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Radiation Laboratory

**ON THE POSSIBILITIES OF DETECTING
ANTINEUTRINOS FROM NUCLEAR EXPLOSIONS**

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FROM NUCLEAR EXPLOSIONS

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August 21, 1964

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ON THE POSSIBILITY OF DETECTING ANTINEUTRINOS FROM NUCLEAR EXPLOSIONS

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ABSTRACT

The possibility of detecting antineutrinos from an underground nuclear explosion has been investigated with a thought toward measurement of the yield of the nuclear device. A secondary consideration was that of doing basic physics experiments with the large antineutrino flux available from a nuclear explosion. Three detector types were studied, all based on the following interaction of antineutrinos with matter: $\bar{\nu} + p \rightarrow \beta^+ + n$. The main assumption made for the detection was that the detector would be placed far enough from the center of the blast to withstand the shock wave, and then to count for long times (of the order of a minute) after the explosion. While background seems to pose no serious problems, the signal rate for any reasonable-sized detector is extremely low, even for moderately large explosions. Due to the inherently low counting rates expected from these detectors, and the geometry that is necessary in this type of experiment, it is concluded that none of the detectors considered would be economically feasible to either measure the yield of a nuclear device or to do basic physics experiments. Some speculations on possible different approaches to the detection of antineutrinos from nuclear explosions are made, and suggestions for further study are given.

I. INTRODUCTION

The fission products from a nuclear explosion provide a strong source of antineutrinos ($\bar{\nu}$), and it has been suggested that these particles might in

fact be used to detect the explosion.^{1,2} It was the purpose of the study reported here to examine the feasibility of detecting $\bar{\nu}$'s from a nuclear device and the possibilities of measuring the yield of the device by means of the $\bar{\nu}$. Two facts must be stated at the outset:

1. The possibility of detecting $\bar{\nu}$ is limited to underground explosions since the fission fragments must be localized.* Most of the $\bar{\nu}$ come from these fragments over a time interval of about a minute after the explosion, so a "count" of them should be taken for about this length of time.

2. The yield referred to above is the total yield in the case of a pure fission device, but only the partial yield (due to fission) in a thermonuclear device, since no $\bar{\nu}$ are generally made in a thermonuclear reaction.

It should be possible to obtain the yield almost immediately after the explosion since the number of $\bar{\nu}$ emitted is directly related to the number of atoms fissioned. This can be seen through the following simple equation:

$$Y = \frac{C}{\epsilon f N} \quad (1)$$

where Y is the fission yield, C is the number of events recorded, ϵ is the detection efficiency, f is the average number of $\bar{\nu}$ /fission, and N is the original number of fissionable nuclei in the device. The accuracy to which Y can be found depends on the accuracy of the detection efficiency, ϵ , and on the statistical accuracy of the number C. The number f has been determined experimentally,³ and is known to an accuracy of 10%. Estimates of the other individual accuracies will be considered in Sec. III.

The basic reaction considered for the detection of $\bar{\nu}$ is the one previously used by Reines and Cowan^{4,5} in their measurements of the free anti-neutrino cross section,

representing the absorption of an antineutrino by a free proton and the subse-

¹R. O. Hundley, RAND Corporation Report RM-2641, Dec. 19, 1960, and W. J. Karzas and R. Latter, RAND Corporation Report RM-2847, Oct. 1961.

²F. Reines, Annual Review of Nuclear Science 10, 15 (1960).

*No considerations of underwater explosions were made in this study.

³R. E. Carter, F. Reines, J. J. Wagner, and M. E. Wyman, Phys. Rev. 113, 280 (1959).

⁴F. Reines and C. L. Cowan, Phys. Rev. 113, 273 (1959).

⁵F. Reines, C. L. Cowan, F. B. Harrison, A. D. McGuire, and H. W. Kruse, Phys. Rev. 117, 159 (1960).

quent emission of a positron and a neutron. (This reaction has a Q-value of 1.8 MeV, and a cross section of 10^{-43} cm².) Other reactions have also been considered, (see Appendix A), but because of their low cross sections and the more difficult detection problems involved, they were felt to be unusable in this application.

There are some other considerations that should be made concerning the high $\bar{\nu}$ flux available from a nuclear explosion. One is the thought of detecting faraway nuclear explosions via the $\bar{\nu}$. This suggestion has been considered adequately at the RAND Corporation,¹ and will not be discussed here except to note the impossibility of such a scheme (see Sec. II for applicable equations). From a pure physics standpoint there are some interesting experiments that should be attempted if a $\bar{\nu}$ detector and a high flux of $\bar{\nu}$ were available:

1. It should be possible to remeasure the free $\bar{\nu}$ cross section, hopefully to higher precision than it is now known (25%).
2. The time dependence of the emission of $\bar{\nu}$ (and thus β^-) from fission might be measured. This dependence is important in the theory of beta decay.⁶
3. The cross sections for other reactions with fission $\bar{\nu}$ might be measurable. They have previously only been estimated (see Appendix A).

In Sec. II a calculation of the expected signal in various situations is made, and in Sec. III different types of detectors are considered. This study was primarily concerned with a particular type of detecting system — that of a reusable, easily moved detector that could be located on the surface of the ground above a contained nuclear explosion. Section IV is concerned with the overall feasibility of this project including a summary and some cost estimates. The appendices contain tabulated information regarding measurements made on background and detector efficiencies, information from studies on various target materials, and a discussion of the reactions considered. The final appendix contains some thoughts and speculations on possible future experiments related to this problem.

II. CALCULATION OF EXPECTED SIGNAL

The following constants and assumptions were used in the calculations.

1. σ_0 (for $\bar{\nu} + p \rightarrow n + \beta^+$) = 1.0×10^{-43} cm².
2. There are 1.5×10^{23} fissions/kiloton in a nuclear fission explosion.

⁶K. Way and E. P. Wigner, Phys. Rev. 73, 1318 (1948).

3. There are, on the average, $6.3 \bar{\nu}$ /fission.
4. The target material will be composed essentially of CH_2 , and will have a density of 1.0 g/cc.*
5. The depth of burial of a device underground is given by

$$D(\text{feet}) = 310Y^{1/3}$$

where Y is the total yield in kilotons.

6. The distance on the surface of the ground from the detector to a point directly above the device is $\frac{1}{2} D$. (See Fig. 2, p. 6.)

First the total number of $\bar{\nu}$ emitted in a nuclear explosion will be calculated. There are

$$(6.3 \bar{\nu}/\text{fission}) \times (1.5 \times 10^{23} \text{ fissions/kiloton}) = 9.5 \times 10^{23} \bar{\nu}/\text{kiloton},$$

and the total number emitted in a blast with a fission yield of Y kilotons is then

$$n(Y) = 9.5 \times 10^{23} Y. \quad (3)$$

Actually $\bar{\nu}$ emission from the fission fragments is time dependent, coincident with the beta decay of the fission fragments, and extends for long times after the explosion. In the first minute, however, more than 98% of the antineutrinos will be emitted.⁶ In the remainder of this report it will be assumed that all counts will be taken for 1 minute, and that 98% of the $\bar{\nu}$ have been emitted.

