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ABSTRACT

Several procedures for calculating the average cross-section per antineutrino from U^{235} fission are given to test the predictions of the two-component neutrino theory. A firm lower limit of $\bar{\sigma}_p > 7 \times 10^{-44}$ cm^2 is deduced from the known decays of the fission products. Three different procedures, if weighted equally, give a "best value" of $\bar{\sigma}_p = 14 \times 10^{-44}$ cm^2 to be compared with the recently increased experimental value $\bar{\sigma}_p = 11 \pm 4 \times 10^{-44}$ cm^2. It is concluded that predictions of the two component neutrino theory are in accord with the experimental results on inverse beta decay.

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INTRODUCTION

The cross section for inverse beta decay provides a further test of the predictions of the two-component neutrino theory.[1] Previous to the development of the two-component concept agreement had been claimed between the directly measured cross section[2] and that calculated from an indirect determination of the antineutrino spectrum from a reactor.[3] After the proposal of a two component neutrino, it was realized that the calculated value of the cross-section should be twice as large as that derived from a four component theory with parity conservation. This factor stems from the fact that the number of initial states in the reaction $\bar{\nu} + P \rightarrow N + e^+$ is reduced by a factor of two.

Because of the uncertainty involved in obtaining the antineutrino spectrum, the disagreement of a factor of two was not interpreted as very significant. The present work was instituted to determine if any of the uncertainties in the antineutrino spectrum could be removed to permit positive conclusions. Our results showed a strikingly larger cross-section than that determined by Cowan and Reines and these results were initially presented at the Mid-West Conference on Theoretical Physics[4] to point up the large discrepancy between our calculated cross-section and the cross-section measured by Cowan and Reines. Since that time, however, a numerical error has been discovered[5] that raises the experimental cross-section by a factor of five. This factor of five now brings the experimental cross-section into agreement with our calculated value and removes the last major experimental discrepancy with the predictions of the two-component neutrino theory. These recent developments thus change the purpose of our paper from one of pointing out a disturbing disagreement to a further confirmation of the two-component neutrino theory.

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CROSS-SECTION OBTAINED FROM EXPERIMENTAL DETERMINATION OF REACTOR BETA SPECTRUM

The most recent and widely used determination of the antineutrino spectrum is that due to Muehlhause and Oleksa.[3] Their determination of the flux of antineutrinos contains (in addition to an experimental measurement of the beta spectrum from a reactor) two assumptions:

(i) The distribution of beta decay end points is assumed to be a gaussian of the form $N(E_{max}) = \exp\ [-E^2_{max}/2(\triangle\ E_{max})^2]$ where the parameter $\triangle\ E_{max}$ is adjusted so that it yields the experimental beta spectrum.

(ii) The equilibrium spectrum of beta rays is assumed to be equal to that of the antineutrinos.

Adoption of (ii) of course limits the use of (i) to the extent that it is employed only for purposes of extrapolating the experimental beta spectrum to higher energies. At attempt to justify (ii) is made on the grounds that, in the energy range of interest (threshold = 1.8 Mev), both the electron and antineutrino are highly relativistic and share equally the energy available. In the present work this assumption has been found to be unsatisfactory. It is the mass effect and the coulomb effect that influence most strongly the <u>low</u> energy electrons; however, these electrons are associated with the <u>high</u> energy neutrinos which are, in turn, just those responsible for driving the reaction.

We have carried out the calculations in which assumption (i) is accepted along with the experimental beta spectrum given by Muelhause and Oleksa but in place of assumption (ii) we have calculated $N_{\bar{\nu}}(E)$ the sum of the individual antineutrino spectra which are complementary to the individual beta spectra whose end points give the proper gaussian distribution. The magnitude of the correction thus effected can be estimated by calculating the ratio,

$$I_{\bar{\nu}}/I_{\beta} = \left[\int N_{\bar{\nu}}\ (E)\ \sigma_p(E)\ d\ E\right] \Big/ \left[\int N_{\beta}(E)\ \sigma_p(E)\ d\ E\right]$$

where $I_{\bar{\nu}}$ is proportional to the reaction rate when a neutrino flux $N_{\bar{\nu}}$ is present and I_{β} is proportional to the reaction rate when a neutrino flux identical with the beta flux is present. The quantity σ_p, which is the cross-section for the inverse beta-decay of the neutron, can be expressed in terms of the comparative half-life (ft value) for the neutron as follows,

$$\sigma_p = \frac{\lambda^3 \ln 2}{2\pi c(ft)_{\text{neutron}}} (E_\nu - \Delta) \left[(E_\nu - \Delta)^2 - 1 \right]^{1/2} , \qquad (1)$$

where λ is the Compton wave length of the electron, E_ν is the antineutrino energy and Δ is the neutron-proton mass difference. Both E_ν and Δ are in units of electron rest masses.

