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Neutrino oscillations and $\bar{\nu}_e$-e scattering

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$\bar{\nu}_e$-e scattering is modified in the presence of neutrino mixing and neutrino oscillation. In the Weinberg-Salam model the results for reactor antineutrinos are insensitive to the degree of mixing, to the extent that the experiment of Reines, Gurr, and Sobel cannot differentiate between no oscillation and complete disappearance of the electron antineutrinos from the beam.

There have been many recent suggestions of neutrino mixing and neutrino oscillations.[1-3] In this paper we point out that $\bar{\nu}_e$-e scattering is modified by neutrino mixing and oscillations, and reanalyze the $\bar{\nu}_e$-e scattering experiment of Reines, Gurr, and Sobel[4] to take account of this possibility.

In the presence of neutrino mixing and oscillations the electron antineutrino $\bar{\nu}_e$, the antineutrino produced with electrons in β decay at time $t=0$ has a probability $P_e(t)$ of being an electron antineutrino at some later time t, and probabilities $P_\mu(t)$, $P_\tau(t)$, ... of being a muon antineutrino ($\bar{\nu}_\mu$), tauon antineutrino ($\bar{\nu}_\tau$), etc.[1-3] Of course, at a fixed time t,

$$P_e(t)+P_\mu(t)+P_\tau(t)+\cdots=1\,. \tag{1}$$

Only the $\bar{\nu}_e$ can scatter from electrons via the charged-current process of Fig. 1, while all of the neutrinos can scatter via the neutral-current process of Fig. 2. If we restrict discussion to those theories of weak interactions in which lepton couplings to the Z_0 are the same for each generation, we can write for the electron-scattering cross section, differential in the recoil kinetic energy E,

$$\frac{d\sigma}{dE}=\Gamma\left[P_e(t)\,|M_1+M_2|^2+\sum_{l\neq e}P_l(t)\,|M_2|^2\right], \tag{2}$$

where Γ represents phase-space factors, and M_1 and M_2 are the matrix elements for Figs. 1 and 2, respectively. Using Eq. (1) we see that

$$\frac{d\sigma}{dE}=\Gamma[P_e(t)(|M_1|^2+2\,\mathrm{Re}M_1^*M_2)+|M_2|^2]\,. \tag{3}$$

It is then straightforward to adapt the standard calculations of $\bar{\nu}_e$-e scattering[5,6] to give

$$\frac{d\sigma}{dE}=\frac{G^2m_e}{2\pi}\left\{P_e(t)\left[4\left(1-\frac{E}{E_\nu}\right)^2+4\left((g_A+g_V)\left(1-\frac{E}{E_\nu}\right)+(g_A-g_V)\frac{m_eE}{2E_\nu^{\,2}}\right)\right]\right.$$
$$\left.+(g_A+g_V)^2\left(1-\frac{E}{E_\nu}\right)^2+(g_A-g_V)^2+\frac{m_eE}{E_\nu^{\,2}}(g_A^{\,2}-g_V^{\,2})\right\}\,, \tag{4}$$

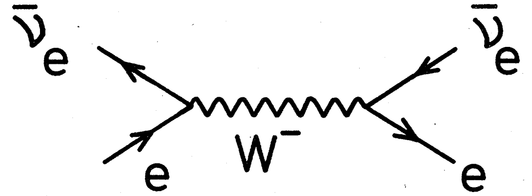

FIG. 1. $\bar{\nu}_e$-e scattering through the charged current.

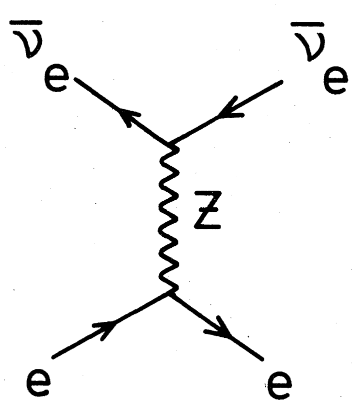

FIG. 2. $\bar{\nu}_e$-e scattering through the neutral current.

TABLE I. σ_{CC} and spectrum parameters β and γ.

