Antineutrino Flux from a Reactor*

C. O. MUEHLHAUSE† AND S. OLEKSA
Brookhaven National Laboratory, Upton, New York
(Received August 29, 1956)

The antineutrino flux distribution from a thermal neutron reactor is determined from a measurement of the equilibrium beta-ray spectrum from thermal neutron fission of U^{235}. The antineutrino distribution is then folded in with the cross sections for $\bar{\nu}(p,n)\beta^+$ and $\bar{\nu}(d,2n)\beta^+$ as a function of antineutrino energy. This determines the average antineutrino pile cross sections, $\bar{\sigma}_p$ and $\bar{\sigma}_d$, respectively, for the above-cited reactions. The results are: $\bar{\sigma}_p=6\times10^{-44}$ cm^2; $\bar{\sigma}_d=2\times10^{-45}$ cm^2.

INTRODUCTION

IN the theory of beta decay it is not *a priori* evident that neutrinos and antineutrinos are distinguishable. Recently, however, two independent studies of the inverse beta reaction have established with good probability that such is the case. In the first[1] of these, $p(\bar{\nu},\beta^+)n$, it was demonstrated that an antineutrino-induced reaction gives rise to emission of a positron. The second[2] reaction studied, $Cl^{37}(\bar{\nu},\beta^-)A^{37}$, was shown not to take place. That is, an antineutrino-induced reaction does not give rise to emission of a negatron. From this, one infers that $\bar{\nu}\neq\nu$. This conclusion is also tentatively drawn from the observations of double beta decay.

In both of the cases cited, a high-power thermal neutron chain reactor employing U^{235} as the fissionable material was used as a source of high intensity antineutrino flux. The antineutrinos are emitted by the β^--active fission products, their intensity being $\sim2\times10^{17}$ per megawatt. These neutrino studies are continuing together with an additional attempt to observe a third reaction,[3] $d(\bar{\nu},\beta^+)2n$.

It is evident that in order to evaluate quantitatively the inverse-beta cross section, one must know the energy distribution of the antineutrinos emitted by a thermal pile. This is especially important in evaluating the relative merits of the first and third reactions. The first ($p\rightarrow n$) has a threshold of $\sim$1.8 Mev and emits two observable particles (β^+ and n). The third ($d\rightarrow2n$) has a threshold of $\sim$4.0 Mev and emits three observable particles (β^+ and $2n$). However, the latter reaction has a considerably smaller cross section than the first. In both cases, it is necessary to integrate the product of the pile antineutrino energy distribution and the respective cross sections (σ_p and σ_d), in order to compute the resulting reaction rates.

This paper presents the results of an experiment[4] which determines the antineutrino energy distribution from U^{235}, and the results of Weneser's calculation[5] of σ_d as a function of antineutrino energy. These, as well as the calculation of σ_p, are used to evaluate $\bar{\sigma}_p$ and $\bar{\sigma}_d$, the average pile antineutrino cross sections for the hydrogen and deuterium reactions, respectively. In addition, the average beta energy obtained from the present measurements is compared with the results given by Wigner and Way.[6]

THEORY

The pile antineutrino energy distribution may be derived from a measurement of the equilibrium beta energy distribution from thermal neutron fission of U^{235}. The transformation of this distribution to the antineutrino spectrum can be accomplished by assuming that the distribution of beta-ray end points is given by a Gaussian of the form:

$$\exp[-E_{\max}^2/2(\Delta E_{\max})^2]. \quad (1)$$

The parameter $\Delta E_{\max}$ is adjusted so that the integral of the product of the Gaussian and the Fermi-allowed beta functions yields the observed beta-ray energy distribution. Once the correct Gaussian distribution of beta end points is known, the antineutrino spectrum can be obtained by integrating this Gaussian over the Fermi-allowed antineutrino functions. The above formal operations include the Coulomb effect.