Now the number per unit area, at a distance R (in meters) from the center of the explosion is

$$n(Y, R) = 9.3 \times 10^{23} \times 10^{-4} Y / 4\pi R^2 = 7.4 \times 10^{18} Y / R^2 (\bar{\nu}/\text{cm}^2). \quad (4)$$

The number of $\bar{\nu}$ detected will depend on the "detection probability," P , which is given by

$$P = \sigma_0 \times (\text{number of target protons}) \times (\text{efficiency of detection}).$$

* See Appendix B for a discussion of various possible targets.

The second factor, in terms of the number of protons per 1000-liter volume of CH_2 , is

$$\begin{aligned} N(\text{per 1000 liters}) &= (2/14) \times 6.02 \times 10^{23} \times 10^6 \\ &= 8.6 \times 10^{28} \text{ protons/1000 liters.} \end{aligned}$$

Thus

$$P(\text{per unit volume}) = \sigma_0 \times 8.6 \times 10^{28} \times \epsilon$$

or

$$P(S, \epsilon) = 10^{-43} \times 8.6 \times 10^{28} \times S\epsilon \quad (5)$$

where S is the volume of target in 1000-liter units, and ϵ is the detection efficiency.

To obtain the total counts expected, Eqs. (4) and (5) are combined to give

$$n(Y, R, S, \epsilon) = 6.4 \times 10^4 YS\epsilon/R^2 \text{ events} \quad (6)$$

where

Y is the fission yield in kilotons,

S is in 1000-liter units of CH_2 ,

R is in meters,

ϵ is the efficiency, $0 \leq \epsilon \leq 1$.

This function is shown in Fig. 1, assuming a detection efficiency of 1 (highly unrealistic), with the yield and target volume as parameters. For example, at 250 meters from a 3-kt explosion, using a 100% efficient 5000-liter detector, the number of events would be 15 in a 1-minute count.

It can be seen quite easily from Eq. (6) that far distant nuclear explosions could not be detected by this method. If a typical distance, R , is 10^6 meters, then the product of Y and S would have to be at least 10^7 to give one event in the detector. For example, this would be equivalent to 10 megatons and a detector of 1 million liters!

If the depth of burial and its dependence on the yield are now brought into discussion, the situation changes somewhat. Referring to Fig. 2, the distances are related to the yield by

$$R = \sqrt{x^2 + D^2} = 1.12D, \text{ for } x = \frac{1}{2} D$$

Fig. 1. The number of antineutrinos detected in a 1-minute count, for a 100% efficient detector, as a function of distance from the nuclear device. Device yield and detector volume are labeled on each curve.

Fig. 2. Diagram showing relative position of nuclear device and antineutrino detector.

and thus

$$R = 1.12 \times 95 Y^{1/3} = 106 Y^{1/3} \text{ meters.}$$

Then

$$n(Y, S, \epsilon) = 5.7 S \epsilon Y^{1/3}. \quad (7)$$

For an efficiency of 1, and 10,000 liters of detection volume, Table I gives some representative values of the number of events expected.

Table I. Yield and number of expected events when device is buried at proper depth. (One-minute count, detector efficiency = 1.)

Y (kt)	n (events)
1	57
3	82
5	98
10	123
50	184
100	265

If, on the other hand, the explosion takes place in a tunnel in the side of a mountain (also containing the $\bar{\nu}$ detector), the situation is somewhat different. The detector would then have good shielding from cosmic rays.* The actual distance that such a detector could be placed from a device and remain intact for the required 1-minute counting time depends on the type of detector (type of materials from which it is constructed, the size, the amount of hardening, etc.), the yield of the device, and the type of rock in which the device is exploded.

Not enough information is available to make good estimates of how close the detector could be placed to the device, but crude estimates based on the detector being able to withstand 10 g's acceleration give, as a lower limit, 100 m for a 1-kt blast and 200 m for a 5-kt blast. These figures are similar to the figures for a buried explosion with the detector on the surface.

* See Appendix C for some applicable measurements of this effect.

Of great importance is the signal-to-noise ratio, the "noise" being any event in the detector that cannot be distinguished from the signal from a $\bar{\nu}$. As can be seen from the number of events expected, the method will only be feasible if it is possible to achieve very low background rates. The background will depend very strongly on the type of detector that is chosen and on the type and amount of shielding that is used. A discussion of these points follows in Sec. III.

III. SPECIFIC DETECTOR TYPES

The choice of a specific detector design affects the counting rate given by Eq. (6), Sec. II, only in determining the magnitude of the efficiency. Thus any real detector will necessarily lower the counting rate data given in Fig. 1 or in Table I by a factor equal to the detector efficiency. The choice of detector should be consistent with the highest possible efficiency and the lowest possible background counting rate. In view of the counting rates expected on the basis of Eq. (6), the standard CH_2 target volume will be taken to be 10^4 liters in the remainder of this section.

From the basic reaction accepted as the most favorable for observation,

there are three detection possibilities: detect both the neutron and the β^+ , detect only the β^+ , and detect only the neutron. Considerations of each of these possibilities are given in the following paragraphs.

A. Detection of both Positron and Neutron

The detector considered here would be similar to the one used by Cowan and Reines in the detection of the free antineutrino,⁵ that is, a large volume of scintillating material containing target protons, (for the reaction), and gadolinium which functions as a neutron absorber. In this detector the standard antineutrino reaction occurs, producing a positron and a neutron. The positron comes to rest and annihilates, releasing characteristic gamma-rays; the neutron is slowed down by the hydrogen in the target and captured by the gadolinium, releasing "capture gamma rays." The gamma radiation from both of these sources is absorbed in the large volume of scintillator, and secondary light from the scintillator is finally detected by photomultiplier tubes.

There is a time delay between the positron annihilation and the neutron absorption, due to the slowing down process, so two voltage signals from the photomultiplier tubes appear separated by a time between about .1 and 10 microseconds. These pulses are also required to fall within predefined characteristic energy intervals. Most of the positron annihilation gamma rays have an energy of 511 keV,⁷ while the neutron-capture gamma rays have energies between about 100 keV and 8 MeV. The choice of energy intervals used in a real detector would depend, of course, on the details of the detector design.

Background is an essential consideration with this type of detector, since the characteristic gamma rays associated with an event must be discernible from the many gamma rays expected from other sources. To help estimate the expected background, measurements were made under various conditions. The results of these measurements, together with a description of the techniques and apparatus used in making them, are given in Appendix C. From these results it is clear that some scheme is necessary to reduce the intensity of the background.

First, consider a scheme in which both the n and β^+ particles are detected in a single tank detector. In such a detector the target protons and the neutron-absorbing gadolinium are situated in a large single tank (say 1000 liters), and photomultiplier tubes look at this volume. From Appendix C it is seen that this size of tank (unshielded) would produce a background counting rate of about 10^5 counts/min. It was seen in Sec. II that under extreme conditions (so close to a blast that the detector would not likely remain intact for the 1-minute counting period) it might be possible in 1 minute to have 10 to 100 real characteristic events occur in the detector. The impossibility of determining the presence of 10 to 100 characteristic signals, each consisting of two pulses separated by less than 10 μ sec, out of a total 10^5 "background" counts is clear. Thus a single large tank is immediately ruled out. The use of shielding to reduce the expected background does not help the situation much; the use of 6 in. of Pb would only reduce the background by a factor of 20, so one would still be faced with an impossible situation.

