Interpretation of $\bar{\nu}$-e^- scattering with reactor antineutrinos*

F. T. Avignone, III and Z. D. Greenwood
Department of Physics and Astronomy, University of South Carolina, Columbia, South Carolina 29208
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Numerically evaluated integrals of the theoretical cross section averaged over the energy spectrum of antineutrinos from ^{235}U in secular equilibrium are presented. The three terms of the cross section were integrated separately to preserve the explicit dependence on C_A and C_V. An updated version of the antineutrino spectrum was used resulting in some noticeable differences from earlier versions. A reinterpretation of the 1976 experimental results of Reines and his co-workers is given.

The elastic scattering reaction $\bar{\nu} + e^- \to \bar{\nu} + e^-$ and its importance in testing gauge theories of leptons has been discussed by Chen and Lee[1] and by Abers and Lee.[2] References to earlier work can also be found in these articles. The recent negative results in the search for parity violation in atomic transitions[3] may cause drastic changes in these theories. Accordingly, accurate knowledge of the $\bar{\nu}$-e^- scattering cross section will probably play an even more important role in the future in that it involves purely leptonic currents. Recently, Reines, Gurr, and Sobel[4] have reported the results of measurements of the cross section for $\bar{\nu}$-e^- scattering in a complex of plastic scintillators exposed to reactor antineutrinos. Their cross sections were presented as factors multiplied by the cross sections predicted earlier by one of us (F.T.A.), based on Feynman–Gell-Mann (FG) theory.[5] The calculations of Ref. 5 can be used to express the experimental cross sections of Ref. 4 in a more conventional way as follows: $\sigma_{\text{expt}}(1.5\text{–}3.0\text{ MeV}) = (7.6 \pm 2.2) \times 10^{-46}\text{ cm}^2$ and $\sigma_{\text{expt}}(3.0\text{–}4.5\text{ MeV}) = (1.86 \pm 0.48) \times 10^{-46}\text{ cm}^2$, where the energy ranges correspond to the observed ranges of electron recoil energy. Since the background interferences in these two ranges are different, these results can be treated to some degree as independent experiments. Examination of Fig. 2 of Ref. 4 leads to the conclusion that the experimental results corresponding to the energy range 1.5–3.0 MeV are outside of one standard deviation from agreement with FG theory and that if the experimental errors are reduced, without shifting the central values significantly, both sets of results may disagree with FG theory. This experimental effort has continued, with new and more accurate results due in the near future.[6]

The proper interpretation of these results requires an accurate knowledge of the energy spectrum of electron antineutrinos from the β decays of the fission products in the core of the source reactor. The details of the methods of calculating this spectrum were given in Ref. 5. That spectrum was based on our knowledge of β-decay energies, branching ratios, and nuclear energy levels reported by early 1970. Since then, a significant amount of nuclear spectroscopic data has appeared in the literature which we have analyzed and included in an updated antineutrino spectrum. The major source of uncertainty in the spectrum is introduced by using semiempirical mass formulas to predict the β-decay energies of isotopes whose decay schemes are not known. The results of the various mass formulas have been shown to be in disagreement with each other and in some cases with experiment[7]; hence it is highly desirable to recalculate the spectrum whenever a significant amount of new nuclear spectroscopic data allows less reliance on such approximations. Since the earlier spectrum of Ref. 5, new detailed spectroscopic data involving 26 nuclei containing 150 β branches and representing 22% of the total fission yield has appeared in the literature. The result is that the β energies, branching ratios, and decay schemes are known for isotopes which represent 73% of the yield of the fission products whereas only 35% were known in our earliest attempt in 1968.[8] The new data reduces the uncertainties in the spectrum significantly. The details of the current spectrum will be published elsewhere; however, the integrals over the spectrum needed to interpret $\bar{\nu}$-e^- scattering experiments are presented below.

The theoretical scattering cross section written explicitly in terms of the vector and axial-vector coupling constants C_V and C_A (Refs. 1, 2, 4) and integrated over the antineutrino spectrum, can be written in the following form:

$$\langle\sigma\rangle = \frac{G^2 M_e}{2\pi}\left[(C_V + C_A)^2 G_1(T_1, T_2) + (C_V - C_A)^2 G_2(T_1, T_2) + (C_V^2 - C_A^2) G_3(T_1, T_2)\right], \quad (1)$$

where the constants C_V and C_A are expressed in the theory of Weinberg and Salam as $C_V = 2\sin^2\theta_W + \frac{1}{2}$

TABLE I. Numerical integrals of the $\bar{\nu}$-e^-scattering cross section.