	Avignone	Davis *et al.*	Reines *et al.*
	(a) 1.5–3 MeV		
σ_{CC}	4.97×10^{-45} cm^2/fission	3.94×10^{-45} cm^2/fission	
β	0.34	0.39	0.88 ± 0.23
γ	6.30	6.90	9.42 ± 1.51
	(b) 3–4.5 MeV		
σ_{CC}	0.59×10^{-45} cm^2/fission	0.44×10^{-45} cm^2/fission	
β	0.60	0.64	0.84 ± 0.17
γ	13.9	15.0	14.13 ± 4.27

where g_A and g_V are the neutral-current coupling constants. In the Weinberg-Salam model

$$g_V=-\tfrac{1}{2}+2\sin^2\theta_W\,,\quad g_A=-\tfrac{1}{2}\,, \tag{5}$$

and $P_e(t)$ is a function of E_ν and the neutrino masses and mixing angles.[1-3]

Reines, Gurr, and Sobel expressed their results in two energy bins for the scattered electron:

$$\begin{aligned}\sigma(1.5\text{–}3\text{ MeV})&=(0.87\pm0.25)\sigma_{CC}\,,\\ \sigma(3\text{–}4.5\text{ MeV})&=(1.70\pm0.44)\sigma_{CC}\,,\end{aligned} \tag{6}$$

where they used the Avignone spectrum[7] to obtain the charged-current results σ_{CC}.

Reines, Gurr, and Sobel set $P_e(t)=1$ (i.e., assuming no oscillations), and analyzed their data to extract g_A and g_V. We suggest that oscillations should be included in the analysis, in which case

$$\begin{aligned}\frac{\sigma(E_1,E_2)}{\sigma_{CC}}=P_e(t;E_1,E_2)[1&+g_A+g_V+(g_A-g_V)\beta]\\ &+\tfrac{1}{4}[(g_V+g_A)^2+2(g_A{}^2-g_V{}^2)\beta+(g_A-g_V)^2\gamma]\,,\end{aligned} \tag{7}$$

where we rely on the rapid cutoff in the antineutrino spectrum to replace the E_2 dependence of $P_e(t)$ with an appropriate average value:

$$\begin{aligned}\beta&=\frac{1}{\alpha}\int_{E_1}^{E_2}dE\int_{E_0(E)}^{\infty}dE_\nu\omega(E_\nu)\frac{m_eE}{2E_\nu{}^2}\,,\\ \gamma&=\frac{1}{\alpha}\int_{E_1}^{E_2}dE\int_{E_0(E)}^{\infty}dE_\nu\omega(E_\nu)\,,\end{aligned} \tag{8}$$

where

$$\alpha=\int_{E_1}^{E_2}dE\int_{E_0(E)}^{\infty}dE_\nu\omega(E_\nu)\left(1-\frac{E}{E_\nu}\right)^2$$

and $E_0(E)=\frac{1}{2}[E+(E^2+2m_eE)^{1/2}]$ is the smallest neutrino energy which gives electrons a recoil kinetic energy E.

The charged-current cross section is given by

$$\sigma_{CC}=\frac{G^2m_e}{2\pi}4\alpha\,. \tag{9}$$

We give values of the spectrum parameters β and γ and the charged-current cross section σ_{CC} in Table I for the Avignone 1970 neutrino spectrum[7] and the Davis *et al.* spectrum.[8] Note that β and γ are not sensitive to the choice of spectrum, while σ_{CC} is.

Using these values we note that we extract slightly different values of the Weinberg angle than Reines, Gurr, and Sobel extracted from their results, in the case when no oscillations occur. This is illustrated in Table II. We therefore determined from Eq. (7) with $P_e(t)=1$ the values of the parameters β and γ implied by the quoted results of Reines, Gurr, and Sobel using the method of least squares and also list these in Table I. It will be noted that these are different from the values we obtain by integrating over the spectrum. In the 1.5–3.0-MeV case the values of β and γ obtained by integrating over the spectrum differ significantly from the values inferred from Ref. 4. Similar calculations by Rosen and Kayser[9] and Barger, Cline, Whisnant, and Phillips,[10] of which

TABLE II. Values of $\sin^2\theta_W$.

	Spectrum		
Energy (MeV)	Avignone	Davis *et al.*	Reines *et al.*
1.5–3.0	$0.26^{+0.06}_{-0.07}$	$0.26^{+0.05}_{-0.07}$	$0.26^{+0.05}_{-0.06}$
3.0–4.5	0.31 ± 0.05	0.30 ± 0.05	0.32 ± 0.05

TABLE III. Values of A, B, and P.

