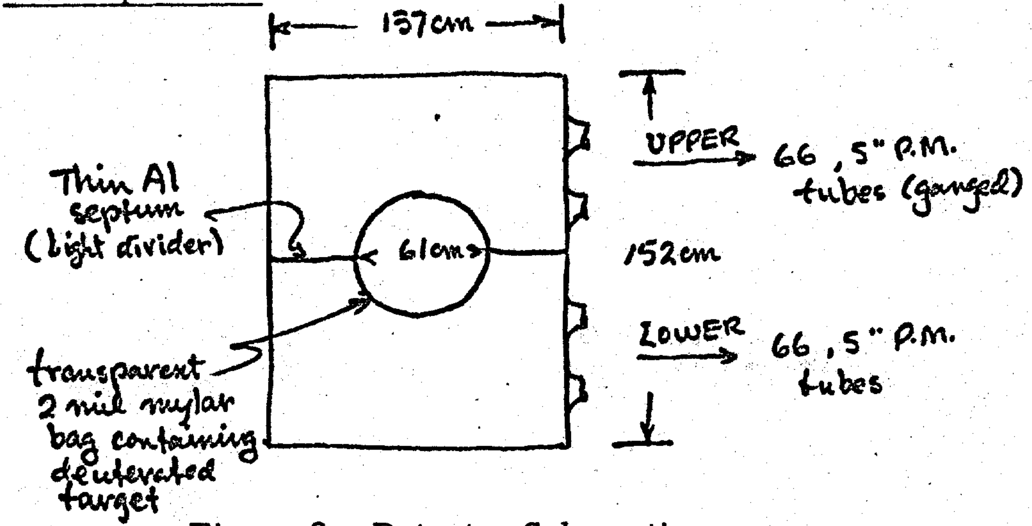

Figure 2. Detector Schematic

Scintillation tank filled with 2200 liters of mineral oil based scintillator. The target consists of 119 liters of deuterated decalin containing Gd to capture thermalized produce neutrons. Response of scintillator inside and outside of bag was balanced to within ~ 20%.

The primary purpose of the detector design (Figure 2.) is to reduce background while manufacturing an acceptable detection efficiency. Several features might be noted:

The neutron capture region is shielded by non Gd bearing region outside the mylar bag. Once the neutron is captured by the Gd in the central bag, the gamma rays are effectively absorbed by the surrounding scintillator. The accidental rate is reduced by the prompt coincidence requirement between the UPPER and LOWER neutron capture pulses. Data consisted of scope films which were taken when the first pulse occurred in the range 1.75 to 6 Mev followed by second and third pulses >1.5 Mev in both upper and lower banks with total energy in each delayed pulse from 5.5 to 10 Mev. A total delayed time gate of 60 μsec was chosen.

Several configurations were employed: bag filled with deuterated scintillator (3.8×10^{27} deuterons, 3×10^{27} protons), bag with scintillator and Gd but no deuterons (p bag), no bag, (d bag). These configurations were run in two modes, one requiring a single delayed coincidence (p mode) and the other requiring a double delayed coincidence (d mode).

The system was calibrated using a neutron source, cosmic rays which passed through the detector and a y^{88} (2.76 Mev total) gamma source.

Analysis of the data by means of a maximum likelihood fit made to the capture time distribution associated with neutrons in the deuterated scintillator yielded the time correlated signal summarized in Table I. For purposes of orientation it is useful to note that the signal rate is ~ 3 counts/day.

A perusal of Table I shows that the double delayed coincidence signal is associated with the presence of deuterons.

TABLE I. SUMMARY OF RESULTS

CONFIGURATION and MODE	RUN TIME (hours)	RATE (hr^{-1})	REMARKS
d bag d mode	1100	0.14 ± 0.03 0.35 ± 0.05	correlated deut. signal accidental (uncorrelated) rate
p bag d mode	200	0.024 ± 0.043 0.34 ± 0.131	correlated deut. signal accidental rate
d bag p mode	45	13.2 ± 3.9	correlated proton signal

Note 1.) All the above runs were made with the reactor on (flux $3 \times 10^{13}\ \overline{\nu}_e / cm^2 sec$)

Note 2.) Data from film with e^+ first pulse 2.25 to 5.5 Mev, subsequent "n captive" pulses 5.7 to 10.0 Mev.

