An essential feature of the experiment is the large scintillation detector required. As described in the following letter, such a detector has been developed which is energy sensitive and of good efficiency for the events in which we are interested. In this way it becomes possible to discriminate against background on an energy basis as well. By means of the foregoing techniques it appears possible to reduce the background to an acceptable figure. The required electronics have been developed. Our thanks and appreciation are due our colleagues: E. C. Anderson, L. J. Brown, F. B. Harrison, F. N. Hayes, C. W. Johnstone, R. L. Schuch, and Captain W. A. Walker for their whole-hearted cooperation in all phases of the work.

* Work is being performed under the auspices of the U. S. Atomic Energy Commission.

[1] W. Pauli, in Rapports du Septième Conseil de Physique Solvay, Brussels, 1933 (Gauthier-Villars, Paris, 1934).

[2] E. Fermi, Z. Physik **88**, 161 (1934).

[3] K. Way and E. Wigner, Phys. Rev. **73**, 1318 (1948).

Large Liquid Scintillation Detectors*

C. L. Cowan, Jr., F. Reines, F. B. Harrison, E. C. Anderson, and F. N. Hayes
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico
(Received February 24, 1953)

THE technique outlined in the preceding letter for the detection of the free neutrino demands a detector having the following properties: (1) the provision of a large number of target protons in the sensitive volume; (2) a good efficiency for the counting of beta-particles, gamma-rays, and neutrons; (3) fair energy resolution; and (4) a controlled short mean detection (capture) time for the neutrons produced in the neutrino capture.

These requirements have been met in the design of a liquid scintillation counter in the shape of a cylinder containing 10.7 cubic feet of solution. A pilot model containing 2 cubic feet of solution was first constructed of brass, followed by the building of two full-scale counters of stainless steel and cold-rolled steel, respectively. The tanks were baked after fabrication to remove absorbed oils which would poison the solutions. The inside surfaces are coated with white Tygon paint.

Three filling solutions were developed:

(1) Toluene containing terphenyl, 2-(1-naphthyl)-5-phenyloxazole (αNPO), and methyl borate (or cadmium propionate in methanol).
(2) Triethylbenzene containing 2,5-diphenyloxazole, αNPO and methyl borate.
(3) Selected pure mineral oil containing 2,5-diphenyloxazole, αNPO, and methyl borate.

These solutions provide proton densities ranging from 4.6×10^{22} to 7.2×10^{22} per cubic centimeter. Control of boron or cadmium content permits selected mean neutron capture times down to about 5 microseconds. The capture times were computed by a Monte Carlo calculation using the Los Alamos MANIAC for a range of primary neutron energies and several cadmium concentrations. The results were checked experimentally with the detector in a preliminary manner by using spontaneous fission pulses in delayed coincidence with the neutrons emitted in such fissions. The optical absorption of the solutions for the scintillation light was reduced by purification and by use of αNPO as a scintillation spectrum shifter. The minimum absorption length accepted was several meters.

Scintillations in the solutions are detected by photomultiplier tubes spaced uniformly around the cylinder walls. Thirty-two tubes are employed in the pilot model and ninety in each full-scale counter. The tubes are balanced for uniform gain by means of their voltage dividers and are connected in parallel in one or more banks as needed. Linear pulse amplifiers, pulse-height analyzers, delayed coincidence analyzers and scalers comprise the associated electronic equipment.

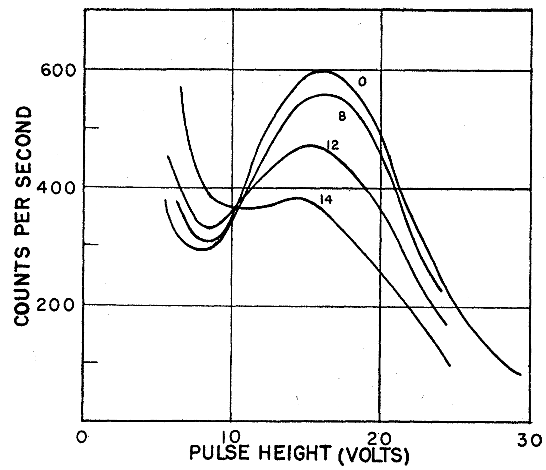

Fig. 1. Pulse-height distribution due to 0.41-Mev γ-rays from Au^{198} as a function of source position in the large detector. The source was on the axis of the cylinder, and the number on each curve indicates the distance in inches above the center. One-volt pulse-height channel widths were used.

Appropriate pipe connections, pumping systems, and reservoirs have been provided for filling the counters. Automatic float-switch systems control the liquid levels, and electronic vapor detectors guard against dangerous spills resulting from leaks and tube breakage. A nitrogen atmosphere is maintained over the solutions to retard hydrolysis and exclude air-borne radioactive contaminants.