⁷S. Berko and F. L. Hereford, Rev. Mod. Phys. 28, 299 (1956).

A modification of the type of detector used by Cowan and Reines to detect the free antineutrino is now considered. The basic detector is a sandwich of three large trays of liquid scintillator. The two outer trays of the sandwich are 24 cm thick, the middle tray (the target) is 8 cm thick and contains gadolinium dissolved in the CH_2 . The outer two trays would be 4.3 meters on a side, the target tray 3.5 meters on a side, and thus the volume of the target would be 1000 liters and the outer trays each 4400 liters.

In normal operation an event would occur in the center tray. The positron from this interaction would come to rest and annihilate; the two resulting (antiparallel) gamma rays would escape the center tray and interact in each of the two outer trays. After a few microseconds the neutron would come to rest in the target and would be captured there by the dissolved gadolinium, resulting in the prompt emission of capture gamma rays with total energy of about 8 MeV. As the number of gamma rays emitted is fairly large (about 15), and as they are emitted isotropically, they will be detected simultaneously in all three scintillators.

Figures 3 and 4 show block diagrams of typical electronics for this setup using two separate logic circuits. The operation is as follows: In Fig. 3 pulses from trays A and C, from a positron annihilation, are amplified and fed to a fast coincidence circuit. It is demanded that these pulses be in the energy interval corresponding to annihilation radiation. The output of this circuit opens a gate for 10 μsec .

The system then detects a neutron in tray B by demanding a triple fast coincidence between pulses from trays A, B, and C, and by demanding that the sum pulse derived from these three detectors fall in the pulse height range appropriate to a neutron capture event. If the outputs of this coincidence circuit and this summing circuit fall within the previous 10- μsec gate a pulse is then generated to trigger a triple-beam oscilloscope which views the three trays. The scope traces can then be used to separate $\bar{\nu}$ events from background events. A real $\bar{\nu}$ event will show as large double pulses on the A and C traces, with a small pulse followed by a delayed large pulse on the B trace (see Fig. 5a). If two cosmic rays pass through the detector, the pairs of pulses will be of the same size. (See Fig. 5c.)

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Fig. 3. Typical electronics needed to detect both the positron and neutron using a modified Reines-Cowan detector with strict logic, capable of differentiating cosmic rays from antineutrinos.

GLL-6410-3080

Fig. 4. Typical electronics needed to detect both the positron and neutron using a modified Reines-Cowan detector with relaxed logic, incapable of differentiating cosmic rays from antineutrinos.

Fig. 5. Typical oscilloscope traces for an antineutrino event (a, b) and for a background event (c) such as cosmic rays, using the circuit of Fig. 3.

Besides the scope display, the direct output from the three tanks could be recorded on magnetic tape whenever the selection criteria are satisfied. This alternative is shown dashed in Fig. 3. The signals could then easily be analyzed by a digital computer.

In Fig. 4 is shown a block diagram of electronics demanding a less restrictive event signature. To isolate the positron, coincident pulses are required from tray B (from the kinetic energy of the positron) and from either or both A and C (from positron annihilation). To isolate the neutron, coincident pulses are required only from trays A and C in the proper energy interval. Since tray B is small compared to A or C, the neutron counting rate should not be much different than with the previous logic, but the electronic requirements will be less. Figure 5b shows three acceptable pulse sequences on the oscilloscopes. The recording and display of the pulses are the same as in the first case (Fig. 3). Note that with this logic (Fig. 4) a cosmic ray burst could be mistakenly identified as an antineutrino event.

The background counting rates for this type of detector with the logic shown in Fig. 3 will now be estimated. On the basis of background data taken at the Nevada Test Site (see Appendix C) the singles rates for the two energy intervals of interest are $N_1 = 470$ and $N_2 = 500$ counts per min per 0.2 liter. The corresponding energy intervals are 0.2 to 0.6 MeV and 1.5 to 8.0 MeV. Type N_1 gamma rays should be seen in trays A and C from a positron being created in tray B, while type N_2 gamma rays should be seen in all three trays from the absorption of a neutron in tray B.

The background rates per tray are obtained by using the relationship that the rate goes as the volume to the $2/3$ power. The results are:

$$N(A, \beta^+) = N(C, \beta^+) = 3.9 \times 10^5 \text{ cpm} = 6.5 \times 10^3 \text{ cps},$$

$$N(A, n) = N(C, n) = 3.6 \times 10^5 \text{ cpm} = 6 \times 10^3 \text{ cps},$$

$$N(B, n) = 1.4 \times 10^5 \text{ cpm} = 2.3 \times 10^3 \text{ cps},$$

$$N(B, \beta^+) = 1.4 \times 10^5 \text{ cpm} = 2.3 \times 10^3 \text{ cps}.$$

To estimate the β^+ -like coincidence rate the assumption was made that the outputs of trays A and C are fed to a coincidence circuit with a resolving time of 10^{-7} sec. The coincidence circuit will then have an output counting rate of $R(A, C, \beta^+) = 2N(A, \beta^+)N(C, \beta^+)\tau = 8.4/\text{sec}$. This is the false positron rate.

To estimate the neutronlike counting rate, a coincidence signal for the presence of a neutronlike signal from both trays A and C was combined with a coincident output of neutronlike pulses from tray B. The resulting rate is $R(A, B, C, n) = 4N(A, n)N(B, n)N(C, n)\tau^2 \approx 3.3 \times 10^{-3}$ if the coincidence resolving time is 10^{-7} sec. This combined rate, $R(A, B, C, n)$, is the rate at which the combined assembly gives a neutron-like signal.

The above paragraphs provide the means to estimate the rate at which background neutrino-like events are generated in this apparatus. A signal from the β^+ event is used to open a gate for 10 μsec . The occurrence of a neutronlike event within this gate is defined as a "neutrino event." The rate of false trigger pulses, and also the rate of false $\bar{\nu}$ events, is $R(\bar{\nu}) = N(\beta^+)N(n) \times 10^{-5} \approx 2.8 \times 10^{-7}$ per sec $\approx 1.7 \times 10^{-5}/\text{min}$.

For the second type of logic the same background numbers can be used to find the false antineutrino events. The rate of false positron signals is $2N(A, \beta^+)N(B, \beta^+) = 3/\text{sec}$ with $\tau = 10^{-7}$ sec. The overall false $\bar{\nu}$ events are

then $N(\beta^+)N(n) \times 10^{-5} \approx 4 \times 10^{-5}/\text{sec}$ or $2.2 \times 10^{-3}/\text{min}$. The above calculation assumes completely random background rates. Correlated background is most likely to be an important consideration in light of the very low rates found above. The correlated rate is impossible to calculate accurately, and very difficult to even estimate. The best method would be to measure the actual background rate. The false $\bar{\nu}$ events, for further discussion, will be taken as the number calculated here for uncorrelated background radiation, but it should be remembered that this is only a lower limit to the actual number of false events.