A value of $I_{\bar{\nu}}/I_\beta \cong 1.6$ is found when the gaussian distribution of end points is assumed. A correction of 60% is thus necessary to the cross-section calculated from the measured beta spectrum if assumption (ii) is employed. If then, (a) we accept the beta spectrum determined by Muehlhause and Oleksa[6] (b) a gaussian distribution of end points is assumed and (c) the cross-section from the two component theory is employed, the predicted average cross-section per antineutrino emitted from the reactor is $\bar{\sigma}_p \cong 14 \times 10^{-44}$ cm^2. This is to be compared with the most recent experimental value[5] $\bar{\sigma}_p = 11 \pm 4 \times 10^{-44}$ cm^2.

LOWER LIMIT OF THE CROSS-SECTION FROM KNOWN DECAYS

In addition to the cross-section calculated from the experimental beta spectrum, we find it possible to establish a firm lower limit on the average cross-section from the known decays of the fission products. In a previous work on the energy release from fission products[7] it was necessary for us to collect all of the experimental data available on the decay of the fission products.[8] The decay schemes and yields included in the compilation accounted for 3.8 of the 6.1 betas/fission.[9] Fission yields were taken from the work of Katcoff[10] and Pappas.[11]

Because the distribution of beta-decay end points is known for these 3.8 betas/fission (see Fig. 1), it was possible to determine the complementary antineutrino spectrum associated with these decays taking into account the asymmetry caused by both the mass effect and the coulomb effect.

Of these 3.8 betas/fission it was found that 1.8 of the beta transitions had end points above threshold (1.8 Mev) for the reaction, and for this group we were able to calculate an average cross-section per antineutrino $\bar{\sigma}_{1.8 \text{ group}} \cong 10 \times 10^{-44}$ cm^2. It is reasonable to assume that virtually all of the neglected 2.3 betas/fission have end points above threshold, since the reason that they do not have determined decay schemes, is their short life time caused by high disintegration energies. Virtually all of the neglected decays belong to those nuclei far removed from stability with very large disintegration energies. It is thus a conservative statement to say that the average cross-section per antineutrino of this neglected group is larger than that of the known group. (Equation 1 shows the cross-section to increase rapidly with energy.) We may thus write the average cross-section per antineutrino for the entire 6.1 betas/fission as,

$$\bar{\sigma}_p > \frac{\bar{\sigma}_{1.8\ \text{group}}\,(1.8 + 2.3)}{6.1} \cong 7 \times 10^{-44}\ \text{cm}^2 .$$

This value then represents a firm lower limit to the cross-section. Because of the increase of σ_p with energy, it is felt that this is a conservative limit.

CROSS-SECTION FROM SUMMATION OF ALL DECAYS

In this section we make an attempt to estimate the contribution of the 2.3 betas/fission whose decay characteristics are not known in order to obtain an estimate of the beta and antineutrino spectrum from the reactor. Since we are interested in the antineutrino spectrum during operation, the 2.3 betas/fission that are not included in the known decays need only have their beta energies estimated without regard to half-life. Since it is realized that this task requires methods of rather questionable accuracy, we estimated the total disintegration energies for the unknown decays from two different sources.[12] It was necessary then to determine a correction factor δ to account for decays to excited states. For this purpose the types of decays were divided into six classes. Parity changes were determined from the strong-spin orbit coupling shell model.[13] The relative weighting of δ for the different classes was determined from a survey of known levels and the constant C is adjusted to give the proper total γ energy release[14] for all of the fission product decays. Fission yields and distributions were again taken from references 10 and 11.