The problem is to deduce the interaction cross-section from these data and this is still in process. The essential difficulty is in the determination of the neutron detection efficiency. Our approach is to use the efficiency from the reaction $\overline{\nu}_e + p$ (d bag, p mode) and then correct the result by taking into account the contribution to $\overline{\nu}_e + p$ from the region outside the bag, the different initial neutron energies, etc. A completely ab initio efficiency calculation is very inaccurate because the result is sensitively dependent on the details of the neutron capture gamma spectrum.

At present there is no indication of a disparity between the theoretical and experimental cross-section but the efficiency evaluation is not yet complete.

III. Status of $\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$

(Gurr and Reines)

Introduction

It is generally believed that the elastic scattering of $\bar{\nu}_e$ on e^- exists (Feynman and Gell Mann Phys. Rev. 109, 193, 1958) but this reaction is not as essential to weak interaction theory as is inverse beta decay. It is however of importance to the beauty of the theory and in astrophysics. There is also something intriguing to consider this basic and simplest weak reaction if it occurs since it does so in the absence of the strong interaction.

The elastic scattering is difficult to observe because the cross-section is minuscule ($\sim 10^{-45}$ cm^2/fission $\bar{\nu}_e$) and the reaction is nondescript. The problem is to detect an electron recoil and distinguish it from natural radioactivity (β^- and γ) as well as from gammas from the $\bar{\nu}_e$ source itself. The approach we are using has two distinctive features:

1. Surround the $\bar{\nu}_e$ target detector by an extensive anti-coincidence
2. Distinguish gamma ray produced recoils by means of a spatial anticoincidence relying on the predominance of the compton effect in a low Z medium.

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* Muon decay also occurs in the absence of the strong interaction but it is more complicated involving as it does the complete lepton family.

The Detector

Figure 3. is a schematic of the detector developed for this experiment.

