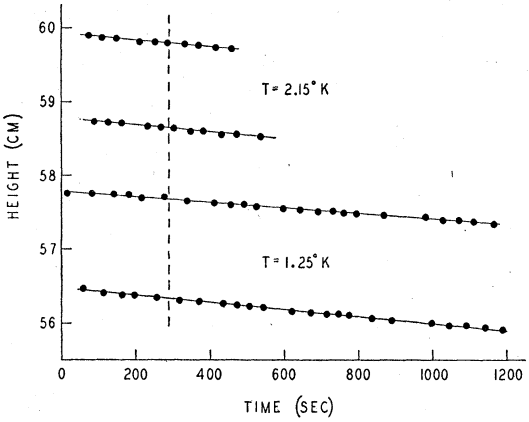

FIG. 2. Height of the meniscus (upper curve of each pair) and bath level as a function of time for 2.15°K and 1.25°K, respectively.

liquid only forms above a certain minimum periphery for the film, it would appear possible to design a superleak which would pass the film only.

* Assisted by the U. S. Office of Naval Research.
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[2] Fairbank, Lynton, and Lane, Phys. Rev. **79**, 211 (1950).
[3] E. F. Hammel and A. F. Schuch, Phys. Rev. **87**, 154 (1952).

Detection of the Free Neutrino*

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AN experiment[1] has been performed to detect the free neutrino. It appears probable that this aim has been accomplished although further confirmatory work is in progress. The cross section for the reaction employed,

$$\nu_- + p \rightarrow n + \beta^+, \tag{1}$$

has been calculated[2,3] from beta-decay theory to be given by the expression,

$$\sigma = \left(\frac{G^2}{2\pi}\right)\left(\frac{\hbar}{mc}\right)^2\left(\frac{p}{mc}\right)^2\left(\frac{1}{v/c}\right), \tag{2}$$

where σ=cross section in barns; p, m, v=momentum, mass, and velocity of emitted positron (cgs units); c=velocity of light (cm/sec); $2\pi\hbar$=Planck's constant (cgs units); and G^2=dimensionless lumped β-coupling constant (=55 from measurements of neutron and tritium β decay).[4] An estimate of the fission fragment neutrino spectrum has been made by Alvarez on the basis of the work of Way and Wigner.[5] From this information, we calculated the expected cross section to be $\sim 6\times 10^{-20}$ barn Consideration of the momentum balance shows that the positron takes off most of the available energy.

The delayed-coincidence technique employed made use of the positron to produce the first pulse and the γ's from the neutron captured in the Cd loaded scintillator solution for the second pulse.[1] The predicted first pulse spectrum due to the positron has a threshold at 1.02 Mev (assuming both annihilation gammas are collected), rises to a maximum at a few Mev, and falls towards zero with increasing energy, vanishing in the vicinity of 8 Mev. Neutron capture times in the vicinity of 5μsec were employed.

The detector was set up in the vicinity of the face of a Hanford reactor and was surrounded on all sides by a shield comprised of 4 to 6 feet of paraffin alternated with 4 to 8 inches of Pb. In order to minimize the effects of tube noise and to eliminate the counting of individual tube after-pulses, the 90 photomultipliers were divided into two banks of 45. The signal from each bank was amplified by a corresponding linear amplifier and fed to two independent pulse-height selecting gates, one of which was set to accept pulses characteristic of the positron signal and the other to accept those characteristic of the neutron-capture gammas. The output pulses from the two "positron" gates were then fed to a coincidence circuit with a resolving time of 0.3 microsecond, and those from the two "neutron" gates to a similar circuit. When a pulse appeared at the output of the "positron" coincidence circuit, an 18-channel time-delay analyzer (with 0.5-microsecond channel widths) was triggered. If a second pulse then appeared at the output of the "neutron" coincidence circuit within nine microseconds after this, a count was registered in the appropriate channel, recording in this manner the number of "delayed coincidences" obtained and the delay time for each. The amplitude of the first or "positron" pulse was simultaneously recorded for each delayed pair by delaying all signals from one of the banks in a third linear amplifier and then impressing them on a ten-channel pulse-height analyzer which was gated whenever a delayed coincidence was obtained. The expected delayed-coincidence rate, allowing for detector efficiencies and for gate settings, was 0.1–0.3 counts/minute. The apparatus was checked using a double-pulser designed for the purpose and by observing cosmic-ray μ-meson decay within the detector. The system was energy-calibrated using a Co^{60} source in the center of the detector as well as by the N^{16} activity in water piped from within the pile to around the detector.