The distribution of end points thus determined for Levy's and Cameron's mass differences are shown in Fig. 1. The predicted composite beta spectrum is then exhibited in Fig. 2 and compared to both the Meuhlhause and Oleksa experiment and a recent determination by the Los Alamos group.[15] The curve obtained from Levy's mass differences is seen to fall between the two experimental determinations. The agreement is perhaps better than should be expected. Cameron's mass differences give a beta spectrum that is weighted more toward the higher energies. The beta spectrum obtained from the known decays tabulated in reference 7 is also exhibited as a function of time after shutdown of the reactor.

Table I

Classification of Beta Transitions

A	Parity Change	Type	δ
Even	Yes	odd-odd → even-even	$C(\frac{6}{A})$
Even	Yes	even-even → odd-odd	$C(\frac{2}{A})$
Even	No	odd-odd → even-even	$C(\frac{3}{A})$
Even	No	even-even → odd-odd	$C(\frac{1}{A})$
Odd	Yes	---	$C(\frac{2}{A})$
Odd	No	---	$C(\frac{1}{A})$

Figure 3 shows the corresponding antineutrino spectra obtained and Table II gives a summary of results for the average cross-section per antineutrino from U^{235} fission products along with the corresponding total beta and anti-neutrino energy per fission. All calculated values fall within the experimental limits of error with the single exception of the cross-section obtained using Cameron's mass differences, but even in this case, a reasonable error on the calculated value could provide overlap.

Table II

Summary of Results:

Total beta and antineutrino energy per fission and cross section for $\bar{\nu} + P \rightarrow N + e^+$.

Basis of Calculations	$I_{\bar{\nu}}/I_\beta$	E_β* (Mev)	$E_{\bar{\nu}}$** (Mev)	σ_p (10^{-44} cm^2)
Lower limit from known decays	---	---	---	> 7
Muehlhause and Oleksa Gaussian	1.61	7.8	10.3	14
Known decays + Levy	1.61	7.4	9.9	10
Known decays + Cameron	1.47	8.8	11.3	19
Cowan-Reines Experiment	---	---	---	11 ± 4

* $E_\beta = \int E \cdot N_\beta (E)\, d E$. ** $E_{\bar{\nu}} = \int E \cdot N_{\bar{\nu}} (E)\, d E$.

CONCLUSIONS

It is concluded that the safest procedure for calculating the average cross-section to be compared with the Cowan-Reines experimental results is the method used in obtaining this cross-section from the experimental determination of the reactor beta spectrum. This is because $I_{\bar{\nu}}/I_\beta$ is reasonably insensitive to the shape of the beta spectrum and to the distribution of beta decay end points. A good measurement of the beta spectrum thus implies a good value for $\bar{\sigma}_p$. On the other hand, the lower limit from known decays plus estimates for the unknown decays give very reasonable agreement with the newly corrected experimental value of the average cross-section. On the basis of the above considerations, it can be said that experiment gives results that are no longer inconsistent with the two-component neutrino theory.

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REFERENCES

1. T. D. Lee and C. N. Yang, Phys. Rev. 105, 1671 (1957); A. Salam, Nuovo Cimento 5, 299 (1957); L. Landau, Nuclear Physics 3, 127 (1957); and H. Weyl, Z. Physik 56, 330 (1929).
2. Cowan, Reines, Harrison, Kruse, and McGuire, Science 124, 103 (1956).
3. C. O. Muehlhause and S. Oleksa, Phys. Rev. 105, 1332 (1957).
4. See Transactions Mid-West Conference on Theoretical Physics, St. Louis, Mo. (April 1958). See also R. W. King and J. F. Perkins, Bull. Am. Phys. Soc. 3, 205 (1958).
5. F. Reines, private communication. We are indebted to Dr. Reines for communicating this latest determination to us in advance of publication.
6. We use, however, the more usual value of 6.1 betas/fission as opposed to the 5 betas/fission suggested by Muehlhause and Oleksa, and employ a more recent ft value for the neutron decay, namely, ft = 1220.
7. J. F. Perkins and R. W. King, Nuclear Science and Engineering, in press.
8. This task was considerably lightened by the kind cooperation of Dr. C. L. McGinnis of the Nuclear Data Group, National Research Council, Washington, D. C.
9. For a complete listing see reference 7.
10. S. Katcoff, Nucleonics 16, 78 (1958).
11. A. C. Pappas, Geneva Conference Paper No. 881 (1955).
12. H. B. Levy, Phys. Rev. 106, 1265 (1957); A. G. W. Cameron, Chalk River Project-690 (1957).
13. M. G. Mayer and J. H. D. Jensen, "Elementary Theory of Nuclear Shell Structure," John Wiley and Sons, Inc., New York, 1955.
14. We have employed a value of 5.5 Mev. Peelle, Zobel, Love, and Maienschein, private communication, report a recently measured value of ~ 6 Mev.
15. R. E. Carter, F. Reines, J. J. Wagner, and M. E. Wyman, private comminucation.

