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Detection of the Free Neutrino: a Confirmation

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A tentative identification of the free neutrino was made in an experiment performed at Hanford (*1*) in 1953. In that work the reaction

$$\nu_- + p^+ \rightarrow \beta^+ + n^0 \quad (1)$$

was employed wherein the intense neutrino flux from fission-fragment decay in a large reactor was incident on a detector containing many target protons in a hydrogenous liquid scintillator. The reaction products were detected as a delayed pulse pair; the first pulse being due to the slowing down and annihilation of the positron and the second to capture of the moderated neutron in cadmium dissolved in the scintillator. To identify the observed signal as neutrino-induced, the energies of the two pulses, their time-delay spectrum, the dependence of the signal rate on reactor power, and its magnitude as compared with the predicted rate were used. The calculated effectiveness of the shielding employed, together with neutron measurements made with emulsions external to the shield, seemed to rule out reactor neutrons and gamma radiation as the cause of the signal. Although a high background was experienced due to both the reactor and to cosmic radiation, it was felt that an identification of the free neutrino had probably been made.

Design of the Experiment

To carry this work to a more definitive conclusion, a second experiment was designed (*2*), and the equipment was taken to the Savannah River Plant of the U.S. Atomic Energy Commission, where the present work was done (*3*). This work confirms the results obtained at Hanford and so verifies the neutrino hypothesis suggested by Pauli (*4*) and incorporated in a quantitative theory of beta decay by Fermi (*5*).

In this experiment, a detailed check of each term of Eq. 1 was made using a detector consisting of a multiple-layer (club-sandwich) arrangement of scintillation counters and target tanks. This arrangement permits the observation of prompt spatial coincidences characteristic of positron annihilation radiation and of the multiple gamma ray burst due to neutron capture in cadmium as well as the delayed coincidences described in the first paragraph.

The three "bread" layers of the sandwich are scintillation detectors consisting of rectangular steel tanks containing a purified triethylbenzene solution of terphenyl and POPOP (*6*) in a chamber 2 feet thick, 6 feet 3 inches long, and 4 feet 6 inches wide. The tops and bottoms of these chambers are thin to low-energy gamma radiation. The tank interiors are painted white, and the solutions in the chambers are viewed by 110 5-inch Dumont photomultiplier tubes connected in parallel in each tank. The energy resolution of the detectors for gamma rays of 0.5 Mev is about 15 percent half-width at half-height.

The two "meat" layers of the sandwich serve as targets and consist of polyethylene boxes 3 inches thick and 6 feet 3 inches by 4 feet 6 inches on edge containing a water solution of cadmium chloride. This provides two essentially independent "triad" detectors, the central scintillation detector being common to both triads. The detector was completely enclosed by a paraffin and lead shield and was located in an underground room of the reactor building which provides excellent shielding from both the reactor neutrons and gamma rays and from cosmic rays.

The signals from a bank of preamplifiers connected to the scintillation tanks were transmitted via coaxial lines to an electronic analyzing system in a trailer van parked outside the reactor building. Two independent sets of equipment were used to analyze and record the operation of the two triad detectors. Linear amplifiers fed the signals to pulse-height selection gates and coincidence circuits. When the required pulse amplitudes and coincidences (prompt and delayed) were satisfied, the sweeps of two triple-beam oscilloscopes were triggered, and the pulses from the complete event were recorded photographically. The three beams of both oscilloscopes recorded signals from their respective scintillation tanks independently. The oscilloscopes were thus operated in parallel but with different gains in order to cover the requisite pulse-amplitude range. All amplifier pulses were stored in long low-distortion delay lines awaiting electronic decision prior to this acceptance.

Manual analysis of the photographic record of an event then yielded the energy deposited in each tank of a triad by both the first and second pulses and the time-delay between the pulses. Using this system, various conditions could be placed on the pulses of the pair comprising an acceptable event. For example, acceptance of events with short time delays (over ranges up to 17 microseconds, depending on the cadmium concentration used) resulted in optimum signal-to-background ratios, while analysis of those events with longer time delays yielded relevant accidental background rates. Spectral analyses of pulses comprising events with short time delays were also made and compared with those with long delays.

This method of analysis was also employed to require various types of energy deposition in the two tanks of a triad. For instance, the second pulse of an event

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could be required to deposit at least a given energy in each tank, and in addition, maximum and minimum limits could be placed on the total energy of the pulse. Application of criteria such as these assisted in discriminating between events satisfying the physical aspects of a neutrino capture and the various backgrounds experienced. Simultaneous presentation of the three tank outputs on the three beams of the oscilloscopes also permitted rejection of pseudo events due to penetrating cosmic rays, thus utilizing the two triads as shields for one another.

The varying rates observed by changing the response of the system assisted in ascertaining that the gamma rays observed did indeed arise in the target tanks. The efficiency of the system was calibrated in each case by the use of a dissolved copper-64 positron source in the target tanks and by using a plutonium-beryllium neutron source. The neutron calibrations utilized the 4.2-Mev gamma ray emitted by the source as the first pulse of a delayed pair, the second being due to capture of the associated neutron in the cadmium. In addition, secondary calibrations were performed each week using the cosmic ray penetration pile-up peak (*7*) and standardized pulsers to check for drift in the apparatus. Standard pulses were recorded each day on the oscilloscope cameras to maintain a constant film calibration. Running counts were made of all single and prompt coincidence rates relevant during the experiment as checks for drift or changes in background. Long-term stability of the equipment was easily maintained, and the results of the two independent triad detectors agreed well throughout the experiment.