An appreciable delayed-coincidence background ($\sim$5 counts/min) was observed which was independent of pile power. The function, delayed-pair rate per unit time *vs* delay time, which was obtained for many background delayed-pair counts, rises from zero at the origin to a maximum at about 3.5 microseconds and then tails exponentially characteristic of the Cd concentrations used, following closely the predicted function obtained in a Monte Carlo calculation for neutron capture in the detector. As the energy of the second pulse of each pair was also characteristic of the gamma radiation from neutron capture in Cd, it may be assumed that the second event of each pair was due to the presence of a neutron in the detector.

A covering GM blanket which reduced the μ-meson counting rate by 75 percent when turned on in anticoincidence reduced this delayed pair rate insignificantly. A six-foot thick water shield installed above the detector and capable of absorbing at least 30 percent of the cosmic-ray nucleonic component also failed to change the delayed-pair rate significantly. Subsequent work in an underground location in which the cosmic-ray background is greatly diminished indicates that the Hanford background is probably due to cosmic rays, for example, neutrons arising from μ^- capture in shield materials, stars which include neutrons and gamma rays energetic enough to create electron-positron pairs, showers, etc.

The change in delayed-coincidence counting rate when the pile went from full power to zero power was detected only for a first pulse gate setting of from 2 to 5 Mev. The accidental background obscured the pile signal below 2 Mev. Table I lists details of the

TABLE I. Listing of data.

Run	Pile status	Length of run (seconds)	Net delayed pair rate counts/min	Accidental background rate counts/min
1	up	4000	2.56	0.84
2	up	2000	2.46	3.54
3	up	4000	2.58	3.11
4	down	3000	2.20	0.45
5	down	2000	2.02	0.15
6	down	1000	2.19	0.13

various runs. Least-squares fits of the observed counting rates in the delayed-time channels lead to the following results:

Pile up (three runs totaling 10 000 seconds): 2.55±0.15 delayed counts/min.

Pile down (three runs totaling 6000 seconds): 2.14±0.13 delayed counts/min.

Difference due to the pile: 0.41±0.20 delayed count/min.

This difference is to be compared with the predicted $\sim\frac{1}{5}$ count/min due to neutrinos, using an effective cross section of $\sim 6\times 10^{-20}$ barn for the process. It is to be remarked that a small channel overlap in the time-delay analyzer would be reflected in an amplified percentage decrease (<0.12 count/min) in the pile difference number. Measurements of the number of fast neutrons leaking from the pile face made with nuclear emulsion plates, and consideration of thed etector shielding employed, rules out neutron-proton recoils as causing this difference.

A more detailed report is in preparation. It is difficult to acknowledge properly the many contributions to all phases of this experiment. We wish to thank our colleagues: E. C. Anderson, L. J. Brown, D. Carter, F. B. Harrison, F. N. Hayes, C. W. Johnstone, Lt. P. R. Powell (USN), R. L. Schuch, Capt. W. A. Walker (USA), M. P. Warren, T. J. White, and J. G. Winston for their devotion to the task. Dr. R. Sard of Washington University was most helpful in discussions relative to cosmic rays. The staff of the Hanford Engineering Works has been wonderfully cooperative during the Hanford phase of the work.

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[1] F. Reines and C. L. Cowan, Jr., Phys. Rev. **90**, 492 (1953); Cowan, Reines, Harrison, Anderson, and Hayes, Phys. Rev. **90**, 493 (1953). Important changes from the detector described in this reference include the use of Dumont K1177 photomultiplier tubes and a sodium silicate-titanium dioxide reflecting surface.

[2] E. Konopinski and H. Primakoff (private communications).

[3] We find it convenient to label the neutrino accompanying β^- emission as ν_-, and that accompanying β^+ emission as ν_+.

[4] E. J. Konopinski and L. M. Langer, *Annual Review of Nuclear Science* (Annual Reviews, Inc., Stanford, California, 1953), Vol. 2, p. 261.

[5] L. W. Alvarez, University of California Radiation Laboratory Report UCRL-328, 1949 (unpublished); K. Way and E. P. Wigner, Phys. Rev. **73**, 1318 (1948). Work in progress at this laboratory tends to indicate that these predictions are high.