T_1 (MeV)	G_1	G_2	G_3
0.4	1.07 ± 0.07	$2.81 \pm 0.16 \times 10^{-1}$	$1.24 \pm 0.13 \times 10^{-1}$
0.6	$9.34 \pm 0.50 \times 10^{-1}$	$2.14 \pm 0.10 \times 10^{-1}$	$1.06 \pm 0.08 \times 10^{-1}$
0.8	$8.02 \pm 0.38 \times 10^{-1}$	$1.59 \pm 0.07 \times 10^{-1}$	$8.88 \pm 0.47 \times 10^{-2}$
1.0	$6.91 \pm 0.32 \times 10^{-1}$	$1.21 \pm 0.05 \times 10^{-1}$	$7.45 \pm 0.38 \times 10^{-2}$
1.2	$5.99 \pm 0.27 \times 10^{-1}$	$9.35 \pm 0.38 \times 10^{-2}$	$6.29 \pm 0.32 \times 10^{-2}$
1.4	$5.13 \pm 0.22 \times 10^{-1}$	$7.15 \pm 0.28 \times 10^{-2}$	$5.24 \pm 0.25 \times 10^{-2}$
1.6	$4.34 \pm 0.18 \times 10^{-1}$	$5.39 \pm 0.20 \times 10^{-2}$	$4.30 \pm 0.20 \times 10^{-2}$
1.8	$3.71 \pm 0.15 \times 10^{-1}$	$4.19 \pm 0.15 \times 10^{-2}$	$3.58 \pm 0.16 \times 10^{-2}$
2.0	$3.12 \pm 0.12 \times 10^{-1}$	$3.17 \pm 0.11 \times 10^{-2}$	$2.92 \pm 0.12 \times 10^{-2}$
2.2	$2.65 \pm 0.10 \times 10^{-1}$	$2.46 \pm 0.08 \times 10^{-2}$	$2.42 \pm 0.10 \times 10^{-2}$
2.4	$2.23 \pm 0.08 \times 10^{-1}$	$1.88 \pm 0.06 \times 10^{-2}$	$1.98 \pm 0.07 \times 10^{-2}$
2.6	$1.87 \pm 0.06 \times 10^{-1}$	$1.44 \pm 0.05 \times 10^{-2}$	$1.62 \pm 0.06 \times 10^{-2}$
2.8	$1.56 \pm 0.05 \times 10^{-1}$	$1.10 \pm 0.04 \times 10^{-2}$	$1.32 \pm 0.04 \times 10^{-2}$
3.0	$1.29 \pm 0.04 \times 10^{-1}$	$8.31 \pm 0.28 \times 10^{-3}$	$1.05 \pm 0.03 \times 10^{-2}$
3.2	$1.07 \pm 0.03 \times 10^{-1}$	$6.35 \pm 0.22 \times 10^{-3}$	$8.51 \pm 0.23 \times 10^{-3}$
3.4	$8.90 \pm 0.26 \times 10^{-2}$	$4.91 \pm 0.18 \times 10^{-3}$	$6.92 \pm 0.18 \times 10^{-3}$
3.6	$7.33 \pm 0.22 \times 10^{-2}$	$3.74 \pm 0.14 \times 10^{-3}$	$5.54 \pm 0.15 \times 10^{-3}$
3.8	$6.02 \pm 0.19 \times 10^{-2}$	$2.85 \pm 0.11 \times 10^{-3}$	$4.44 \pm 0.13 \times 10^{-3}$
4.0	$4.88 \pm 0.17 \times 10^{-2}$	$2.14 \pm 0.09 \times 10^{-3}$	$3.51 \pm 0.11 \times 10^{-3}$
4.2	$4.03 \pm 0.15 \times 10^{-2}$	$1.65 \pm 0.07 \times 10^{-3}$	$2.84 \pm 0.10 \times 10^{-3}$
4.4	$3.29 \pm 0.13 \times 10^{-2}$	$1.25 \pm 0.05 \times 10^{-3}$	$2.26 \pm 0.09 \times 10^{-3}$
4.6	$2.68 \pm 0.11 \times 10^{-2}$	$9.41 \pm 0.39 \times 10^{-4}$	$1.80 \pm 0.07 \times 10^{-3}$
4.8	$2.17 \pm 0.09 \times 10^{-2}$	$7.09 \pm 0.30 \times 10^{-4}$	$1.43 \pm 0.06 \times 10^{-3}$
5.0	$1.73 \pm 0.07 \times 10^{-2}$	$5.26 \pm 0.22 \times 10^{-4}$	$1.12 \pm 0.05 \times 10^{-3}$
5.2	$1.41 \pm 0.06 \times 10^{-2}$	$4.00 \pm 0.17 \times 10^{-4}$	$8.89 \pm 0.37 \times 10^{-4}$
5.4	$1.12 \pm 0.05 \times 10^{-2}$	$2.99 \pm 0.13 \times 10^{-4}$	$6.96 \pm 0.29 \times 10^{-4}$
5.6	$8.94 \pm 0.38 \times 10^{-3}$	$2.23 \pm 0.09 \times 10^{-4}$	$5.43 \pm 0.23 \times 10^{-4}$
5.8	$7.09 \pm 0.30 \times 10^{-3}$	$1.66 \pm 0.07 \times 10^{-4}$	$4.21 \pm 0.18 \times 10^{-4}$
6.0	$5.53 \pm 0.23 \times 10^{-3}$	$1.22 \pm 0.05 \times 10^{-4}$	$3.22 \pm 0.14 \times 10^{-4}$