The performance of these counters has been investigated by analyzing their output pulse rate and pulse-height spectrum with alpha-, beta-, and gamma-sources immersed at various points throughout their volumes and by using external neutron sources. Their response was found to be rather insensitive to source position (see Fig. 1), and their uniformity was considerably better in the full-scale counter than in the pilot model. It was found that the efficiency for counting 0.5-Mev gamma-radiation is about 75 percent. Figure 2 is a plot of data obtained with an external neutron source, a 6-inch thick lead shield around the detector, and with no cadmium or boron in the solution. The $p(n, \gamma)d$ peak is well resolved from the recoil proton background and that arising from capture gammas in the lead shield.

The performance of the system for delayed coincidence counting was tested by measuring the decay time of the cosmic ray μ-mesons stopping in the scintillator. Delayed coincidences falling

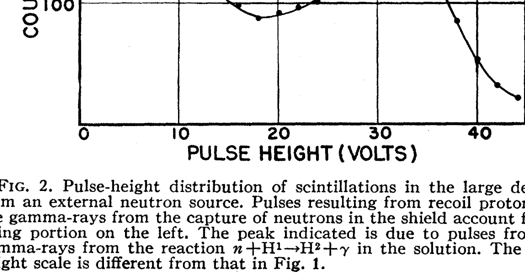

Fig. 2. Pulse-height distribution of scintillations in the large detector from an external neutron source. Pulses resulting from recoil protons and the gamma-rays from the capture of neutrons in the shield account for the rising portion on the left. The peak indicated is due to pulses from the gamma-rays from the reaction $n+H^1\rightarrow H^2+\gamma$ in the solution. The pulse-height scale is different from that in Fig. 1.

in the proper energy channels were measured with and without GM counter umbrella in anticoincidence.

The results showed an exponential time distribution with a mean life of 2.2±0.05 μsec.[1] The large area of the detector permitted collection of the cosmic-ray data in counting times of about 30 minutes for the complete determination.

In the course of this work, several applications to problems of current interest were made. Cylindrical inserts, empty and open at the top, were placed in the large counter. A survey of native radioactive contamination of a number of shielding materials placed in the insert revealed that samples of stainless steel were very clean; mild steel was slightly active; while lead, tap water, and photomultiplier tubes were considerably contaminated. A live dog was lowered into the insert and counted before and after injection of a solution containing 10^{-7} curies of radium. It was concluded that a radium content of about 5×10^{-9} curies could have been detected. By doubling up, a human being could be lowered into the counter which covered almost all of the solid angle. A number of people, men and women, were thus counted, with counting rates well above background. A water "human phantom" was made and a potassium salt dissolved in it. A counting efficiency of 10 percent for K^{40} in this geometry was found. The counting rates from the human beings agreed well in most cases with the rate expected from the potassium in their bodies. Studies of neutron shielding external to the detector were also done.

It is, of course, clear that phenomena which are distinguished by two or more events in delayed coincidence can be considered for study by means of such large detectors, and various inserts can be employed where needed, for instance, in the individual counting of the two gamma-rays from positron annihilation. Detailed discussions of investigations with the large detectors will be published in due course. The authors wish to thank L. Brown, R. Schuch, and Captain W. A. Walker for their assistance in the construction and testing of the detectors, C. W. Johnstone for the design of the electronic equipment, and T. J. White and D. Carter for help in computations.

* This work is being performed under the auspices of the U. S. Atomic Energy Commission.
[1] This value is in agreement with the results of E. P. Hincks and W. E. Bell, Phys. Rev. 84, 1243 (1951); 88, 168 (1952).

The Mechanism of the Reaction $O^{16}+h\nu\rightarrow 4He^4$†

C. A. Hsiao and V. L. Telegdi
Institute for Nuclear Studies and Department of Physics, University of Chicago, Chicago, Illinois
(Received March 16, 1953)

Although $\sigma(h\nu)$ for the reaction $O^{16}(\gamma,\alpha)3\ He^4$ has recently been reported[1] for quanta up to 70 Mev on the basis of 700 "oxygen stars" observed in nuclear emulsions, little is known about the mechanism of this reaction and, in particular, whether and which excited states of C^{12} and Be^8 are involved as intermediate steps in a cascade:

$$\text{(a)}\ O^{16}+h\nu\rightarrow C^{12*}+\alpha_1;\quad \text{(b)}\ C^{12*}\rightarrow Be^{8*}(Be^8)+\alpha_2;$$
$$\text{(c)}\ Be^{8*}(Be^8)\rightarrow\alpha_3+\alpha_4.\quad (1)$$

For $h\nu<23$ Mev, Goward and Wilkins[2] have concluded from 66 stars that ~50 percent of the events lead to the ground state of Be^8 via a 9.7-Mev state in C^{12}, while Livesey and Smith[3] reported a change of mechanism for $h\nu>23$ Mev on the basis of 83 events. The behavior around 25 Mev is of particular interest, as it is there that the selection rules imposed by charge independence[4] predict a radical change in mechanism.

