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Neutrino oscillations and the modulation of neutrino-electron scattering

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Neutrino flavor oscillations modulate the cross section for neutrino-electron scattering. This modulation can seriously affect the interpretation of the present data on reactor-neutrino–electron scattering, and can greatly amplify the effective cross section for accelerator neutrinos.

Electronic neutrinos (ν_e) scatter elastically from electrons by means of both charged- and neutral-current interactions, whereas neutrinos of other flavors scatter through neutral currents alone. Consequently, neutrino flavor oscillations[1-3] involving electronic neutrinos will change the cross section for neutrino-electron scattering. Since the charged-current ν-e cross section is much larger than the neutral-current cross section,[4] this change can be appreciable.

To illustrate this effect, let us consider a beam which, at time t, is an admixture of electronic and muonic neutrinos:

$$|\nu(t)\rangle = \alpha(t)|\nu_e\rangle + \beta(t)|\nu_\mu\rangle\,, \tag{1}$$

where

$$|\alpha(t)|^2 + |\beta(t)|^2 = 1\,. \tag{2}$$

The lepton-family eigenstates are themselves linear combinations of the mass eigenstates ν_1 and ν_2.[1] As long as the masses of ν_1 and ν_2 are vanishingly small in comparison with the energy of the scattering process, and as long as both charged- and neutral-current interactions conserve lepton-family flavor, the cross section for the scattering of $\nu(t)$ by an electron will be

$$\sigma(\nu(t),e) = |\alpha(t)|^2\sigma(\nu_e,e) + |\beta(t)|^2\sigma(\nu_\mu,e)\,, \tag{3}$$

where $\sigma(\nu_e,e)$ and $\sigma(\nu_\mu,e)$ are the elastic cross sections for ν_e and ν_μ, respectively. Given that $\sigma(\nu_e,e)$ is larger than $\sigma(\nu_\mu,e)$,[4] it is obvious that if $\nu(t)$ is a pure ν_μ at time $t=0$, its cross section will increase once it has developed a ν_e component; and if $\nu(t)$ starts out as a pure ν_e, its cross section will decrease.

For a neutrino (or antineutrino) beam which is an admixture of many different flavors f,

$$|\nu(t)\rangle = \sum_f \alpha_f(t)|\nu_f\rangle\,, \tag{4}$$

Eq. (3) generalizes to

$$\sigma(\nu(t),e) = \sum_f |\alpha_f(t)|^2\sigma(\nu_f,e)\,. \tag{5}$$

However, if neutrinos couple universally to the neutral current, then all the cross sections for nonelectronic neutrinos are equal, and $\sigma(\nu(t),e)$ depends only on how the incoming flux is divided between electronic neutrinos and nonelectronic neutrinos.

For the effects of neutrino oscillations to be detected, the neutrinos must travel a distance at least of the order of their oscillation length before they scatter from an electron target. A recent experiment[2] suggests that neutrino oscillations do exist, and that they set a value on the mass difference $\Delta \equiv (m_1{}^2 - m_2{}^2)$ between the ν_1 and ν_2 mass eigenstates of approximately (1 eV)^2. Since this value of Δ corresponds to an oscillation length of 2.5 m for 1-MeV neutrinos, and since the oscillation length scales linearly with neutrino momentum, it seems most unlikely that experiments performed to date with the high-energy (>1 GeV), muon-type neutrinos available at large accelerators would have been sensitive to modulations of the neutrino-electron scattering cross section. Thus we are left with the experiments performed at reactors with low-energy ($\approx$1–4 MeV), electronic antineutrinos.[5]

But here we encounter a problem. Because $\bar{\nu}_e$-e elastic scattering involves both charged and neutral currents, it is sensitive to the interference between them. As we have shown elsewhere,[4] present data on this process are consistent with the prediction of destructive interference derived from the Weinberg-Salam model with $\sin^2\theta_W \approx \frac{1}{4}$ and no neutrino oscillations; however, they are not sufficiently accurate to rule out other possibilities including constructive interference and the absence of any coherent interference between charged and neutral currents. Since neutrino oscillations have the effect of reducing the $\bar{\nu}_e$ cross section, they can simulate a destructive interference even when it is not actually taking place, and thus they can

TABLE I. Theoretical reactor-neutrino cross sections as fractions of σ_{V-A}, the pure charged-current cross section without oscillations; $\langle\beta^2\rangle$ is the average admixture of "ν_μ" induced in the reactor beam by neutrino oscillations.