It should be noted, however, that in the energy range of interest (>2 Mev) the observed equilibrium spectrum of beta rays is essentially the desired antineutrino spectrum. This is so because for energies $\gg mc^2$ both the electron and antineutrino are highly relativistic, and share approximately equally the energy available in beta decay. Though a slight improvement may be

TABLE I. Calculated values of σ/g^2 for the proton and deuteron at three antineutrino energies.

E_ν Mev	σ_p/g_p^2 cm^2	σ_d/g_d^2 cm^2
5.5	16.1×10^{-21}	8.47×10^{-22}
8.5	47.3×10^{-21}	8.47×10^{-21}
13.5	13.6×10^{-20}	4.20×10^{-20}

* Work performed under the auspices of the U. S. Atomic Energy Commission.
† Now at Republic Aviation Corporation, Farmingdale, New York.
[1] Cowan, Reines, Harrison, Kruse, and McGuire, Science **124**, 103 (1956).
[2] R. Davis, Bull. Am. Phys. Soc. Ser. II, **1**, 219 (1956).
[3] F. Reines (private communication).
[4] C. O. Muehlhause, Brookhaven National Laboratory Report BNL-242 (T-38), 1953 (unpublished); C. O. Muehlhause and S. Oleksa, Phys. Rev. **100**, 1266 (1955).
[5] J. Weneser, following paper [Phys. Rev. **105**, 1335 (1957)].
[6] E. Wigner and K. Way, Phys. Rev. **73**, 1318 (1948).

realized by working backwards to the initial Gaussian end-point distribution, and thence forward to the final antineutrino distribution, this last operation is not carried out in the present work. Instead, the adjusted Gaussian is determined simply for purposes of extrapolating the data to higher energies.

σ_p as a function of antineutrino energy is readily obtained from a knowledge of the beta decay of the neutron[7] ($n_{12\,\mathrm{min}} \rightarrow p + \beta^- + 782$ kev):

$$\sigma_p = \frac{g_p^2}{2\pi}\left(\frac{\hbar}{mc}\right)^2\left(\frac{E_\nu}{mc^2} - \frac{M_n - M_p}{m} - 1\right) \times\left[\left(\frac{E_\nu}{mc^2} - \frac{M_n - M_p}{m} - 1\right)^2 - 1\right]^{\frac{1}{2}}, \quad (2)$$

where E_ν is the incoming neutrino energy and g the coupling constant ($g_p^2 = 0.50 \times 10^{-22}$) is obtained from the decay of the neutron.[8]

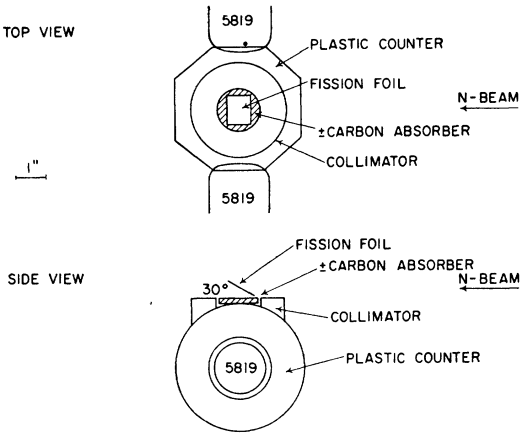

FIG. 1. Plastic counter, U^{235} foil, and beam arrangement.

For the H^1 process, both the tensor and scalar interactions contribute:

$$g_p^2 = 3g_T^2 + g_S^2. \quad (3)$$

For the H^2 process to lowest order, only the tensor interaction contributes:

$$g_d^2 = 3g_T^2. \quad (4)$$

g_d^2 is therefore uncertain to the extent that g_T^2/g_S^2 is unknown. A reasonable value[7] for this ratio is apparently 3/2, and therefore $g_d^2 = 0.40 \times 10^{-22}$.

Weneser has computed σ_d/g_d^2 for three different incoming antineutrino energies. These are given in Table I along with σ_p/g_p^2 for comparison.