To estimate the expected real signal rate it is first necessary to consider the detector efficiency. For the logic characterized by Fig. 3, consider the effects of gamma ray absorption within tray B. If the $\bar{\nu}$ event occurs within tray B there is a certain probability that the 511-keV gamma rays will not escape this tray. The thickness of this tray has in fact been chosen to make this escape probability equal to 0.5. Thus the self-absorption in the target contributes a factor of 0.5 to the overall efficiency.

The gamma rays that escape from tray B must interact in tray A and tray C in order to be detected. The thickness of these trays has been selected to make this interaction probability 0.88 for each tray. To detect a positron event there must be interactions in both trays, which means a factor of $(0.88)^2 = 0.76$ must be applied to the overall efficiency. For this interaction it is also necessary to consider the possibility that the annihilation gamma rays were headed in a direction that would result in their escape from the detector. This effect is estimated by finding the average solid angle that tray A or tray C subtends at the various interior points of tray B. This term is estimated to contribute a factor of 0.93 to the overall efficiency. It is also necessary to estimate the neutron detection efficiency. This will be assumed to contribute 0.25 to the efficiency.*

Combining the above numbers gives a composite number for the effect.

$$\epsilon(\text{combined}) = (0.30) \times (0.90) \times (0.25) \times (0.76) \times (0.40) = 0.02$$

neutron	solid	fraction	gamma	gamma
detection	angle	in elec-	ray inter-	ray escape
factor	factor	tronic	action prob-	probability
		window	ability	

* A similar efficiency has been measured by Reines et al.^{5,8} for a similar detector geometry.

⁸F. Reines, Ann. Rev. Nucl. Sci. 10, 1 (1960), and Science 141, 778 (Aug. 30, 1963). Also private communication.

The estimated accuracy in this efficiency is about 20%, and the 2% is probably an upper limit to what the actual efficiency would be for such a detector and logic. For the second type of logic, characterized by Fig. 4, the efficiency will be larger. There should be efficiencies of about 95% for the detection of the positron in tray B, about 30% for the detection of one 0.511-keV gamma ray, and about 30% for the detection of the neutron. This leads to an overall efficiency of about 8.5%. Again this number is probably good to 20% (i. e., the efficiency is not greater than 10%).

It might be interesting to calculate what would be expected on very reduced requirements of the event signature. Consider the case where only the kinetic energy of the positron is detected (in the center tray) and the neutron in trays A and C. The number of false β^+ pulses would then be about 2.3×10^3 /sec, and the number of false neutron pulses about 1.2/sec. The number of false $\bar{\nu}$ would then be about 0.03/sec or less than 2/min. The efficiency of such a system would be about 28%.

In Table II the above numbers are tabulated and expected real counting rates are given for different sized nuclear explosives. L1 stands for logic 1 (depicted in Fig. 3), L2 for logic 2 (depicted in Fig. 4), and L3 for logic 3 (described immediately above).

Table II. Expected signal and noise for a 1000-liter sandwich detector (1-minute count).

Yield, kt	n(inter- actions in detec- tor) ^a	L1		L2		L3	
		Real	False	Real	False	Real	False
1	5.7	0.11	2×10^{-5}	0.48	2×10^{-3}	1.6	2
3	8.2	0.16	2×10^{-5}	0.70	2×10^{-3}	2.3	2
5	9.8	0.20	2×10^{-5}	0.83	2×10^{-3}	2.7	2
10	12.3	0.25	2×10^{-5}	1.0	2×10^{-3}	3.4	2
50	18.4	0.37	2×10^{-5}	1.6	2×10^{-3}	5.1	2
100	26.5	0.53	2×10^{-5}	2.3	2×10^{-3}	7.4	2

^aFrom Table I.

Note that even with 10 of these 1000-liter units in the high logic case the number of real events is too low to be useful. Either case L2 or L3 might be usable to detect the $\bar{\nu}$ from a nuclear explosion since background does not

appear to be a problem. The statistical uncertainty involved in the number of real events recorded precludes using one of these detectors as a yield-measuring device.

Instead of building many of these separate units each with 1000 liters of target volume, it would be possible to construct the overall detector by cascading the modular units, as shown in Fig. 6.

Fig. 6. A modular unit made from "stacking" a number of individual units to make, for example, 10,000 liters of target material. The A and C units each would contain about 3000 liters and the B units each 1000 liters of CH_2 .

This unit would be a linear array of scintillator trays where the large gamma ray detection trays of 4400-liter volume are shared by neighboring units. The main effect of using this cascade technique would be a reduction in the cost estimate by about 20-30% arising from requiring less scintillator, less solute, fewer phototubes, and less shielding. The change in the electronic circuitry would be minimum, and should offer no serious problems.

B. Detection of Positron Alone

Another method of detecting the presence of an antineutrino, using the basic reaction $\bar{\nu} + p \rightarrow \beta^+ + n$, is to use more completely the unique event signature left by the annihilation of the positron, and to ignore the neutron. The hope would be to achieve a higher efficiency than was possible with the large tank detector (2.2%), by breaking up the large volume into smaller units. The increased efficiency would come from using NaI to detect the 511-keV gamma rays instead of a liquid scintillator.

Consider a detector, diagrammed in Fig. 7, made of an 8-cm-long cylinder of CH_2 viewed by two NaI crystals mounted on photomultiplier tubes. When a $\bar{\nu}$ enters the central target volume and interacts with a proton, producing a positron and a neutron, the neutron most probably will escape the detection volume, but the positron will in most cases annihilate in the CH_2 . There is a certain probability, depending on where the positron annihilates, that one of the resulting 511-keV gamma rays will be absorbed in each NaI crystal, and thus a coincident count will be recorded. The average efficiency

of this type of detector is determined in part from this probability. To isolate the event requires not only the fast time coincidence of these gamma rays, but also that each have 511 keV energy.

Fig. 7. Block diagram of typical electronics needed for the detection of the positron alone.

The electronic circuit used for this application is also shown in Fig. 7. The number of slow (triple) coincidence counts recorded will then be the true number of β^+ events in the target volume multiplied by the average efficiency of the detector.

The "background" in such a detector will be simply the number of accidental coincidences — that is, those which do not arise from the annihilation of a β^+ . This accidental rate can be estimated by using the equation

$$C_{acc.} = 4N_1N_2N_f\tau_s^2 \quad (8)$$

where N_1 and N_2 are the number of counts per second in the energy gates from crystal 1 and crystal 2, respectively, N_f is the number of fast accidental coincidences, and τ_s is the resolving time of the slow coincidence circuit.

