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[10]The generation structure for all the fields in our model requires the existence of $\Phi(0,0,-\xi)$ if $\Phi(0,0,\xi)$ is introduced. However, these two fields are related by charge conjugation.

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Detection of Weak Neutral Current Using Fission $\bar{\nu}_e$ on Deuterons

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The weak-neutral-current reaction $\bar{\nu}_e + d \rightarrow n + p + \bar{\nu}_e$ has been observed concurrently with the charged-current process $\bar{\nu}_e + d \rightarrow n + n + e^+$ using an instrumented D_2O target exposed to an $\bar{\nu}_e$ flux of 2.5×10^{13} cm^{-2} sec^{-1}. The measured neutral-current cross section, $(3.8\pm0.9)\times10^{-45}$ cm$^2/\bar{\nu}_e$, is consistent with the Weinberg-Salam model, dependent in this case only on the axial-vector contribution. The charged-current reaction cross section is $(1.5\pm0.4)\times10^{-45}$ cm$^2/\bar{\nu}_e$, in fair agreement with expectation.

We report the detection of the weak-neutral-current (NC) reaction $\bar{\nu}_e + d \rightarrow n + p + \bar{\nu}_e$ and a concurrent measurement of the charged-current reaction (CC) $\bar{\nu}_e + d \rightarrow n + n + e^+$.

This experiment was conducted at the 2000-MW fission reactor at the Savannah River Plant in the well-shielded environment used in the $\bar{\nu}_e + e^-$ experiment.[1] The drastic background reduction made possible by this shielding allowed the detection of the NC reaction with use of only the product neutron as a signature. The feasibility of this method was demonstrated in 1974,[2] when an upper limit for the weak-neutral-current reaction was determined.

Weak neutral currents have been observed with very high-energy muon-type neutrinos at CERN[3] and at the Fermi National Accelerator Laboratory.[4] Until the present work the only $\bar{\nu}_e$ reaction involving neutral currents was $\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$.[1]

Theoretical analysis of other neutral-current reactions by Hung and Sakurai[5] determines the neutral-current couplings between neutrinos and hadrons within a twofold "vector-axial ambiguity."[5,6] More recently, a large number of results on neutral-current interactions have been analyzed and the ambiguity appears to be eliminated in favor of the Weinberg-Salam model.[7]

In this experiment, using low-energy reactor $\bar{\nu}_e$'s, the NC cross section is unique in that it depends only on the axial-vector (Gamow-Teller) contribution[8] and is therefore independent of the Weinberg angle. In this case, the ambiguity is particularly easy to resolve; the Weinberg-Salam solution predicts a cross section for this reaction which is four times larger than the alternative possibility.

The detector system is shown in Fig. 1. The target consists of 268 kg of extremely pure (99.85%) heavy water. Immersed in the D_2O are ^{3}He-filled gas proportional counters[9] which detect the neutron via the reaction $^3\mathrm{He} + n \rightarrow p + {}^3\mathrm{H} + 764$ keV. The entire detector is enclosed in a

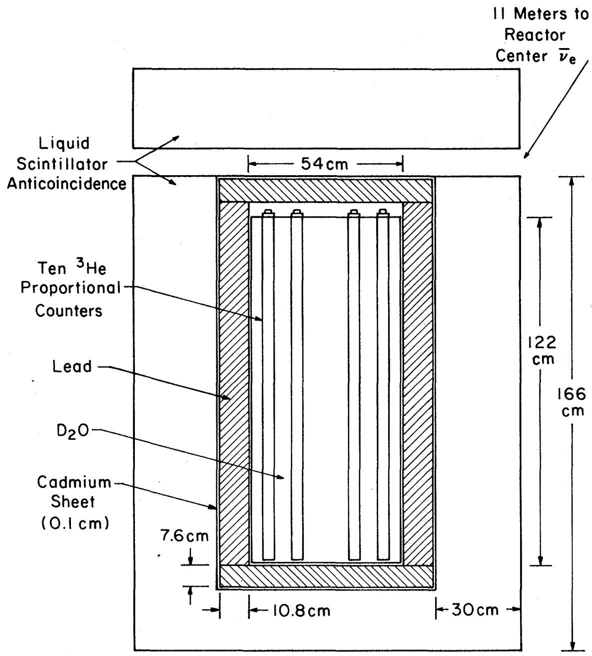

FIG. 1. Schematic diagram of the detector (side view).