We present here some preliminary results derived from 230 stars observed in 400-μ Ilford *E*1 plates irradiated with 48-Mev bremsstrahlung. The insert in Fig. 1 shows the energy distribution $N(E_T)$ of these events ($E_T=\Sigma_1^4E\alpha_i=h\nu-14.43$ Mev). There is some indication of peaks corresponding to the "level absorption"

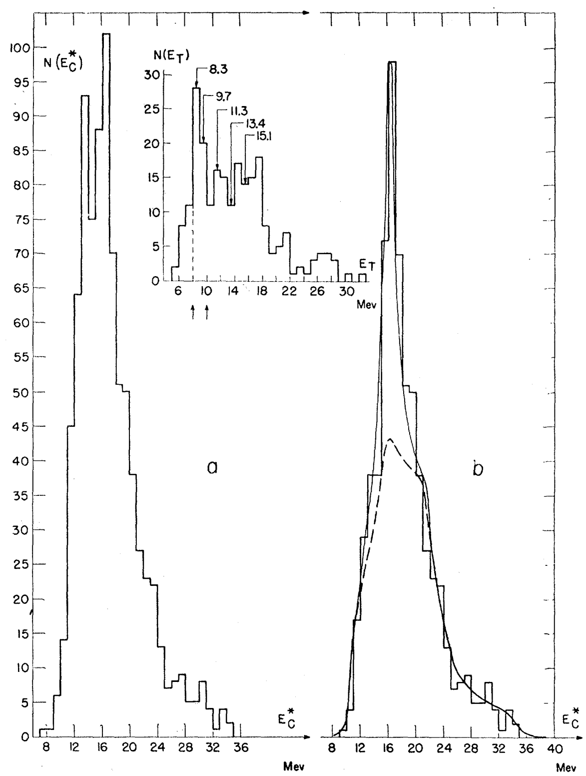

Fig. 1. (a) Experimental E^* distribution from events with $E_T>8$ Mev; (b) experimental E^* distribution (histogram) from events with $E_T>10$ Mev and calculated distribution curve for $E_C^*=16$ Mev, $E_{Be}^*=3$ Mev. Insert: $N(E_T)$ of analyzed events.

as reported by other workers[1,3] with better statistics; the location of peaks given by reference 1 is indicated by arrows.

For a cascade mechanism (1) proceeding via a C^{12} level of E_C^* excitation, one has

$$E_C^*=h\nu-|B_a|-4E_1/3=E_T+|B_b|-4E_1/3,\qquad(2)$$

where E_1 = energy of α_1, B_a = binding energy in step *a*, B_b = binding energy in step *b*. Applying (2) to *all four* E_i ($i=1,\cdots 4$) of any event a significant E_C^* and three spurious E_C^* values are obtained. The distribution $N(E_C^*)$ of these $4n$ E_C^* values from n events will exhibit a peak (or peaks) at the E_C^* of the level(s) involved, superimposed on a continuum corresponding to α_2, α_3, and α_4. Knowing $N(E_T)$, the shape of this continuum can be calculated from the dynamics of the problem upon assuming values for E_C^* and E_{Be}^*. Figure 1(a) shows $N(E_C^*)$ for 209 stars with $E_T>8$ Mev (i.e., $h\nu>22.4$ Mev). It displays a very prominent peak at $E_C^*\simeq16$ Mev and a minor one at $E_C^*\simeq13$ Mev, while nothing corresponding to a 9.7-Mev level appears. Equation (2) shows that $E_T\geqslant8.7$ Mev+Coulomb barrier is required to excite a level at 16.0 Mev; we have therefore redrawn the distribution $N(E_C^*)$, as shown by the histogram in Fig. 1(b), considering now only events with $E_T>10$ Mev. This histogram shows a single peak near 16 Mev, while the peak at 13 Mev has disappeared. An $N(E_C^*)$ histogram for the events with $8\leqslant E_T\leqslant10$ Mev, not reproduced here, confirms that a level at about 13 Mev (probably the known[5] level at 13.2 Mev) participates strongly in this energy range.

The dotted curve in Fig. 1(b) is the continuum distribution to be expected if one assumes $E_C^*=16$ Mev, $E_{Be}^*=3$ Mev, and the absence of angular correlations in either step of the cascade. Superimposing a peak corresponding to a 16-Mev level of 1.8-Mev *experimental* half-width leads to the full drawn curve in excellent agreement with experiment.