Nuclear Scattering of High-Energy Neutrons

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THE so-called "optical model" of the nucleus has been reexamined in the light of recent measurements[1–3] of the total neutron cross sections of various nuclei for neutron energies ranging from 30 Mev to 400 Mev. Using the nuclear model and method of calculation described by Fernbach, Serber, and Taylor,[4] an attempt was mace to fit the measured cross sections by adjusting the values of R, the nuclear radii K, the inverse mean free path for absorption of neutrons in nuclear matter, and V, the average potential encountered by a neutron inside the nucleus. Both K and V were allowed to depend upon the neutron energy, but were assumed to be the same for all nuclei. Calculations were made only for neutron energies greater than 50 Mev because of the feeling that below this energy the approximations which were used in solving the scattering problem would not be valid.

The ratio $\sigma_{\text{total}}/\pi R^2$ may conveniently be expressed as a function of k_1R, with k_1/K as a parameter, where k_1 is the increase in the magnitude of the propagation vector of a neutron upon entering the nucleus. It was observed that $\sigma_{\text{total}}/\pi R^2$ is a maximum for k_1R equal to 2.0, for all values of k_1/K. Hence k_1R_{lead} was taken to be equal to 2.0 at 85 Mev, the neutron energy at which the maximum in the experimental lead cross section occurs. It was then possible, by using the measured cross sections of Pb, Cd, Cu, Al, and C at 85 Mev, to find a value of k_1 and a set of nuclear radii which would correspond to any chosen value of k_1/K. A search was then made for values of K and k_1 as a function of energy, for several assumed values of k_1/K at 85 Mev, which would give good agreement between all the experimental and

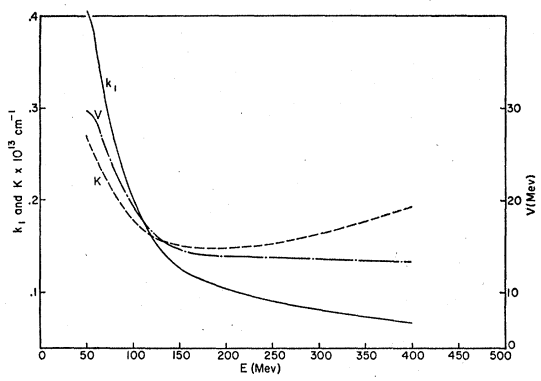

FIG. 1. Energy dependence of k_1, K, and V.

calculated cross section between 50 and 150 Mev, as well as at 400 Mev. By assuming a value of k_1/K of 1.25 at 85 Mev, it was possible to choose the energy dependence of K and k_1 in such a way that the calculated cross sections for all the nuclei considered agreed within quoted experimental errors with the observed cross sections in the neutron energy range of 65 to 400 Mev. The re-

TABLE I. Nuclear radii of C, Al, Cu, Cd, and Pb as determined from the best fit of their total neutron cross sections.

Nucleus	$R\times 10^{13}$ (cm)	$R\times 10^{13}/A^{\frac{1}{3}}$
C	3.52	1.54
Al	4.49	1.50
Cu	5.80	1.45
Cd	6.86	1.42
Pb	8.12	1.37

sulting curves of K and k_1 as a function of energy are shown in Fig. 1, together with the values of V corresponding to k_1. The nuclear radii which were obtained are given in Table I, and the calculated and observed cross sections are compared in Fig. 2.

The value of K at 85 Mev may be changed by ±50 percent without causing serious disagreement between calculated and ob-

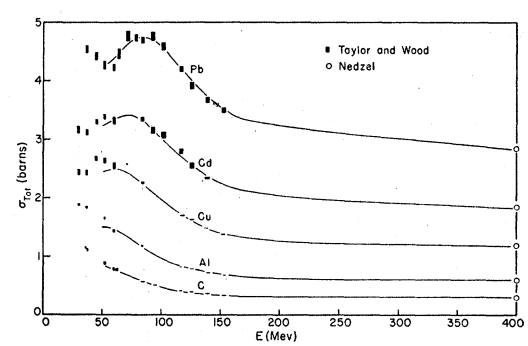

FIG. 2. Observed and calculated total neutron cross sections of Pb, Cd, Cu, Al, and C as functions of neutron energy.

served cross sections. Corresponding to this spread in K, however, there is possible a spread of only ±10 percent in k_1 and ±3 percent in the radius of any of the nuclei considered. There appears to be a definite minimum in K as a function of energy somewhere be-