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Weak neutral disintegration of the deuteron by reactor antineutrinos*

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The spectrum of antineutrinos emitted by beta decaying products of ^{235}U in secular equilibrium has been recalculated using more recent experimental decay-scheme data. The new data involve 26 nuclides with 150 β branches and represent 22% of the total fission yield. The cross section for the reaction $\bar{\nu}_e + d \to p + n + \bar{\nu}_e$, which proceeds only via the weak neutral current, is shown to be predicted consistently by three theoretical treatments in the literature. The total cross section was calculated by weighting the cross section by the normalized antineutrino spectrum and is 7.4×10^{-45} cm^2.

I. INTRODUCTION

The Lorentz and isospin character of the weak neutral current is of fundamental interest at present mainly because neutral currents are natural consequences of the various gauge theories of weak and electromagnetic interactions (see, for example, Refs. 1–3). There are several experimental examples in which the observation of weak neutral processes were made using high-energy muon neutrinos. A well-known example is the elastic scattering of nucleons via the reaction $p(\nu_\mu,\nu_\mu)p$.[4] The disintegration of the deuteron by electron-antineutrinos via the reaction,

$$\bar{\nu}_e + d \to n + p + \bar{\nu}_e \,, \tag{1}$$

which can only occur via the weak neutral current was proposed by King and Ahrens, and by Gaponov and Tyutin.[5] Also, total cross sections have been calculated for reactor antineutrinos (see, for example, Ref. 6). Recently the measurement of the cross section for this reaction was experimentally shown to be feasible[7]; hence, the theoretical prediction of the total cross section based on a reliable antineutrino spectrum becomes important.

There are fundamental reasons why the cross section for reaction (1) with low-energy antineutrinos should be carefully measured. The actual quantity determined by such a measurement would be the axial-vector coupling constant associated with the semileptonic weak interaction of the neutral components of the isovector currents. This measurement would be to neutral currents what the measurement of the axial-vector coupling constant in the decay of ^{12}B, for example, is to charge-exchange currents. High-energy neutrino experiments are not nearly as reliable for the determination of a coupling constant, since induced tensor interactions, momentum-transfer-dependent form factors, and the presence of both vector and axial-vector interactions seriously complicate the interpretation. In the low-energy limit only the isovector axial-vector matrix element contributes, allowing the direct determination of that coupling constant alone.[6,8]

The prediction of the total cross section requires an accurate knowledge of the spectrum of antineutrinos from the β decays of the equilibrium fission products within the core of the source reactor. The total cross section can be defined as follows:

$$\bar{\sigma} \equiv \int_0^\infty \sigma(q)P(q)dq \,, \tag{2}$$

where $\sigma(q)$ is the reaction cross section for an incident antineutrino of energy q and $P(q)dq$ is the probability that any given antineutrino will have energy between q and $q+dq$. The quantity $P(q)$ is simply obtained from the antineutrino spectrum $N(q)$, discussed below, by straightforward normalization. The antineutrino spectrum given in this paper is a new version of our earlier spectra[9,10] and contains detailed decay-scheme information updated to early 1977. There is an increase of about 12% in the predicted value of $\bar{\sigma}$ when the present spectrum is used over that quoted in Ref. 6 which was calculated with the spectrum given in Ref. 9. This change is larger than the 10% accuracy which is predicted in the recently completed feasibility study described in Ref. 7. There are two recent conflicting values of $\bar{\sigma}$ in the literature, although both were calculated with the spectrum given in Ref. 9. Ahrens and Lang[6] give the value $\bar{\sigma}=6.5\times10^{-45}$ cm^2, while Gurr *et al.*[11] give a value of $\bar{\sigma}=4.4\times10^{-45}$ cm^2 based on the theoretical calculations of Gapanov and Tyutin.[5] The theoretical cross section of Gapanov and Tyutin, and of King and Ahrens were both weighted with the antineutrino spectrum again in the present work, and were found to give the same value of $\bar{\sigma}=6.5\times10^{-45}$ cm^2 when weighted by the spectrum of Ref. 9, and the value of $\bar{\sigma}=7.4\times10^{-45}$ cm^2 when weighted by the updated spectrum given in this paper. We have also looked in detail at the results of the most recent theoretical treatment of this problem,[8] and it is easily shown that with a simple but important correction, both the differential and total cross sections of Ref. 8 are practically the same as those given in Refs. 5 and 6 when considered at low energy. An experimental upper limit on the cross section of $\bar{\sigma}=2.64\times10^{-44}$ cm^2 is given in Ref. 11 which is a factor of 3.6 greater than the present theoretical value. This factor was quoted as 6 based on the theoretical total cross section ($\bar{\sigma}=4.4\times10^{-45}$ cm^2) quoted in Ref. 11. We believe this latter value of $\bar{\sigma}$ to be in error.

