fragments are not delayed-neutron precursors. This assumption is based upon the fact that the neutron binding energies of these light fragments are considerably greater than those of nuclei lying just above the closed shells at 50 and 82 neutrons[3] and is supported by the results of this experiment. The existence of delayed neutron precursors in the Cf^{252} light-fragment region would considerably complicate present interpretation of delayed-neutron phenomena, an interpretation that grows more complex as the experimental knowledge increases.[14]

ACKNOWLEDGMENT

The authors would like to thank Dr. L. Glendenin for his friendly advice and comments.

[14] L. Glendenin and E. Steinberg, *Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1955* (United Nations, New York, 1956), Paper P/614.

PHYSICAL REVIEW VOLUME 112, NUMBER 3 NOVEMBER 1, 1958

Inverse Beta Decay and the Two-Component Neutrino*

R. W. KING,† *Purdue University,‡ Lafayette, Indiana*

AND

J. F. PERKINS, *Lockheed Aircraft Corporation, Marietta, Georgia*

(Received July 14, 1958)

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 $\bar{\sigma}_p > 7\times10^{-44}$ cm² is deduced from the known decays of the fission products. Three different procedures, if weighted equally, give a "best value" of $\bar{\sigma}_p = 14\times10^{-44}$ cm² to be compared with the recently increased experimental value $\bar{\sigma}_p = 11\pm4 \times10^{-44}$ cm². It is concluded that predictions of the two-component neutrino theory are in accord with the experimental results on inverse beta decay.

INTRODUCTION

THE cross section for inverse beta decay provides a further test of the predictions of the two-component neutrino theory.[1] Prior 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.

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

* Work done under the auspices of the U. S. Atomic Energy Commission.

† Summer (1958) visitor at the University of California Radiation Laboratory, Berkeley, California which is operated under the auspices of the United States Atomic Energy Commission.

‡ Assisted in part by contract with the Air Force Office of Scientific Research.

[1] T. D. Lee and C. N. Yang, Phys. Rev. **105**, 1671 (1957); A. Salam, Nuovo cimento **5**, 299 (1957); L. Landau, Nuclear Phys. **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 *Proceedings of the Mid-West Conference on Theoretical Physics* (St. Louis, Missouri, March, 1958). See also R. W. King and J. F. Perkins, Bull. Am. Phys. Soc. Ser. II, **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.

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 $N(E_{\text{max}}) = \exp[-E_{\text{max}}^2/2(\Delta E_{\text{max}})^2]$, where the parameter ΔE_{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. An 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 *low*-energy electrons; however, these electrons are associated with the *high*-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 Muehlhause 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

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

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

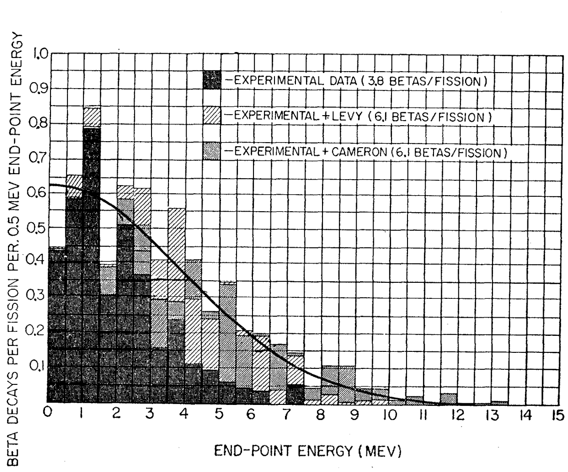

FIG. 1. Distribution of beta-decay end points.

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,

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

where λ is the Compton wavelength 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 $\bar{\sigma}_p \cong 14\times10^{-44}$ cm^2. This is to be compared with the most recent experimental value[5] $\bar{\sigma}_p = (11\pm4)\times10)^{-44}$ 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

[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 Sci. and Engr. **3**, 126 (1958).

[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**, No. 4, 78 (1958).

[11] A. C. Pappas, *Proceeding of the International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1955* (United Nations, New York, 1956), paper No. 881.

Mev) for the reaction, and for this group we were able to calculate an average cross section per antineutrino $\bar{\sigma}_{1.8\text{ group}} \cong 10\times10^{-44}$ cm². 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 lifetime 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. [Eq. (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,

$$\bar{\sigma}_p > \frac{\bar{\sigma}_{1.8\text{ group}}(1.8+2.3)}{6.1} \cong 7\times10^{-44}\text{ cm}^2.$$

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.

TABLE I. Classification of beta transitions.

A	Parity change	Type	δ
Even	Yes	odd-odd→even-even	$C(6/A)$
Even	Yes	even-even→odd-odd	$C(2/A)$
Even	No	odd-odd→even-even	$C(3/A)$
Even	No	even-even→odd-odd	$C(1/A)$
Odd	Yes	···	$C(2/A)$
Odd	No	···	$C(1/A)$

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 as shown in Table I. 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.