	(i) $\sin^2\theta_W=0.22$			(ii) $\sin^2\theta_W=0.25$		
	Avignone	Davis *et al.*	Reines *et al.*	Avignone	Davis *et al.*	Reines *et al.*
			(a) 1.5–3.0 MeV			
A	0.29	0.27	0.054 ± 0.101	0.33	0.31	0.062 ± 0.110
B	0.43	0.46	0.64 ± 0.14	0.50	0.54	0.76 ± 0.16
P	1.53 ± 0.86	1.53 ± 0.93	4.20 ± 9.51	1.13 ± 0.76	1.07 ± 0.81	1.77 ± 9.13
			(b) 3.0–4.5 MeV			
A	0.18	0.16	0.07 ± 0.07	0.20	0.18	0.08 ± 0.09
B	0.83	0.88	0.87 ± 0.21	1.01	1.08	1.05 ± 0.27
P	4.97 ± 2.44	5.16 ± 2.75	11.9 ± 14.49	3.47 ± 2.20	3.44 ± 2.44	8.16 ± 10.80

we learned after completion of an earlier version of this paper, obtain, from slightly different spectra, results for β and γ consistent with ours.

In Table III we present a reanalysis of the data in the presence of oscillations. We write

$$\frac{\sigma}{\sigma_{CC}}=AP+B\,, \qquad (10)$$

and for values of $\sin^2\theta_W=0.22$ and 0.25, which are in the presently preferred region,[11] quote A and B for each of the three sets of spectrum parameters in the table, together with the value of P extracted from the data. We emphasize the extreme sensitivity of the parameter A to the value of β and reach the conclusion that there is no evidence for neutrino oscillations in the $\bar{\nu}_e$-e data of Reines, Gurr, and Sobel.

We conclude by noting that it would be most desirable for future data on $\bar{\nu}_e$-e scattering to be published in absolute units such as cm²/fission, and not relative to the calculated charged-current cross section which is sensitive to the spectrum. While Table III shows that the extraction of P from the data on σ/σ_{CC} is essentially independent of the choice of the Avignone or Davis *et al.* spectrum, this spectrum independence is artificial.

TABLE IV. Values of $\bar{A}$ and $\bar{B}$ (cm²/fission) and P.

	(i) $\sin^2\theta_W=0.22$		(ii) $\sin^2\theta_W=0.25$	
	Avignone	Davis *et al.*	Avignone	Davis *et al.*
	(a) 1.5–3.0 MeV			
$\bar{A}$	1.44×10^{-45}	1.06×10^{-45}	1.64×10^{-45}	1.22×10^{-45}
$\bar{B}$	2.14×10^{-45}	1.81×10^{-45}	2.49×10^{-45}	2.13×10^{-45}
P	1.52 ± 0.86	2.36 ± 1.17	1.12 ± 0.76	1.80 ± 1.02
	(b) 3.0–4.5 MeV			
$\bar{A}$	1.06×10^{-46}	7.04×10^{-47}	1.18×10^{-46}	7.92×10^{-47}
$\bar{B}$	4.90×10^{-46}	3.87×10^{-46}	5.96×10^{-46}	4.75×10^{-46}
P	4.83 ± 2.44	8.75 ± 3.69	3.45 ± 2.20	6.66 ± 3.28

Using our calculations with the Avignone 1970 spectrum we estimate the observed σ to be

$$\sigma(1.5\text{–}3\ \text{MeV})=(4.52\pm1.24)\times10^{-45}\ \text{cm}^2/\text{fission}\,,$$
$$\sigma(3\text{–}4.5\ \text{MeV})=(1.00\pm0.26)\times10^{-45}\ \text{cm}^2/\text{fission}. \qquad (11)$$

Writing $\sigma=\bar{A}P+\bar{B}$, we tabulate $\bar{A}$ and $\bar{B}$ in Table IV for the Davis *et al.* and Avignone spectra, and give the value of P extracted from the "data" of Eq. (11). The sensitivity to the neutrino spectrum is now apparent in discrepancies between corresponding values of P, $\bar{A}$, and $\bar{B}$ in Table IV.

To summarize, we have shown that there is no evidence for neutrino oscillations in the $\bar{\nu}_e$-e scattering data of Reines, Gurr, and Sobel. Given the value of the Weinberg angle, future experiments of increased sensitivity may provide information on $P_e(t)$. We would recommend that the cross sections measured in these experiments be published in absolute units.

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