II. THE THEORETICAL CROSS SECTION

In the two theoretical treatments of the antineutrino disintegration of the deuteron given by King and Ahrens, and by Gapanov and Tyutin,[5] the same general form of the Hamiltonian was used in which charge independence could be easily incorporated. In addition, the same allowed approximation was made which results in only the isovector, axial-vector interaction contributing through the matrix element of $\tau_3\vec{\sigma}$. In addition, the D-state contribution was neglected in the deuteron wave function in both of these treatments. The work by Gapanov and Tyutin[5] included a finite range correction, while such a correction was also included in the later work of Ahrens and Lang.[6] It is not surprising then that the differential cross sections $d\sigma(q)/dE_k$, in nucleon energy E_k, can easily be shown to be identical. The differential cross sections of both Gapanov and Tyutin[5] and Ahrens and Lang[6] were integrated numerically over E_k and found to be in excellent agreement with the integrated cross section $\sigma(q)$ given in closed form in Ref. 6. All of these cross sections give a total cross section of $\bar{\sigma}=7.4\times10^{-45}$ cm^2 when folded into the present spectrum.

The calculations given in Ref. 8 are based on the theory of Weinberg and Salam, while in this case also the D-state contribution to the deuteron wave function was neglected. In the low-energy limit then the momentum-dependent form factors $F_1^{(3)V}=F_2^{(3)V}=0$ and the expression for $d\sigma(q)/dE_k$ given in their equation (2.15) should reduce to those given in Refs. 5 and 6. We find, however, that it does not, and, in fact, numerical integration of their differential cross section over E_k differs from their plot of $\sigma(q)$, given in their Fig. 2, by a constant factor. This factor is found to be $(1-\gamma r_{0t})^{-1}$, where $\gamma=(mE_d)^{1/2}=45.71$ MeV and in which m is the reduced nucleon rest-mass energy and E_d is the binding energy of the deuteron ($E_d=2.225$ MeV). The quantity r_{0t} is the triplet effective range ($r_{0t}=0.008\,666\,13$ MeV^{-1}). Apparently this factor was introduced in making the approximation that the nuclear force has a zero effective range in the final state but has a finite effective range in the bound deuteron state. This inconsistency leads to an extra factor of $(1-\gamma r_{0t})^{-1}$ in the differential cross section. Somehow this factor canceled in their analytical integration of $d\sigma(q)/dE_k$ over E_k, and the final result for $\sigma(q)$, plotted in their Fig. 2 of Ref. 8, is in agreement with the analytically integrated result of Ref. 6 and with the numerically integrated results of both Refs. 5 and 6. If the factor in question is removed and if the coupling constants are defined as in Ref. 6, the differential cross section of Ref. 8 can be written for low-energy antineutrinos, and for zero effective range, as follows:

$$\frac{d\sigma(q)}{dE_k}=\frac{2G^2}{\pi^2}\frac{m^{3/2}\gamma(\gamma a_s-1)^2E_k^{1/2}(q-E_d-E_k)^2}{(mE_ka_s^2+1)(\gamma^2+mE_k)^2}, \quad (3)$$

which is in exact agreement with the corresponding results given in Refs. 5 and 6. In Eq. (3), a_s is the singlet scattering length (-0.1201 MeV^{-1}), and $G=2.769\times10^{-22}$ cm^2/MeV. We have numerically integrated Eq. (3) over E_k, which requires no further approximation, and found that it reproduces Fig. 2 of Ref. 8 and gives the same total cross section as given by the expressions in both Refs. 5 and 6.