In order to calculate the accidental rate it is necessary to have some idea of the individual singles counting rates, so background rates were taken under various conditions, and the results are shown in Appendix C. A typical background rate for an unshielded 5-in. -diameter, 4-in. -thick NaI crystal, in the region of 511 keV with a width of about 10%, is seen to be about 20 cps. For a 3-in. crystal this rate should be about 15 cps, which is assumed for N_1 and N_2 . N_f can be estimated by knowing the total number of counts per second in each channel and assuming a fast resolving time of 5×10^{-8} sec. On the basis of measurements the total singles rates were about 5000 cps for a 5-in. -diameter, 3-in. -thick crystal, which gives about 2.5 cps for N_f .

The overall accidental rate can now be calculated with the above numbers, assuming a slow resolving time of 1 μ sec. The number of accidental coincidences is then (by Eq. (8)):

$$C_{acc.} = 4 \times 15 \times 15 \times 2.5 \times (10^{-6})^2 = 2.3 \times 10^{-9}/\text{sec} = 1.4 \times 10^{-7}/\text{min.}$$

Again, this number is only a lower limit to the actual accidental coincidences, due to ignoring the correlated background. If the diameter of the target cylinder is taken to be 5 in. then the volume of target is about 1 liter, so that 10,000 of these detectors are needed to make the required 10,000 liters of target. If all the detector outputs are then added, the total accidental rate would be

$$C_T = 1.4 \times 10^{-7} \times 10^4 = 1.4 \times 10^{-3}/\text{min.}$$

This number should be compared to the number of expected real events. (see Table I, Section II). The background although not known well, should probably not be a problem in this type detector. It would also be possible to shield the crystals and reduce the background even further. For example, 2 in. of Fe shielding would reduce the background by a factor of about 10.

In order to check these background figures, and to measure the detection efficiency, a single unit was built using two 5-in. -diameter, 4-in. -thick NaI crystals and a transistorized fast-slow coincidence circuit especially built for

this application.⁹ Efficiency measurements were made by placing a calibrated Na²² positron source¹⁰ at various positions between the two coaxial NaI crystals. Disks of polyethylene (CH₂), each 7 mm thick, filled the 8-cm-thick cylindrical volume between the crystals. Thus the efficiency measurements included the attenuating effect of the target material on the 511-keV gamma rays. The pulse height windows in each single channel were set to bracket the 511-keV peak so that each edge cut the peak at a point a factor of 2 down from the maximum height.* (This includes 76% of the counts in the 511-keV photopeak.) The overall resolving time of the coincidence circuit, determined experimentally, was $\tau \approx 50$ nsec.

For the source (at the time of measurement this source gave 55,200 β^+ /min) in the geometrical center of the target, Table III shows the typical rates obtained on the various scalers shown in Fig. 7 in a 1-minute count.

Table III. Counting rates for a 1-minute count.

Scaler	Counts per minute
Singles (1)	5562
Singles (2)	5015
Fast coinc.	2536
Slow coinc.	642

This maximum efficiency (all other source positions yield smaller solid angles and larger average attenuation paths) is 642/55,200, or 1.2% of the β^+ present were detected. If "90% windows" are used (each edge cuts the peak at 1/10 maximum height and the windown includes 97% of the area of the peak), the real rate will go up a factor of 1.6 while the accidental rate will go up a factor of 3.5.

The average efficiency, $\bar{\epsilon}$, was calculated (see Appendix D) on the basis of measurements made with the positron source, and turned out to be $(0.30 \pm 0.1)\%$ for the 5-in. -diam $\times$ 4-in. -thick NaI crystal and 50% windows,

⁹R. C. Kaifer, Electronics Engineering Division, Lawrence Radiation Laboratory, Livermore.

¹⁰J. A. Miskel, Chemistry Division, Lawrence Radiation Laboratory, Livermore.

*This is about a 10% window since the measured resolution (FWHM) of these crystals for 662-keV gamma rays was nominally 10%.

and $(0.48 \pm 0.1)\%$ for 90% windows. Table IV gives some values of the counting rates expected for this detector under different conditions. It includes estimates of counting rates expected for various sizes of scintillator, amounts of shielding, volume of target, and electronic window widths.

Each NaI crystal-phototube combination has a very small amount of K^{40} impurity which decays (the half-life is 1.27×10^9 years) via β^- decay to Ca^{40} , which emits a 1.46-MeV gamma ray. This gamma ray has a finite probability of producing an electron-positron pair in the center target region, and the annihilation of this positron will be detected by the system and will become part of the "background."

The magnitude of this "accidental" event depends on the amount of K^{40} and the geometry of the system. In order to determine how large an effect this was, measurements were taken with the following results: Unshielded, the singles background rate, * with 50% windows, was about 1000 per minute in each channel, and the slow coincidence rate, with the space between the crystals filled with CH_2 , was about 0.6 per minute. The expected slow coincidence rate, on the basis of the measured resolving time of the coincidence circuit and the singles rate, was 10^{-7} /minute. To check whether the high accidental rate was due to the K^{40} impurity, data were taken under various conditions of geometry and shielding. The results are shown in Table V.

* Taken in Bunker No. 302, Site 300, LRL.

Table IV. Summary of expected real and accidental counts from various "positron-only" detectors.
(For 10-kt yield.)

Target thick- ness, cm	NaI crystals diam × thickness in.	Total volume, liters	Number of units	Shielding	Electronic window width, %	$\bar{\epsilon}$, % ^a	Total No. ^b reals/min	Total No. acc./min	Signal Noise
8	5 × 3	10,000	10,000	None	—	100	123	0.001	—
"	"	"	"	2 in. Fe	—	100	123	.0001	—
"	"	"	"	None	50	0.25	0.31	.001	310
"	"	"	"	None	90	0.39	0.48	.004	120
"	"	"	"	2 in. Fe	90	0.39	0.48	.0004	1200
"	7 × 3	"	5,100	"	90	0.57	0.70	.0002	3500
4	"	5,000	"	"	90	1.8	1.1	.0002	6000
"	"	10,000	10,200	"	90	1.8	2.2	.0002	1.1×10^4
5	12 × 3	"	1,740	"	90	1.1	1.4	0.0023	609

^aSee Appendix D.

^bSee Table I, Section II.

Table V. Comparison of expected and measured triple coincidence background rates.

Details	Expected rate/min	Measured rate/min
Normal separation (8 cm between crystals)	10^{-7}	0.6
Ten times normal separation (80 cm)	10^{-7}	0.08
Ten times normal separation; 2 in. Fe around one crystal	10^{-8}	0 (20 min)
Normal separation (8 cm); 1 in. Fe around whole detector	10^{-9}	0.3

On the basis of these measurements plus a single-channel spectrum showing a small, 1.46-MeV K^{40} gamma-ray peak, it was concluded that these crystals had an impurity level much too high to be used in a detector of this type. These accidental counts would completely swamp any real signal.

One means of eliminating these (K^{40} contamination) events is to replace the target with a plastic (or liquid) scintillator. Standard scintillation fluor is composed of CH, and replacement by this would mean a factor of 2 increase in the number of detection units needed, so it will be assumed that the target will be composed of CH_2 (and will probably be a scintillating liquid). A third phototube will look at this volume and a fast signal taken from it (see Fig. 7). A fast coincidence is then demanded among the two NaI pulses and a pulse from the target scintillator. This will eliminate the effect of K^{40} in the NaI crystals, as the two 511-keV gamma rays cannot give pulses in both of the NaI crystals and the center scintillator simultaneously. No linear signal is felt to be necessary.