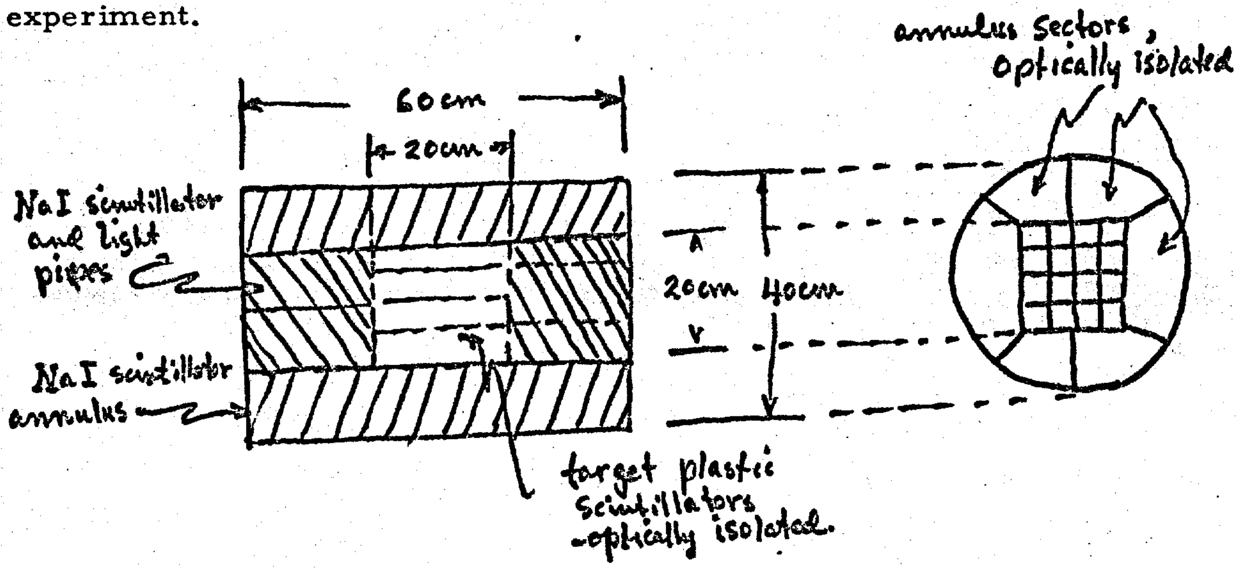

Figure 3. Detector Schematic

Notes: The NaI light pipes are coded to reveal in which plastic detector the signal occurred. Pulse shape is used to distinguish the event as in the plastic (short pulse ~ 200 ns). To be considered a pulse must occur in only one plastic scintillator. The entire assemblage is immersed in a liquid anticoincidence detector.

This detector (2.2×10^{27} target electrons) and a fission $\bar{\nu}_e$ flux of $3 \times 10^{13}/\mathrm{cm}^2$ sec the theory predicts the rate given in Table II.

TABLE II. Expected Signal Rate*

Recoil Electron > E (Mev)	Rate counts/day
0.5	16
1.0	7.2
1.5	3.3
2	1.5
2.5	0.6
3	0.3
3.5	0.1

* For perfect energy resolution. Because of the steeply falling spectrum the rate is enhanced in the actual detector.

Status

We have spent the last several months installing and tuning up the system. Various sources of background are revealing themselves. Table III gives a summary of the reduction in background so far achieved as various system contraints are imposed.

TABLE III. Background Reduction

	Configuration	Rate (min. $^{-1}$)
1.)	No oil in tank 1.6 Mev threshold and in one plastic channel only	365
2.)	Same as 1.) plus requirement pulse be fast (plastic)	26
3.)	Same as 2.) but oil in tank	13
4.)	Same as 3.) but no annulus anticoincidence pulse > 30 Kev	1.42 ± .04
5.)	Camera film analysis result (1.) through 4.) is logic camera trigger rate)	$0.51^{+.03}_{-.02}$

The preliminary signal, with runs so far characterized by incomplete constraints, for recoil electrons > 2 Mev is 0.48 ± .06/min. It is significant that the reaction is unseen within the quoted statistical uncertainty -- the bulk of the background is not reactor associated. If we denote the reactor associated signal as Δ and take it to be $\leqslant 0.1$/min, then allowing for the finite system resolution the expected signal $S \sim 3$/day and

$$\frac{\Delta}{S} \leqslant \frac{0.1 \times 60 \times 24}{3.} < 50$$

This limit can obviously be improved by running for longer times.

Comments on the Background

One of the sources of background appears to be Bi^{214} internal contamination. This isotope is a pure β^- emitter with an end point of 3.2 Mev. Its presence was deduced from the presence of delayed coincidences between the Bi^{214} electron and the α (7.2 Mev ~ 160 μsec) from the daughter Po^{214}. Suspect as the location is the aluminized mylar which is used to optically isolate the various plastic elements from each other. Unfortunately, the small α particle range implies a low delayed coincidence efficiency so that it does not in itself offer hope for significant background rejection. Various remedies which are under consideration are 1.) raise the energy threshold so as to optimize signal to background, 2.) improve the energy resolution by using more efficient photomultiplier tubes (P.M. tubes now in the detector have only ~ 10% photocathode efficiency -- available are tubes with 25% efficiency). We are hesitant to replace the mylar because we might unwittingly introduce other contamination in the process. In this connection, we note that all known β^- emitters < 2 Mev with the exception of Bi^{214} (which arises from long-lived parents) have had ample opportunity to decay in the 2 1/2 years since the detector was sealed.

An additional source of background (~ 5 Mev) is due to cosmic rays. It is anticipated that this background can be reduced somewhat by improved tuning of the 500 gallon liquid anticoincidence in which the NaI, plastic detector is immersed.

The work continues.

One by product of this investigation is expected to be an improved measurement of the cross-section for $\bar{\nu}_e + p \rightarrow n + e^+$. By means of a parallel set of electronics, we will look for the kinetic energy and annihilation radiation from the product positron. In this side experiment a coincidence will be sought between sections of the annulus and a target plastic.