Experimental Results

Using this equipment near one of the reactors at the Savanaah River Plant, the following results were obtained bearing on the reaction expressed by Eq. 1.

1) A reactor-power-dependent signal was observed which was (within 5 percent) in agreement with a cross section for reaction 1 of 6.3×10^{-44} cm^2. The predicted cross section (*8*) for the reaction, however, is uncertain by ± 25 percent. In one set of runs, the neutrino signal rate was 0.56 ± 0.06 count per hour, and with changed requirements it was 2.88 ± 0.22 counts per hour. The total running time, including reactor-down time, was 1371 hours. The signal-to-background ratio associated with the higher signal rate quoted was about 3 to 1. The neutrino signal was greater than 20 times the accidental background associated with the reactor.

2) A signal rate produced by reaction 1 must be a linear function of the number of protons provided as targets for the neutrinos. This was tested by diluting the light water solution in a target tank with a heavy water solution to yield a resultant proton density of one-half of normal. The neutron detection efficiency measured using the plutonium-beryllium source was essentially unchanged. The reactor signal fell to one-half of its former rate.

3) Reaction 1 states that the first pulse of a delayed pair observed must be due to the annihilation radiation of a positron in the target tank. This would produce one ½-Mev gamma ray entering each detector tank of the triad simultaneously after some degradation in the water target. Events were thus chosen which satisfied these time and spatial conditions. Analysis of the pulse-amplitude spectra of these gamma rays associated with short time-delay events yielded spectra which matched that produced by the dissolved copper-64 source, having a peak at about 0.3 Mev. Spectra obtained for the first pulse of events with long delays (accidental events) were, on the other hand, monotonically decreasing with energy, as was the background spectrum producing the accidental events.

A differential absorption measurement was made using first a 3/16-inch and then a ⅜-inch-thick lead sheet between the target tank and one scintillation tank of a triad. The measured neutron detection efficiency was changed to about 70 percent of its former value in the first case and to about 45 percent in the second. The reactor signal rate fell sharply, however, as required for events with first pulse gamma rays of 0.5 Mev originating in the target tank.

4) The second pulse of the delayed pair signal observed was identified as being due to the capture of a neutron by cadmium in the water target. In addition to the prompt spatial coincidence required and the total-energy limits of 3 to 11 Mev imposed on a pulse for acceptance, analysis of the time-delay spectrum yielded excellent agreement with that expected for the cadmium concentration used in the target water (*7*). Doubling of the cadmium concentration produced the expected shift in the time-delay spectrum without increasing the signal rate. Removal of the cadmium from the target water resulted in disappearance of the reactor signal.

5) As it is possible for a fast neutron or energetic gamma ray entering the detector from the outside to produce pseudo events with many of the characteristics of true neutrino captures, the observed reactor signal was tested for these effects. A strong americium-beryllium neutron source was used outside the detector shield to produce pseudo signals. Tests of the pseudo signal with the lead sheet described in paragraph 3 resulted in a negligible drop in rate beyond that accounted for by the lowered neutron detection efficiency mentioned in paragraph 3, in contrast with the strong response of the reactor signal. The spectrum of first pulse amplitude of the neutron-produced signal with short time delays fell monotonically with increasing energy, in contrast with the characteristic spectra obtained with both the reactor signal and the dissolved copper-64 positron source.

The results of the heavy water dilution measurement described in paragraph 2 also militates against reactor-produced neutrons or gamma rays as the agent producing the signal observed.

Finally, a gross shielding experiment was performed in which the detector shield was augmented by bags of sawdust saturated with water. When stacked, the density of the added shield was 0.5 grams per cubic centimeter, its minimum thickness was 30 inches, and its average thickness was about 40 inches. This absorber would reduce the signal caused by neutrons to about one-tenth of its former rate, depending somewhat upon the direction of the incoming neutrons, and would produce a similar decrease in a signal caused by gamma rays. No decrease was observed in the reactor signal within the statistical fluctuations quoted in paragraph 1.

References and Notes

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2. C. L. Cowan, Jr. and F. Reines, invited paper, American Physical Society, New York Meeting, Jan. 1954; The results of the present work were presented in a Post deadline paper, American Physical Society, New Haven Meeting, June, 1956.

3. We wish to thank the many people at the Los Alamos Scientific Laboratory who assisted in the preparation of the experiment and to mention especially A. R. Ronzio, C. W. Johnstone, and A. Brousseau for their help in the chemical and electronic problems. M. P. Warren and R. Jones were invaluable members of the group during both the preparation and field phase of the problem. We also wish to thank the E. I. du Pont de Nemours Company and their personnel at the Savannah River Plant for their constant cooperation and assistance during our stay at the reactor. This work was performed under the auspices of the U.S. Atomic Energy Commission.

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6. Triethylbenzene scintillator, studied first in connection with the Hanford experiment in the search for higher proton densities, was purified by methods developed in collaboration with A. R. Ronzio. POPOP, a scintillation spectrum shifter, was developed by F. N. Hayes. Hayes, Rogers, and Ott, *J. Am. Chem. Soc.* **77**, 1950 (1955).
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8. This value for the predicted cross section is calculated from the decay of the neutron as observed by J. M. Robson [*Phys. Rev.* **83**, 349 (1951)] and the spectrum of beta radiation from fission fragments as measured by C. O. Muehlhause at Brookhaven National Laboratory. We are indebted to Muehlhause for communication of his results in advance of publication.