and $C_A = \frac{1}{2}$. The quantities $G_i(T_1, T_2)$ are the integrals of the energy dependence of the cross section over the antineutrino spectrum and are given by

$$G_1(T_1, T_2) = \int_{T_1}^{T_2} \int_{\omega_1}^{\omega_2} P(\omega) d\omega dT, \quad (2)$$

$$G_2(T_1, T_2) = \int_{T_1}^{T_2} \int_{\omega_1}^{\omega_2} P(\omega)(1 - T/\omega)^2 d\omega dT, \quad (3)$$

$$G_3(T_1, T_2) = \int_{T_1}^{T_2} \int_{\omega_1}^{\omega_2} P(\omega) \frac{M_e c^2 T}{\omega^2} d\omega dT. \quad (4)$$

In the above expressions, T is the kinetic energy of the recoil electron while T_1 and T_2 represent the endpoints of the observed electron energy range and ω is the antineutrino energy with ω_1 being the minimum antineutrino energy which kinematically can scatter an electron with recoil energy T. The maximum antineutrino energy available in the spectrum is denoted by ω_2 and is 10.70 MeV in the present spectrum. The quantity $P(\omega)$ is the probability that a reactor antineutrino will have energy ω and is obtained by normalizing the spectrum. The results of the integrations are given in Table I.

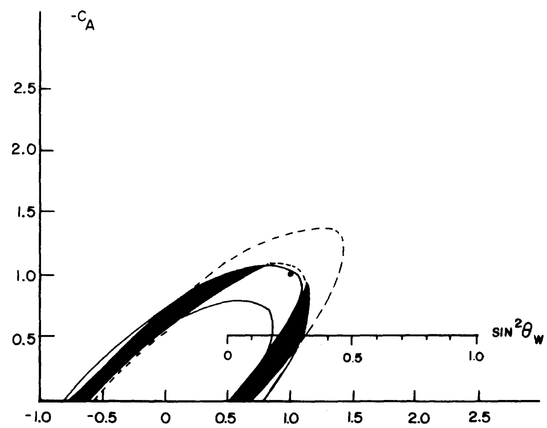

FIG. 1. Regions of the vector and axial-vector coupling-constant plane which are consistent with the present re-interpretation of the experimental results given in Ref. 4. The solid lines correspond to electron recoil energies over the range 1.5–3.0 MeV, while the dashed lines correspond to the range 3.0–4.5 MeV. The black region of the plane corresponds to values of C_A and C_V consistent with both sets of experimental results. The black dot at $C_V = -C_A = 1$ represents the prediction of FG theory.

The integrals given in Table I were used in Eq. (1) to determine combinations of the coupling constants C_A and C_V which are in agreement with the experimental data. The regions of the C_V-C_A plane which are in agreement with the experiment are shown in Fig. 1. This plot has small differences from that given in Ref. 4 and shows that the experimental results corresponding to the range of electron recoil from 3.0 to 4.5 MeV are in somewhat better agreement with FG theory than indicated in Ref. 4. In addition, the data when analyzed in the framework of the Weinberg-Salam model correspond to a value of $\sin^2\theta_W = 0.25 \pm 0.05$, compared to the value 0.29 ± 0.05 reported in Ref. 4 based on the calculations of Ref. 5, which indicates quantitatively that the recent changes in the spectrum alone are responsible for changes of about 16% in the values of $\sin^2\theta_W$ which are consistent with experiment. It is also apparent from Fig. 1 that a significant reduction in the experimental uncertainties may well result in the conclusion that the cross sections over both energy ranges are in disagreement with FG theory. In any case the calculations presented here should be used to interpret future experimental results.

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