The efficiency of this system should not be adversely affected by this change since most β^+ formed will have kinetic energy which will be lost in the target volume generating a light pulse which will be seen by the third phototube. Thus most β^+ will generate a triple coincidence in the electronic circuit.

C. Detection of the Neutron Alone

In order to have high efficiency this detector would most practically be a large tank of liquid scintillator serving as both target and detector. The

neutron formed by way of a $\bar{\nu}$ absorption would have a good chance of being slowed down and captured (by some dissolved gadolinium for example) and thus give rise to capture gamma rays. These would in turn give rise to scintillation pulses in photomultiplier tubes viewing the volume.

The efficiency of such a device should be relatively high (about 50%, as estimated by Reines et al.^{5,8}). For a 10,000-liter detecting volume, and a 10-kt device buried at proper depth, 123 $\bar{\nu}$ events are expected, and thus about 60 real "counts" should be recorded.

The problem with this detector is background (mainly from cosmic rays and natural radioactivity in the earth). An energy gate set to record only pulses representing capture gamma ray energies (between say 1.5 and 8 MeV) would help isolate a true event from a background event. From Appendix C the number of background events one would expect in such an energy window, with 2 in. Pb shielding surrounding 10,000 liters, is something in the neighborhood of 10^5 "accidental" counts compared to 60 "real" counts. Clearly this is not a practical situation. Any realistic amount of shielding would not lower this rate enough, as can also be seen by the experimental counts obtained inside a tunnel (Appendix C), with about 1300 feet of rock cover. Even in the much more limited energy gate of 4 to 8 MeV, the number of accidentals would be of the order of 1500 counts/min for the 10,000-liter volume.

The difficulty with the detection of the neutron alone is the lack of any unique event signature, plus the impracticability of shielding such a large volume of scintillator. What must be done to lower the background is to somehow break up the volume into smaller units and use the unique signals obtainable from the associated positron decay. This is accomplished by either of the first two types of detectors, discussed in sections A and B. Either of these is felt to be much superior to a detector of neutrons only.

IV. SUMMARY AND CONCLUSIONS

For antineutrinos associated with beta decay, many of the known possible reactions with matter have been considered in order to establish whether or not an antineutrino detector was feasible. The only interaction which seems possible in order to just observe an antineutrino from a nuclear explosion is the inverse beta decay reaction

All other possible reactions have cross sections less than this one. In addition, the detection problems for the other reactions are orders of magnitude more difficult. This is simply because there do not exist unique event signatures for the other reactions as there does for this inverse beta decay reaction.

The principal difficulties associated with the observation of the above reaction, and thus the detection of an antineutrino, are the extremely low signal rates expected in any real detector. Background probably would not pose too serious a problem. For example, the signal from a 10,000-liter detection volume, observing the antineutrino flux from a buried 10-kt explosion, is typically 10 events in a 1-minute count, along with at least 0.02 background events. Nothing obvious can be done to increase the signal rate, which is governed so strongly by the low efficiency of this type of detector. Any real detector would also have to be hardened to withstand severe earth-motion shock, but detailed considerations of this phase of the problem have not been undertaken in this study.

Two types of possible detectors have been studied in detail here and both seem capable of barely detecting an antineutrino from a nuclear explosion, but one is clearly better in counting rate and cost. Both use existing materials and existing electronics, and the engineering required to build either type should require nothing particularly novel. Either detector would be large, of the order of $10 \times 10 \times 10$ ft. Neither detector would be useful for making yield measurements due to the large uncertainties in the efficiency, and the large statistical error involved with the low counting rates obtainable. (See Eq. (1), Sec. I.) The low signal rates also make these detectors impracticable for doing basic physics experiments.

The main costs of the positron-only detector come from photomultiplier tubes and NaI crystals and would run between \$20 million and \$30 million. The cost of the modified Reines-Cowan detector would be roughly \$1 million. Table VI shows a rough cost breakdown of each detector type.

Table VI. Cost estimates of detectors.

<u>A) Positron-only detector</u>		
Two NaI crystals, 7-in. diam, 3-in. thick		\$3750
Photomultiplier tubes and bases		1000
Electronic circuit (parts and labor)		350
Miscellaneous hardware, including target material		400
Shielding: 4 in. lead		100
		<u>\$5600 per unit</u>
Number of units (for 10,000 liters total)		<u>× 5100 units</u>
	<u>Total Cost</u>	\$28.6 million
<hr/>		
<u>B) Modified Reines-Cowan detector</u>		
(Order of magnitude estimate — 10,000 liters of target)		
One thousand 5-in. photomultiplier tubes		\$200,000
Electronics (parts and labor)		100,000
Hardware (materials and labor)		50,000
Shielding (4 in. lead)		200,000
Scintillation liquid and solute, etc.		200,000
	Subtotal	<u>\$750,000</u>
Contingency		50,000
	<u>Total Cost</u>	<u>\$0.8 million</u>

On the basis of the signal-to-noise ratio both detectors are good, with the positron-only type probably better. On the basis of cost, the modified Reines-Cowan detector is by far the better choice, but even here the cost is formidable.

It should be pointed out specifically that the signal expected in any detector depends basically on four factors:

1. The antineutrino flux, $\phi_{\bar{\nu}}$.
2. The number of target protons, N_p .
3. The solid angle geometry of the detector, Ω .
4. The efficiency of the detector.

Almost nothing can be done with $\phi_{\bar{\nu}}$ and Ω since these are dictated by the nuclear device and the fact that the detector must be far enough away to remain intact for at least 1 minute. The only remaining parameters are N_p and ϵ , and if further work were done on this problem it could be directed towards increasing these quantities. If either N_p or ϵ could be increased an order of magnitude the detector would be much more feasible.

This would mean, for example, developing some material with much higher density of protons/cc, but which still has the properties needed to make it a scintillator. To increase the efficiency it most probably would be necessary to develop a whole new type of detector for the positrons and neutrons, and leave the ideas of Reines and Cowan. No obvious types are apparent at this time.

Some different approaches to this subject of the detection of antineutrinos from nuclear explosions, which have come to light during the course of this study, are given in Appendix E. While these suggestions and speculations are not directly in the spirit of the present report, they could be systematically studied in further work on this problem. They are only offered for what they are worth, and are not meant to be carefully worked out suggestions.

Acknowledgments

The authors would like to thank Dr. Hans Mark of Lawrence Radiation Laboratory, Livermore, and Dr. Frederick Reines of Case Institute of Technology, Cleveland, Ohio, for suggestions and discussions concerning this study.