III. THE ANTINEUTRINO SPECTRUM

We have assumed, as in the earlier calculations,[9,10] that the antineutrino spectrum from a reactor core is that of the fission products of ^{235}U in secular equilibrium. The details of the general method of calculating the spectrum are given in Refs. 8 and 9 and will only be outlined here.

The number of antineutrinos of energy q per fission, per unit energy range, from the fission products in secular equilibrium is given by

$$N(q)=\sum_j Y_j(ZA)b_jP_j(q), \quad (4)$$

where $Y_j(ZA)$ is the total yield of the fission product of charge Z and mass A, which decays through the jth branch, b_j is the jth β branching ratio and $P_j(q)$ is the theoretical, allowed, Coulomb-corrected antineutrino spectrum normalized to give a total probability of unity. In the present work we have used an approximate relativistic Fermi function $F(q,Z,A)$ which is based on the original Bethe-Bacher approximation for the complex Γ function,[12] combined with the mass and finite-size correction factor used in Bhalla's more recent work.[13] A simplifying approximation is very important in this calculation because spectra of approximately 650 β decays are Coulomb corrected at each point for numerical integration which means $F(q,Z,A)$ is used about 10^5 times. An accurate, iterative procedure for calculating the complex Γ function for this many computations is extremely time consuming and would require a reduction in the accuracy of numerical integration. With the above approximation, the Fermi function can be written as follows:

$$F(\eta,Z,A)=\frac{4(1+S/2)}{[\Gamma(3+2S)]^2}\left(\frac{2R(A)}{\hbar/m_0c}\right)^{2S}\frac{2\pi y}{1-e^{-2\pi y}}\times\{\tfrac{1}{4}[(1+\eta^2)(1+4\gamma^2)-1]\}^S, \tag{5}$$

where $S+1=[1-(Z\alpha)^2]^{1/2}$, $\gamma=\alpha Z$, $y=\gamma(1+\eta^2)^{1/2}/\eta$, $R(A)=1.2\times10^{-13}A^{1/3}$ cm, and η is the electron momentum in units of m_0c. The approximation for the complex Γ function used above was shown earlier to be far superior to the nonrelativistic approximation.[14] We find, for example, that for 2-MeV electrons at $Z=90$, the difference between an accurate calculation of the relativistic Fermi function and the nonrelativistic approximation is 92%, whereas, for the above approximation, the difference is 5%. The resulting changes in the antineutrino spectrum are small but observable and represent the elimination of a source of systematic error.

The sources for the fission yields and charge distributions, and β-decay Q values used for predicting the β shapes of decays associated with products of unknown decay schemes, are the same as those used in Ref. 10. A search of the literature shows that the changes in these parameters are not nearly as important as the effects produced by the new spectroscopy data. In addition we need rely far less on the theoretical prediction of β end-point energies and branching ratios because only 27% of the total yield of fission products is associated with nuclides of unknown decay schemes, whereas in the earlier treatments of Refs. 9 and 10 this figure was 65% and 49%, respectively. The new spectroscopy data consist of 26 new decay schemes containing 150 β branches and represent 22% of the total fission yield. The resulting fission spectrum of antineutrinos is shown in Fig. 1 and is also given in Table I for computational purposes along with the uncertainties propagated from uncertainties in the input data.