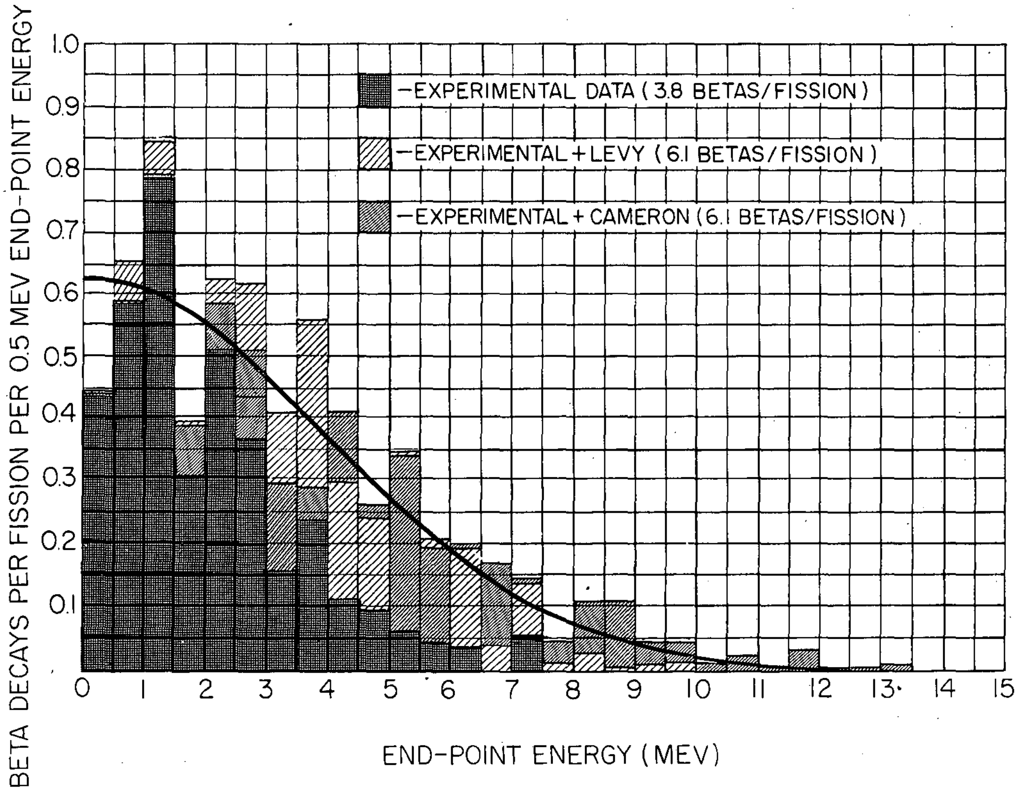

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Fig. 1. Distribution of Beta Decay End Points.