APPENDIX A

REACTIONS BY WHICH ANTINEUTRINOS MIGHT BE DETECTED*

The following reactions were considered:

1. $\bar{\nu} + p \rightarrow \beta^+ + n.$
 2. $\bar{\nu} + d \rightarrow \beta^+ + n + n.$
 3. $\bar{\nu} + (\text{nucleon}) \rightarrow \bar{\nu} + (\text{nucleon}).$
 4. $\bar{\nu} + (\text{electron}) \rightarrow \bar{\nu} + (\text{electron}).$
- } Elastic scattering

The last two reactions have been rather carefully considered by Karzas

*There are four types of neutrinos now believed to exist: two, ν_{μ} and $\bar{\nu}_{\mu}$, are associated with the muon; and two, ν_e and $\bar{\nu}_e$, are associated with ordinary beta decay. The antineutrino in the latter category is the one of concern here.

and Latter,² who conclude the cross sections are less than or equal to the cross section for reaction 1 (10^{-43} cm^2). In view of the extra difficulties in detecting recoil nucleons or electrons as compared to detecting positrons, reactions 3 and 4 are not felt to be usable. The real difficulty lies in the fact that there exists no unique event signature in the case of the scattering of $\bar{\nu}$.

Reaction 2 has a Q-value of -4.0 MeV as compared to -1.8 MeV for reaction 1. Since the energy spectrum of $\bar{\nu}$ from fission falls rapidly with increasing energy,⁶ the expected counting rate for reaction 2 will be from one to two orders of magnitude lower than that for reaction 1.

For these reasons reaction 1 was chosen to be the only realistic one to try to use.

APPENDIX B

POSSIBLE TARGETS FOR DETECTION OF ANTINEUTRINOS THROUGH THE $\bar{\nu} + p \rightarrow \beta^+ + n$ REACTION

The optimum target will have the largest number of protons per unit volume and the largest half-thickness for the absorption of 511-keV gamma rays, consistent with each other. It should also be relatively easy to handle and not require special equipment.

In Table VII is shown a representative list of some possible materials.* The numbers important in selecting a target material are the number of protons per cm,³ the half-thickness for absorption of 511-keV gamma rays, and the product of these two. The half-thickness, $\gamma_{1/2}$, was calculated from the relation $\gamma_{1/2} = (2/\mu\rho)\ln 2$, where μ is the mass absorption coefficient and ρ is the density.

For application of Sec. III(B), either paraffin or polyethylene is an acceptable choice since both are easy to handle and have a large product of proton density and $\gamma_{1/2}$. Octane, pentane, and liquid ammonia have higher

* Physical constants used in Table VII were obtained from ref. 11. Values of μ not contained in these tables were obtained by interpolation.

¹¹K. Siegbahn, Beta- and Gamma-Ray Spectroscopy (North-Holland Publishing Co., Amsterdam, 1955); A. H. Wapstra, G. J. Nijgh, and R. Van Lieshout, Nuclear Spectroscopy Tables (North-Holland Publishing Co., Amsterdam, 1959); and Handbook of Chemistry and Physics, 1962-63 Ed. (Chemical Rubber Publishing Co., Cleveland, Ohio).

values of $\rho_H \gamma_{1/2}$, but all these substances are liquids and require the use of special packaging and handling techniques.

Because of its higher melting point and lower coefficient of expansion, polyethylene seems to be a better potential target material than paraffin.

Table VII. Some possible target materials.

Substance	Remarks	Mol. wt	Weight fraction of H	Density g/cc	Density of hydrogen	$\gamma_{1/2}$ cm	Hydrogen/cc $\times$ half-thickness
NH ₃	Liquid ammonia	17	0.176	0.817	0.144	9.36	1.35
C ₈ H ₁₈	Octane	114	.158	.704	.111	9.90	1.10
C ₅ H ₁₂	Pentane	72	.167	.626	.105	10.3	1.08
C ₂₅ H ₅₂	Paraffin	352	.148	.89	.132	7.76	1.02
CH ₂	Polyethylene	14	.143	.96	.137	7.21	0.988
LiH	Lithium hydride	8	.125	.78	.098	9.76	.956
B ₁₀ H ₁₄		122	.115	0.78	.090	9.49	.854
H ₂ O	Water	18	.111	1.00	.111	7.2	.799
CH	Styrene (lab. fluor)	13	0.077	1.06	.082	7.00	.574
H ₂	Liquid hydrogen	2	1.00	0.070	0.070	5.72	0.400

APPENDIX C

BACKGROUND MEASUREMENTS

Background measurements were taken at LRL-Livermore Site, Site 300, and at the Nevada Test Site. Plastic and NaI scintillators were used under various shielding conditions. The details of crystal size and shielding are given in the following tables and graphs.

The equipment was calibrated using sources of Na²² (1.28- and 0.511-MeV gamma rays), Cs¹³⁷ (0.662-MeV gamma ray), and PuBe (4.43- and 2.22-MeV gamma rays), and a precision pulser was used to check stability of the electronics. Spectra were recorded on a multichannel analyzer.

Tables VIII and IX give, respectively, typical background counting rates in plastic scintillators and in NaI scintillators in various locations and under various shielding conditions.

Figures 8 and 9 show, respectively, energy spectra of the background taken with plastic and NaI scintillators.

Table VIII. Summary of background measurements made with a 2×4 -in. plastic scintillator (0.206 liter) on an RCA 6810 photomultiplier tube.

Location	Shielding	Energy window 1.5-8.0 Mev		Energy window 4.0-8.0 MeV	
		cpm	cpm per 1000 liters*	cpm	cpm per 1000 liters*
LRL, Bldg. 112 500 ft altitude	None	226	6.9×10^4	32	1.0×10^4
LRL, Bldg. 112	2 in. Pb	83	2.5×10^4	25	7.9×10^3
NTS, N tunnel portal 6000 ft altitude	None	472	1.4×10^5	58	1.8×10^4
NTS, inside N tunnel	1300 ft, rock cover	742	2.4×10^5	1.0	320

*These figures are obtained from a $(\text{Volume})^{2/3}$ scaling of the measured background. Since the volume used to make the measurements was very small compared to 1000 l, the scaled figures may be poor estimates of the true background. They are felt to be at least reasonable lower limits to the background, and are most likely good to an order of magnitude.

Table IX. Summary of background measurements made with NaI scintillator. Counts are those falling within a 50% window (76% of peak area) around 511 keV.

Location	Shielding	cpm	Crystal size, diam $\times$ height, in.
LRL, Bldg. 112	None	37.0	2×2
LRL, Bldg. 112	1 in. Fe	20.3	"
LRL, Bldg. 112	2 in. Fe	10.8	"
Site 300, LRL (Bunker 302)	None	1135	5×4
Site 300, LRL (Bunker 302)	1 in. Fe	430	"
Site 300, LRL (Bunker 302)	2 in. Fe	314	"

Fig. 8. Background radiation at various locations taken with a plastic scintillator. The abbreviations used are as follows: NTS-G means the Nevada Test Site in tunnel G; NTS-N means the Nevada Test Site in tunnel N; NTS-N PORT means the Nevada Test Site at the portal of tunnel N; LRL-112 means the Livermore site in Bldg. 112.

Fig. 9. Background radiation at Site 300, LRL, taken with an NaI crystal. The number of counts per minute is plotted versus the energy.