The quoted uncertainties are obtained by varying the values of the yields, β-decay Q values and charge distributions over their ranges of uncertainty and calculating the shift $\delta_i(q)$ in the spectrum of the ith β branch at energy q. The total uncertainty due to that parameter is then given by

$$\delta N(q)=\left\{\sum a_i[\delta_i(q)]^2\right\}^{1/2}, \tag{6}$$

where a_i is proportional to the product of the branching ratio and yield. These uncertainties for the errors in the various sets of parameters are then combined as independent errors.

IV. SUMMARY AND CONCLUSIONS

It can be argued that the measurement of the cross section for the disintegration of the deuteron, by low-energy electron antineutrinos, can independently yield the value of the isovector, axial-vector coupling constant of the weak neutral current. It was shown above that the differences in the total cross section $\bar{\sigma}$ given in Refs. 6 and 11, using the results of the earlier theoretical treatments of Refs. 5 and 6, are in fact the result of an error and that both predict the value given in Ref. 6 when the older antineutrino spectrum[9] is used. When the present spectrum is used, a value of $\bar{\sigma}=7.4\times10^{-45}$ cm^2 is predicted using the numerically integrated, differential cross sections

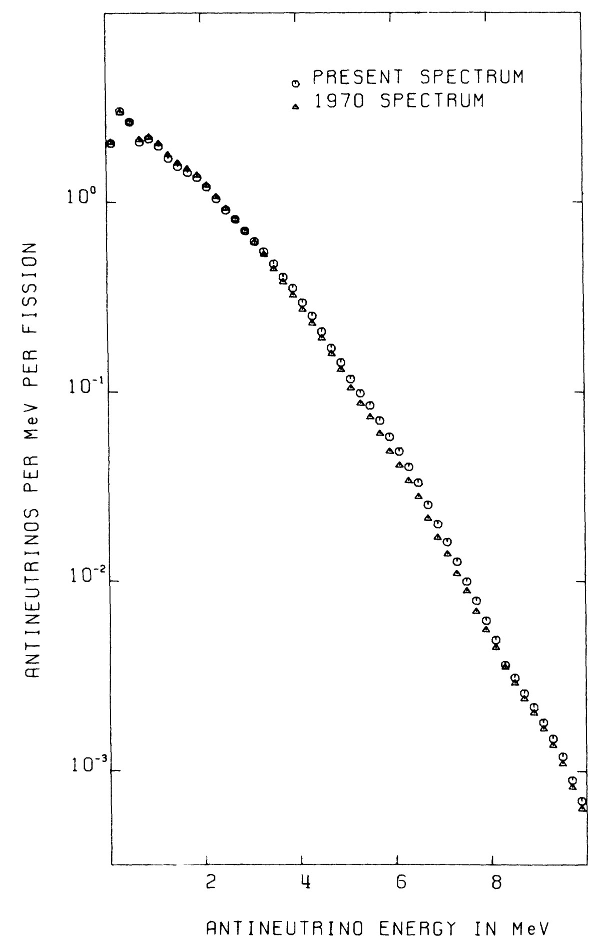

FIG. 1. Theoretical fission spectrum of antineutrinos.

TABLE I. Theoretical spectrum of antineutrinos from ^{235}U fission products in secular equilibrium. $N(q)$ is given in antineutrinos per MeV per fission.