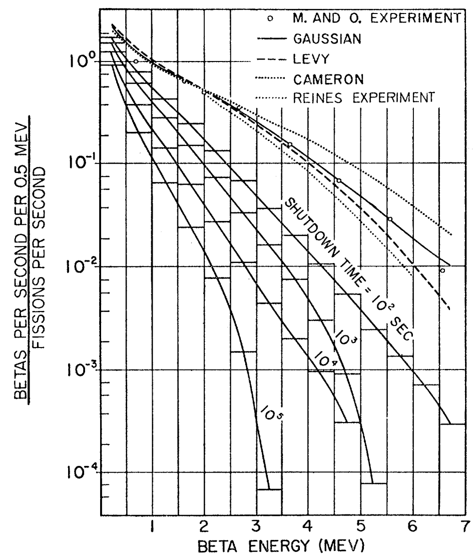

FIG. 2. Energy spectrum of betas from U[235] fission products. (Also included is the spectrum as a function of time after shut down of the reactor.)

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 Muehlhause 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.

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 antineutrino 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.

[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] Carter, Reines, Wagner, and Wyman (private communication).

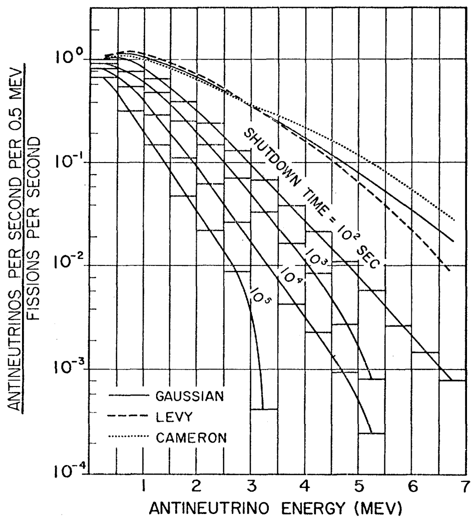

FIG. 3. Energy spectrum of antineutrinos from U^{235} fission products. (Also included is the spectrum as a function of time after shut down of the reactor.)

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.

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[a] (Mev)	$E_{\bar{\nu}}$[b] (Mev)	σ_p (10^{-44} cm²)
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

a $E_\beta = \int E N_\beta(E)dE$.
b $E_{\bar{\nu}} = \int E N_{\bar{\nu}}(E)dE$.

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.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge our debt to Dr. J. C. Flack of Lockheed Aircraft Corporation for his generous assistance in making this work possible. The authors also express their thanks to M. O. Burrell and G. E. Duncan for their help in carrying out the calculations.

PHYSICAL REVIEW VOLUME 112, NUMBER 3 NOVEMBER 1, 1958

Search for Electric Monopole Pairs from the 3.82-Mev State of Ca^{48}†

K. E. EKLUND AND R. D. BENT*
Columbia University, New York, New York
(Received July 15, 1958)

A search was made for 3.82-Mev electric monopole pairs from the reaction $Ca^{48}(p,p')Ca^{48*}$ using a $CaCO_3$ (35% Ca^{40}, 62% Ca^{48}) target, 6.0-Mev protons, and an intermediate-image spectrometer. No 3.82-Mev pairs from Ca^{48} were observed with an intensity as great as 0.3% that of the 3.35-Mev electric monopole pairs from Ca^{40}. This result suggests that the 3.82-Mev state of Ca^{48} decays predominantly by gamma emission. This could occur if the 3.82-Mev state has spin >0, or if there are lower excited states in Ca^{48}.

I. INTRODUCTION

THE first excited state of the doubly closed shell Ca^{48} nucleus is thought to be at 3.82 Mev.[1] This is unusually high for a first excited state, which suggests that it may have 0^+ spin and parity like the first excited states of O^{16} and Ca^{40}. If this is the case, then single gamma emission to the 0^+ ground state is forbidden, and the state should decay by pair emission.

A previous search was made[2] for electric monopole pairs from the 3.82-Mev state of Ca^{48} using a scintillation pair spectrometer.[3] No strong 3.8-Mev pairs were observed; however, because of the poor resolution of this spectrometer (31% at 3.35 Mev), weak 3.8-Mev pairs would have been obscured by strong 3.35-Mev pairs from Ca^{40}. This experiment has therefore been repeated with better resolution using an intermediate-image pair spectrometer.

† Work partially supported by the U. S. Atomic Energy Commission.
* Now at Indiana University, Bloomington, Indiana.
[1] C. M. Braams, thesis, Utrecht, 1956 (unpublished).

[2] Kruse, Bent, and Eklund, Bull. Am. Phys. Soc. Ser. II, 2, 29 (1957).
[3] R. D. Bent and T. H. Kruse, Phys. Rev. 109, 1240 (1958).