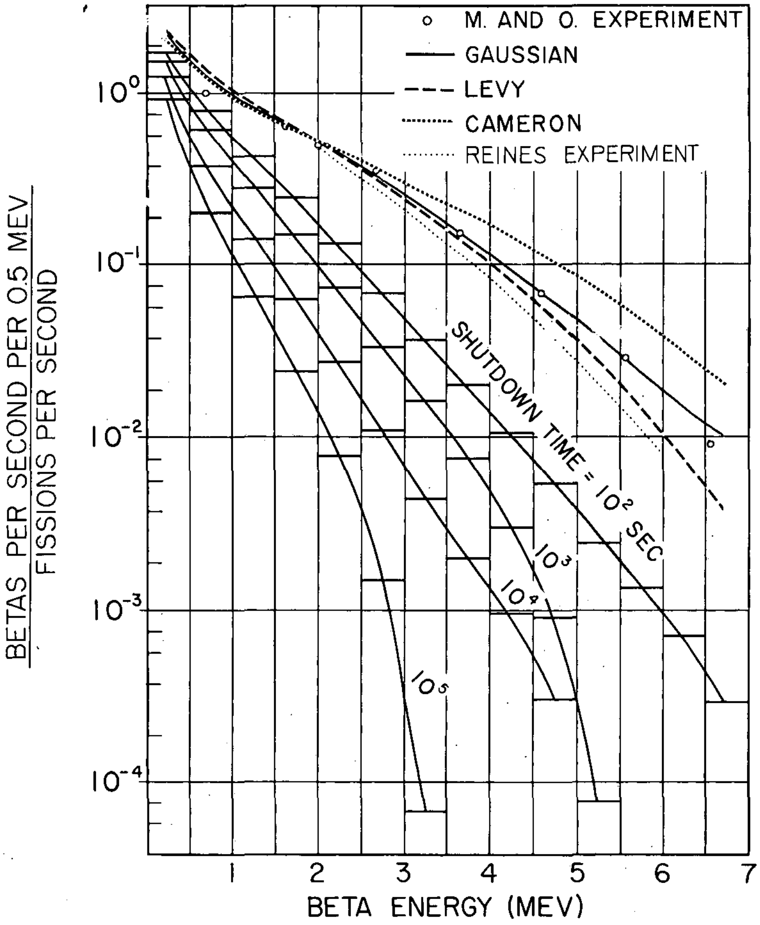

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Fig. 2. Energy Spectrum of Betas from U^{235} Fission Products. (Also included is the spectrum as a function of time after shut down of the reactor.)

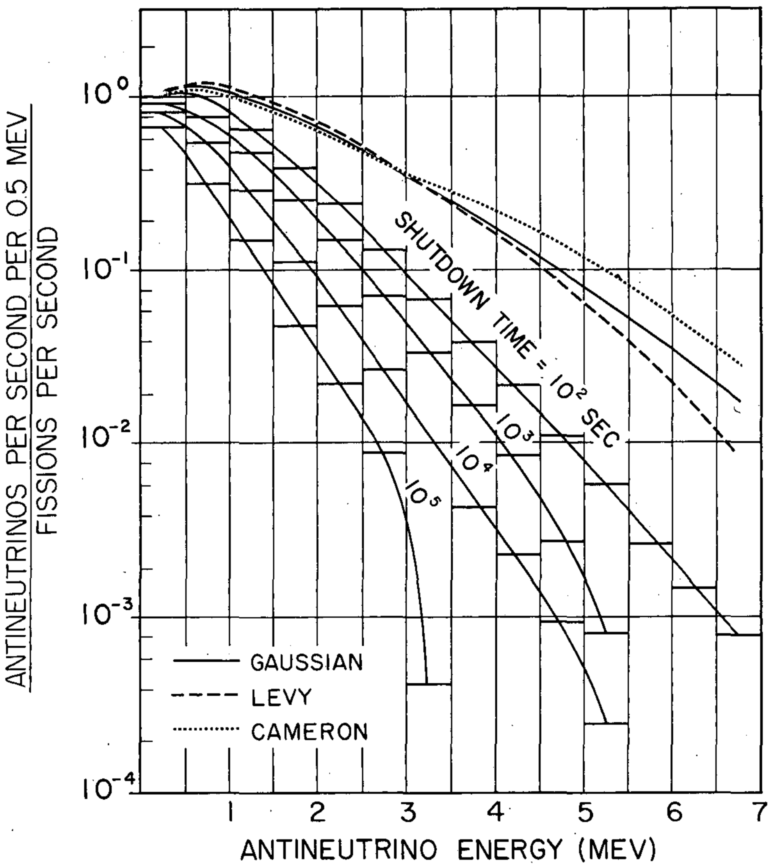

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Fig. 3. Energy Spectrum of Antineutrinos from U^{235} Fission Products. (Also included is the spectrum as a function of time after shut down of the reactor.)