q (MeV)	$N(q)$	q (MeV)	$N(q)$
0.2	3.87 ± 0.21	5.6	$(7.80 \pm 0.32) \times 10^{-2}$
0.4	2.80 ± 0.15	5.8	$(6.46 \pm 0.26) \times 10^{-2}$
0.6	1.98 ± 0.11	6.0	$(5.30 \pm 0.22) \times 10^{-2}$
0.8	2.12 ± 0.12	6.2	$(4.41 \pm 0.18) \times 10^{-2}$
1.0	2.06 ± 0.11	6.4	$(3.64 \pm 0.15) \times 10^{-2}$
1.2	1.90 ± 0.12	6.6	$(2.90 \pm 0.09) \times 10^{-2}$
1.4	1.59 ± 0.10	6.8	$(2.25 \pm 0.07) \times 10^{-2}$
1.6	1.47 ± 0.09	7.0	$(1.79 \pm 0.05) \times 10^{-2}$
1.8	1.39 ± 0.08	7.2	$(1.45 \pm 0.04) \times 10^{-2}$
2.0	1.27 ± 0.08	7.4	$(1.15 \pm 0.03) \times 10^{-2}$
2.2	1.13 ± 0.08	7.6	$(8.98 \pm 0.23) \times 10^{-3}$
2.4	$(9.78 \pm 0.60) \times 10^{-1}$	7.8	$(6.87 \pm 0.18) \times 10^{-3}$
2.6	$(8.60 \pm 0.52) \times 10^{-1}$	8.0	$(5.54 \pm 0.14) \times 10^{-3}$
2.8	$(7.65 \pm 0.52) \times 10^{-1}$	8.2	$(4.40 \pm 0.11) \times 10^{-3}$
3.0	$(6.57 \pm 0.47) \times 10^{-1}$	8.4	$(3.35 \pm 0.08) \times 10^{-3}$
3.2	$(5.86 \pm 0.42) \times 10^{-1}$	8.6	$(2.81 \pm 0.07) \times 10^{-3}$
3.4	$(5.11 \pm 0.36) \times 10^{-1}$	8.8	$(2.36 \pm 0.06) \times 10^{-3}$
3.6	$(4.41 \pm 0.31) \times 10^{-1}$	9.0	$(1.97 \pm 0.05) \times 10^{-3}$
3.8	$(3.76 \pm 0.27) \times 10^{-1}$	9.2	$(1.64 \pm 0.04) \times 10^{-3}$
4.0	$(3.23 \pm 0.23) \times 10^{-1}$	9.4	$(1.33 \pm 0.05) \times 10^{-3}$
4.2	$(2.72 \pm 0.19) \times 10^{-1}$	9.6	$(1.06 \pm 0.06) \times 10^{-3}$
4.4	$(2.28 \pm 0.16) \times 10^{-1}$	9.8	$(7.95 \pm 0.49) \times 10^{-4}$
4.6	$(1.91 \pm 0.14) \times 10^{-1}$	10.0	$(6.05 \pm 0.38) \times 10^{-4}$
4.8	$(1.57 \pm 0.11) \times 10^{-1}$	10.2	$(4.46 \pm 0.28) \times 10^{-4}$
5.0	$(1.30 \pm 0.09) \times 10^{-1}$	10.4	$(3.05 \pm 0.19) \times 10^{-4}$
5.2	$(1.09 \pm 0.08) \times 10^{-1}$	10.6	$(1.89 \pm 0.12) \times 10^{-4}$
5.4	$(9.17 \pm 0.65) \times 10^{-2}$		

$d\sigma(q)/dE_k$ of either Gapanov and Tyutin[5] or of Ahrens and Lang.[6] The low-energy limit of a recent treatment of the antineutrino disintegration of the deuteron in the framework of Weinberg and Salam theory, given by Ali and Dominguez,[8] was also investigated. It was found that their differential cross section $d\sigma(q)/dE_k$, when numerically integrated over E_k, did not reproduce their plot of $\sigma(q)$ until an erroneous factor of $(1-\gamma r_{0t})^{-1}$ was removed. Their differential cross section then is internally consistent and at low energy is equivalent to the zero-effective-range results given in the articles of Ref. 5.

Finally, an improved version of the spectrum of antineutrinos from the fission products of ^{235}U in secular equilibrium is presented. The improvement arises by including recently published, experimentally determined β-decay Q values and branching ratios of 150 β branches in 26 nuclei representing 22% of the total yield. In addition, a far more accurate approximation to the relativistic Fermi function was used in the calculation of each point of every individual antineutrino spectrum.

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