EXPERIMENTAL TECHNIQUE AND RESULTS

The beta-ray spectrometer consisted simply of a plastic scintillation counter having a mean dimension

[7] J. M. Robson, Phys. Rev. **83**, 349 (1951); **100**, 933 (1955).
[8] E. J. Konopinski and L. M. Langer, *Annual Review of Nuclear Science* (Annual Reviews, Inc., Stanford, 1953), Vol. 2, p. 261.

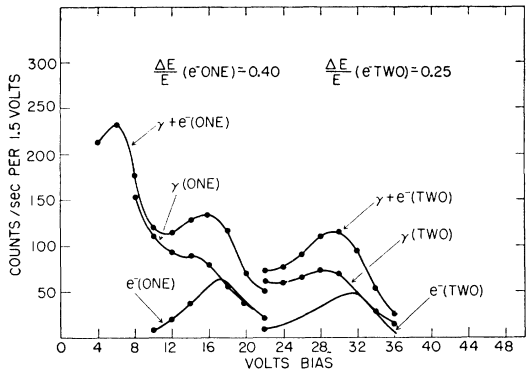

FIG. 2. Response of plastic counter to Bi^{207} radiation. $\gamma + e^-$ is obtained with no absorber between the source and counter; γ is obtained with an aluminum absorber between the source and counter; and e^- is obtained from the difference of $\gamma + e^-$ and γ. Operation using one or two photomultipliers is given.

~10 cm. The counter subtended ~30% of the source and possessed ~20% energy resolution for 1-Mev electrons. The beam and counter arrangement are shown in Fig. 1.

A plastic detecting medium is suitable because (a) the surface albedo is small, (b) the bremsstrahlung loss is small for energies <10 Mev, and (c) the pulse height response to fast neutrons is negligible. An average thickness ~10 cm is adequate to stop electrons of energy <10 Mev.

More than one photomultiplier is desirable because (a) more light and improved resolution is obtainable, and (b) improved uniformity of response from various portions of the counter results.

The performance of this counter to a Bi^{207} source of 1.03-Mev electrons is shown in Fig. 2. Curve *A* is for one-tube operation and curve *B* is for two-tube operation. The source was placed at various positions around the counter to demonstrate that the pulse height was constant to 5%. The Compton edge of a number of gamma rays as well as the end point of the 4.9-Mev β^- ray from Cl^{36} was used for energy calibration. The electronic gear consisted simply of a Beva Model 153 nonoverload amplifier and an Atomics Instrument Company Model 510 single-channel pulse-height analyzer.

The counter was placed outside a thermal neutron beam from the Brookhaven reactor (see Fig. 1) and the U^{235} foil (~80 mg/cm²) just above it at a suitable angle (~30°) to the beam. Counting rates were taken as a function of bias with and without a graphite absorber between the foil and counter. This latter operation was for the purpose of separating β^- and γ rays. A counter-in-beam arrangement was found applicable, but suffered from (a) high counting rates, and (b) background structure. In particular, the in-beam background exhibited the Compton edge of the 2.2-Mev H^1 capture γ ray resulting from neutron absorption in the plastic. Neither of these disadvantages was

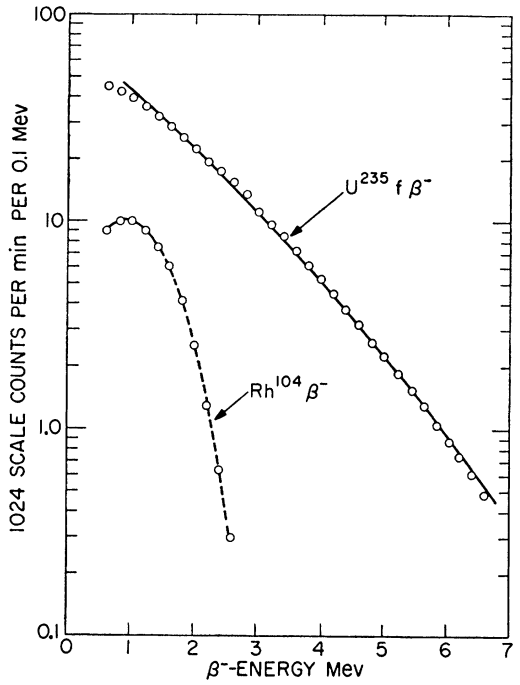

FIG. 3. Differential spectra of beta rays resulting from thermal neutron absorption in U^{235} and Rh^{103}. The data have been normalized with respect to cross section and thickness. The solid curve is that to be expected from the Gaussian for which $\Delta E_{max}=3.85$ Mev.