Pb-Cd shield and immersed in a 2200-liter liquid scintillator anticoincidence detector. Not shown in the schematic is the massive lead, concrete, and water shielding surrounding the anticoincidence detector. The system is located in a $\bar{\nu}_e$ flux of 2.5×10^{13} cm^{-2} sec^{-1}.

Events arising from a neutron capture in the ^{3}He counters which meet the trigger requirements are recorded, as are neutron captures and pulses produced in the liquid-scintillator anticoincidence system within ±2 msec of a trigger. Data are analyzed for single-, double-, and triple-neutron events, both while the reactor is on and while it is off.

The anticoincidence system initiates a 1.8-msec block for every event above an upper threshold of approximately 2.2 MeV. This eliminates most neutrons associated with cosmic-ray muons.

A ^{252}Cf neutron source was used for system stability checks and, along with Monte Carlo programs, determined the neutron detection efficiency (η) to be 0.32 ± 0.02. The programs not only corrected the spectral differences between the source and the signal, but also independently calculated the efficiency.

In the absence of reactor backgrounds, the single-neutron reactor-associated event rate is a measure of the NC. Additional single-neutron events occur when only one of the two product neutrons in the CC reaction is detected. The reactor-associated two-neutron rate is used together with the neutron detection efficiency to determine the CC rate. Table I, set A, summarizes the results obtained with the reactor on and off. The observation of an on-off difference for both single- and double-neutron events at the level of approximately 6 and 4 standard deviations, respectively, is taken to be clear evidence for a reactor-associated signal. The difference for events with three neutrons is expected to be zero.

Reactor-associated backgrounds: (1) *Single-neutron events*.—To demonstrate that the observed NC signal is not due to reactor-associated neutrons, two tests were performed. In the first preliminary test, we drained existing water

TABLE I. Summary of data: Set A with original shielding configuration; set B with additional 4π shielding.

Number of neutrons	Reactor "ON" (events per day)	Reactor "OFF" (events per day)	"ON" − "OFF" (events per day) (reactor associated)
		Set A	
	52.3 days live	38.3 days live	
1	799±9	729±8	70±12
2	71±1	66±1	5±1.4
3	13.7±0.5	12.8±0.6	0.9±0.8
		Set B	
	14.7 days live	20.7 days live	
1	396±5	325±4	71±6
2	56±2	51±2	5±2.8
3	12.5±0.9	10.4±0.7	2.1±1.1

shielding tanks and monitored the reactor-associated rate. The change in the reactor-associated rate due to the water removal implies a 1-standard-deviation upper limit of <3 counts per day from high-energy neutrons.

Since low-energy neutrons (~ 1 MeV) can be channeled into our detector from arbitrary directions specific to the shielding geometry, we entirely surrounded the apparatus with an additional 6.5 cm of hydrogenous materials as a second differential shielding test. Table I, set B, summarizes the results obtained with this shielding. Comparing Table I, sets A and B, we see a reduction in the single-neutron background by more than a factor of 2, while the reactor-associated signal remains essentially constant.

Once again, limits can be set from these data for reactor neutrons that penetrate the shielding. The additional 6.5 cm of shielding implies a factor of 9 reduction in a 1-MeV neutron flux. The data of set A (before the shielding) should have nine times the neutron background (B). A neutrino signal (S) would remain unaffected. Accordingly,

$$S+9B=70\pm 12 \quad (\text{set } A),$$

$$S+B=71\pm 6 \quad (\text{set } B)$$

from which

$$B=-0.1\pm 1.7 \text{ day}^{-1}$$

which can be interpreted as a 1-standard-deviation upper limit of two neutrons per day.

(2) *γ rays.*—Limits on a reactor-associated γ-ray signal from the photodisintegration of the deuteron, $\gamma+d\to n+p$, are deduced from reactor-associated γ-ray measurements with a 330-kg NaI detector[1] replacing the D_2O ^3He detector. This yields a reactor-associated background contribution of less than 0.3 per day at 1 standard deviation.