APPENDIX D

CALCULATIONS AND MEASUREMENTS OF AVERAGE EFFICIENCY OF DOUBLE- NaI -CRYSTAL POSITRON DETECTOR

Measurement

A small "point source" of Na^{22} with an activity of 1040 disintegrations per second¹⁰ was used for the efficiency measurements. The measurement of the average efficiency was made with the following geometry: the two 5×4 -in. crystals were 8 cm apart (face to face) with the space between filled with 7-mm-thick polyethelene disks; the Na^{22} source was placed at various positions on and off axis between the crystals and measurements were taken of the singles rate in each crystal, of the fast coincidence rate, and of the triple (slow) coincidence rate. The efficiency at each point was then calculated by taking the ratio of the number of slow coincidences to the number of positrons emitted per unit time. These separate efficiencies were then weighted by their appropriate volume factors to obtain an overall average efficiency. Thirty-two individual measurements of efficiencies were made to determine the average efficiency of this geometry, which turned out to be $(0.30 \pm 0.07)\%$.

Calculations

Simple hand calculations were made of average efficiency for a number of different geometries including the particular one used in the measurement described above.

The calculation was based on an effective solid angle, an average path length in the target (CH_2) material for the photon, and known interaction probabilities and peak-to-total ratios.¹²

The calculated efficiency, with the source at the central point, agreed with the measured value well within the accuracy of the calculation ($\sim 15\%$). Based on this agreement, calculations of the average efficiency for other sets of crystals and geometries were made and are given in Table X.

¹²W. F. Miller and W. J. Snow, *Nucleonics* 19, 174 (1961); and J. B. Marion, 1960 Nuclear Data Tables, Part 3, page 51, et seq.

Table X. Average efficiencies calculated for double-NaI-crystal positron detectors.

Crystal size, diam $\times$ ht, in.	Geometry ^a	Window	$\bar{\epsilon}$, %	$\bar{\epsilon} \times N^b$
5 $\times$ 3	8 cm between	50%	0.25	0.63
"	"	90%	0.40	1.0 ^c
7 $\times$ 3	"	"	0.56	2.7
"	4 cm between	"	1.9	4.6
12 $\times$ 3	5 cm between	"	1.1	9.9

^aSpace between filled with polyethelene.

^bProduct of average efficiency and the number of protons in the target volume.

^cArbitrarily normalized to 1.0.

APPENDIX E

FURTHER THOUGHTS AND SPECULATIONS ON THE BASIC ANTINEUTRINO DETECTION PROBLEM

In this appendix are listed some ideas on different approaches to the detection of antineutrinos from nuclear explosions. They are gathered together here since they are not in the spirit of the original study program, but are related to it, and did arise during the course of this study. These are meant to be only speculations, and very little thought has been given to the practicability of any of them. For example, no detailed study has been made of the existence of suitable targets for the antineutrino interactions. These ideas might be useful as bases for further work.

(1) It might be worthwhile to examine the possibility of "stimulating the emission" of positrons from a nucleus by the action of an antineutrino field, in analogy to the de-excitation of metastable atomic states with visible light. The effect obtained might be enough to overcome the low efficiencies inherent in the type of detectors discussed in this study.

This scheme would function in the following way (see Fig. 10):

Fig. 10. Decay scheme of nucleus X to nucleus Y.

The target would be a nucleus X in a state unstable to positron emission and would spontaneously decay to nucleus Y with a long half-life. There would be a small average number of positrons per unit time from this target, and these could be detected by, say, the "positron-only" detector described in Sec. III(B). If now an antineutrino field is turned on in the vicinity of nucleus X, an increase in the decay rate should take place, yielding more positrons per unit time than previously. It is this increase that could be detected and which would indicate the presence of antineutrinos. If the positron decay goes to an excited state of Y and is followed by the emission of a gamma ray, then this event could be further isolated from background. The important question is whether or not this increase of positron decay rate, via the presence of the antineutrino field, would be greater than the antineutrino capture by a free proton. The advantage of this process is that the density of target nuclei might be made greater, since one of the limiting things in the conventional scheme was the low density of target protons available in any real detector.

(2) A scheme related to that described in (1) is one along the lines suggested by Sunyar and Goldhaber.¹³ They describe a possible "threshold neutrino detector," but a similar hypothetical one for antineutrinos will be suggested below.

Consider a nucleus X as shown in Fig. 11, either stable or unstable to positron emission, with a very long half-life. If an antineutrino is added

¹³A. W. Sunyar and M. Goldhaber, Phys. Rev. 120, 871 (1960).

Fig. 11. Speculated transitions between nucleus X and nucleus Y.

to X with sufficient energy the following reactions theoretically could take place:

The detector would then be designed to look for characteristic gamma rays from nucleus Y with energy E, and annihilation gamma rays, or electrons from the beta decay of Y^* and annihilation gamma rays. One difference between this scheme and the one described in (1) is that the gamma ray de-exciting Y^* is seen only when an antineutrino is absorbed in this case. It would also serve as a threshold detector for antineutrinos, the threshold energy being determined by the energy difference between X and Y^* and the mass of a positron.

(3) A suggestion¹⁴ along different lines is to add to the available antineutrino flux by surrounding the nuclear device by a material such as Li^7 . Neutrons from the device would be captured by the lithium with the following reaction taking place:

¹⁴Drs. H. Mark and E. Teller, Lawrence Radiation Laboratory, private communication.

Li^8 has a half-life of 0.85 sec and decays by β^- decay to Be^8 . The end-point energy is 13.0 MeV.¹⁵ Another possible target would be B^{11} with the following reaction:

B^{12} has a half-life of 20 msec and an end-point energy of 13.4 MeV. This scheme does not affect the antineutrino flux which arises from the beta decay of the fission fragments, but adds to this flux.

These added antineutrinos have a spectrum with a higher end-point energy than the fission spectrum, and thus a larger percentage of the released antineutrinos can react with the target protons. This will be realized through a higher cross section for the reaction. A rough calculation shows that for this scheme the number of antineutrinos passing through the detector, for a given nuclear device, could be about equal to the number emitted from fission. If a thermonuclear device is used, on the other hand, there will be many more antineutrinos released since the neutrons from both sources are useful for producing these secondary antineutrinos.

This does not seem to be a reasonable way to determine the yield, however, since many reactions have to be taken into account: for example, first the number of neutrons emitted by the device, second the $n + \text{Li}^7 \rightarrow \text{Li}^8$ reaction, and finally the Li^8 beta decay. The errors associated with going back through these reactions, even with good statistics on the antineutrino count, would be so large that a reasonable determination of the yield could not be made. The direct detection of antineutrinos from the fission fragments is a much preferred way to determine the yield.

The short times involved in the release of these secondary antineutrinos, as compared to the approximately 1 minute required for the fission fragment decay, add other possibilities. For example, the detector might be placed much closer, and the information obtained before the shock wave reaches the detector.

Further discussion of these possibilities and suggestions is left for another study.

¹⁵ 1960 Nuclear Data Tables, Part 4, National Research Council, Washington 25, D. C.

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