present in the off-beam arrangement. Integral count rates were kept $<2\times10^5$/min.

The absolute intensity could be determined to ~20% uncertainty by placing in the beam a thin (~50 mg/cm²)Rh^{103} foil of the same size and position as the U^{235} foil. No other substance appeared suitable. This material has a thermal cross section of 140 barns and is activated to a 44-sec (half-life) β^- emitter of 2.6-Mev energy. The thickness of the foils used naturally resulted in a certain distortion of the low-energy end of the spectrum. No corrections were made for this.

Various subsidiary experiments were performed to demonstrate that photo- and Compton electrons produced by the foil acting as a radiator were negligible. These consisted of doubling the thickness of the U^{235} foil and/or sandwiching it between thin Th^{232} foils.

The results of the spectral determination of the beta rays from U^{235} and Rh^{104} are given in Fig. 3. The statistics and reproducibility are within the circles which indicate the experimental points. The two curves have been normalized with respect to cross section and thickness. The ratio of their integrals is 5 ± 1 instead of the accepted value of 6.1 ± 0.3. The solid curve shown for U^{235} is the beta spectrum to be expected from a Gaussian end-point distribution in which $\Delta E_{max}=3.85$ Mev. The average energy per beta obtained from Fig. 3 is approximately 1.5 Mev which indicates an average beta energy per fission of about 9 Mev. This is somewhat higher than the value quoted by Wigner and Way.[5] An additional qualitative disagreement was also observed in the performance of the experiment; namely, the time required to reach equilibrium for the high-energy beta-rays appeared to be less than that indicated by Wigner and Way. However, an experiment in which a time analysis of the beta yield is performed would be required to check this point.

Using (2) and Table I together with the Gaussian extrapolation for energies >7 Mev, one obtains:

$$\bar{\sigma}_p=6\times10^{-44}\ \text{cm}^2,\quad \bar{\sigma}_d=2\times10^{-45}\ \text{cm}^2.$$

CONCLUSION

The deuteron reaction rate is thirty times less than that for hydrogen. However, its more distinctive reaction mode should compensate for this reduced rate. The cross section is close to that calculated for chlorine[2] (in which ν is substituted for $\bar{\nu}$).

An improved measurement of the fission beta spectrum could be obtained by employing a beta-ray lens spectrometer into which a U^{235} foil and a thermal neutron beam could be introduced. It would also be desirable to time-analyze the beta spectrum by employing a rotating cadmium shutter in the neutron beam. In addition, the average beta-ray energy per fission could be independently determined with a beta-ray calorimeter.

It is evident from this and the following paper that a higher energy antineutrino source would be very desirable. Such a source originating from a specific beta-active nucleus, for example, could be obtained from the $B^{11}(d,p)B^{12}$ reaction. A one ampere beam of several Mev deuterons is required. The pulsed feature permits separation of the prompt $B^{11}(d,n)C^{12}$ reaction in that the half-life of B^{12} is ~20 msec. With proper time analysis of the B^{12} yield, a clean antineutrino source extending in energy to ~13 Mev would be available. Similar possibilities exist for $Li^7(d,p)Li^8$.

ACKNOWLEDGMENTS

The authors wish to thank M. Meer for assisting in data taking, and D. E. Alburger for providing them with a Bi^{207} source. We are also greatly indebted to J. Weneser for the calculation of σ_d and to E. P. Wigner for valuable discussion of the results.