(3) *Reactor neutrinos.*—(a) The D_2O target is impure, containing a proton-to-deuteron ratio of 0.15%. Inverse β decay of these protons is calculated to contribute 1.7 events per day to the neutrino background. (b) Monte Carlo computer programs and a neutron source measurement have shown that the background contribution due to neutrons from the inverse β reaction $\bar{\nu}_e+p\to n+e^+$ in the surrounding liquid scintillator is 11 ± 1 day^{-1}. In this case, the vast majority of the 2×10^4 product neutrons/day are thermalized in the liquid scintillator and stopped by the cadmium and lead shielding before entering the D_2O.

In sum, the neutrino background contributes $1.7+(11\pm 1)=12.7\pm 1$ events per day to the single-neutron rate and the nonneutrino background has an upper limit of 3 day^{-1}. We increase our error by ± 3 day^{-1} to take maximal account of the nonneutrino background possibility and decrease the rate by 12.7 ± 1 to allow for the neutrino background. Since the single-neutron background is much smaller in the best shielded configuration (set B), we use this to determine the single-neutron signal; i.e., $S_{1n}=71\pm 6-(12.7\pm 3)=58\pm 7$ day^{-1}.

The observed two-neutron signal (S_{2n}^{CC}) due to the charged-current reaction is

$$S_{2n}^{CC}=\eta^2 R^{CC},$$

where R^{CC} is the total charged-current rate in the detector and η is the neutron detection efficiency. Since the two-neutron rates for data sets A and B agree within the statistical uncertainties we combine these data to obtain

$$R^{CC}=\frac{5\pm 1.3}{(0.32\pm 0.02)^2}=49\pm 13 \text{ day}^{-1}.$$

The single-neutron contribution from the CC reaction is

$$S_{1n}^{CC}=2\eta'(1-\eta')R^{CC},$$

where $\eta'=0.89\eta$, and 0.89 is due to a more stringent single-neutron acceptance window. Thus,

$$S_{1n}^{CC}=20\pm 6 \text{ day}^{-1}.$$

The NC signal S^{NC} is given by

$$S^{NC}=S_{1n}-S_{1n}^{CC}=(58\pm 7)-(20\pm 6)$$
$$=38\pm 9 \text{ day}^{-1}.$$

The theoretical cross section[10,11] for the neutral-current process is 5.0×10^{-45} cm$^2/\bar{\nu}_e$, resulting in a predicted rate of 50 ± 3 day^{-1}. The ratio of observed rate to predicted rate is therefore

$$\frac{38\pm 9 \text{ day}^{-1}}{50\pm 3 \text{ day}^{-1}}=0.8\pm 0.2$$

and the observed neutral-current cross section is determined to be $(3.8\pm 0.9)\times 10^{-45}$ cm$^2/\bar{\nu}_e$.

The predicted charged-current cross section[11] is 2.1×10^{-45} cm$^2/\bar{\nu}_e$ resulting in an expected two-neutron rate of 7 ± 0.6 day^{-1} in our detector. The ratio of the observed to the predicted two-neutron rate is

$$\frac{5\pm 1.3 \text{ day}^{-1}}{7\pm 0.6 \text{ day}^{-1}}=0.7\pm 0.2,$$

and the observed charged-current cross section[12] is determined to be $(1.5 \pm 0.4)\times 10^{-45}$ cm$^2/\bar{\nu}_e$.

The measured neutral-current cross section is thus seen to be compatible with the Weinberg-Salam model and with the equivalent Hung and Sakurai[6] solution "A," and incompatible with the alternate "B" solution of Hung and Sakurai for which the observed-to-predicted ratio is 3.0 ± 0.8.

The uncertainty in the neutrino spectrum [10 to 30% increasing with energy (Davis *et al.*[11])], is not an important factor for these results at the present level of precision. The experiment is being continued to reduce the statistical errors which dominate the uncertainties. For the higher-precision data to come, we intend to have measured the $\bar{\nu}_e$ flux with use of the reaction $\bar{\nu}_e + p \rightarrow n + e^+$.

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