Case \ Electron energy	$1.5 \leq T \leq 3$ MeV	$3 \leq T \leq 4.5$ MeV
Destructive interference (Weinberg-Salam model, $\sin^2\theta = \frac{1}{4}$)	$0.83-0.32\langle\beta^2\rangle$	$1.21-0.21\langle\beta^2\rangle$
Constructive interference (two Z^0 bosons)	$2.20-1.68\langle\beta^2\rangle$	$2.76-1.77\langle\beta^2\rangle$
No coherent interference	$1.51-1.0\langle\beta^2\rangle$	$1.97-0.98\langle\beta^2\rangle$

lead one to misinterpret the experimental data.[5]

With this in mind, we reanalyze the theoretical predictions for the elastic scattering of reactor neutrinos in the presence of neutrino oscillations. In our earlier work[4] we considered three possibilities for the underlying weak-interaction Hamiltonian: (i) the Weinberg-Salam model with $\sin^2\theta_W \simeq \frac{1}{4}$, (ii) a model with at least two Z^0 bosons which gives the same results as (i) for lepton-quark neutral current, but leads to constructive interference in $\bar{\nu}_e$-e scattering[6], and (iii) no coherent interference between charged and neutral currents. The predicted cross sections were expressed as multiples of σ_{V-A}, the theoretical cross section in the appropriate energy range for the pure $(V-A)$ charged-current interaction with no neutrino oscillations. We consider the same three cases again, and we express the cross sections in units of the same σ_{V-A} as before; the results are given in Table I, where the parameter $\langle\beta_2\rangle$ represents the average fraction of "$\bar{\nu}_\mu$" that appears in the reactor neutrino beam as a consequence of oscillations. Here "$\bar{\nu}_\mu$" stands for an arbitrary mixture of $\bar{\nu}$ flavors not including $\bar{\nu}_e$.[7]

The coefficients of $\langle\beta^2\rangle$ in Table I are always negative for the general reasons already discussed in this paper, and their magnitudes indicate that the reduction of the cross section can be substantial. In the lower-energy bin, for example, it varies from 39% for one interference pattern to 77% for another when the neutrino makes a full oscillation into $\bar{\nu}_\mu$ (i.e., $\langle\beta^2\rangle = 1$). Theoretical values for fractional oscillations together with the present experimental data[5] are shown in Table II.

Unfortunately the data are not sufficiently accurate for us to determine the correct interference pattern, or the precise value of the oscillation parameter $\langle\beta^2\rangle$.[7] It is readily apparent from Table II that the greater the degree of oscillation, the closer the constructive interference case moves towards the data, and the further the Weinberg-Salam destructive case moves from it. If, for example, we take $\langle\beta^2\rangle = \frac{1}{2}$ and look at the predictions in the lower-energy bin in Table II, we find that the experimental data are within 2 standard deviations of all three interference cases. Alternatively we can assume the validity of the Weinberg-Salam model and try to use the data to set limits on $\langle\beta^2\rangle$. In the lower-energy bin, the central value of the cross section is very close to the predicted value without oscillations, and the values within 1 standard deviation cover the range $0 \leq \langle\beta^2\rangle \leq 0.66$ (see Table II). In the higher-energy bin, the 1-standard-deviation limit is incompatible with the Weinberg-Salam model, while the 2-standard-deviation limit allows the full oscillation range, $0 \leq \langle\beta^2\rangle \leq 1$. Obviously, no firm conclusions can be drawn at this time.

Another approach to this general question, and one which could be taken in future experiments, is to use accelerator neutrinos instead of reactor ones. The initial beams will then consist of muonic neutrinos, and oscillations will amplify the cross section for elastic scattering by electrons. From Eq. (3), the amplification factor is given (even when the oscillation involves many families)

TABLE II. Experimental and theoretical cross sections as fractions of σ_{V-A} and for various values of the average "$\bar{\nu}_\mu$" admixture, $\langle\beta^2\rangle$. If the oscillation involves two families, Ref. 2 favors $0.25 \leq \langle\beta^2\rangle \leq 0.40$. A maximal oscillation involving three families would correspond to $\langle\beta^2\rangle = \frac{2}{3}$.

Case \ Electron energy	$1.5 \leq T \leq 3$ MeV			$3 \leq T \leq 4.5$ MeV		
$\langle\beta^2\rangle =$	$\frac{1}{3}$	$\frac{1}{2}$	$\frac{2}{3}$	$\frac{1}{3}$	$\frac{1}{2}$	$\frac{2}{3}$
Destructive interference (Weinberg-Salam model $\sin^2\theta_W = \frac{1}{4}$)	0.72	0.67	0.62	1.13	1.1	1.06
Constructive interference	1.63	1.35	1.07	2.17	1.88	1.58
No coherent interference	1.17	1.01	0.84	1.64	1.48	1.32
Experimental data (Ref. 5)		0.87 ± 0.25			1.7 ± 0.44	

by

$$A \equiv \frac{\sigma(\nu(t)e)}{\sigma(\nu_\mu e)} = 1 + \langle\alpha^2\rangle \frac{\sigma(\nu_e e) - \sigma(\nu_\mu e)}{\sigma(\nu_\mu e)}, \tag{6}$$

where $\langle\alpha^2\rangle$ is the average fraction of electronic neutrinos introduced into the beam by oscillations. For the Weinberg-Salam model with $\sin^2\theta_W = \frac{1}{4}$, we find that[4]

$$A_{WS} = 1 + 6\langle\alpha^2\rangle, \tag{7a}$$

while for the constructive interference case with two Z^0 bosons, we have

$$A_{2Z} = 1 + 18\langle\alpha^2\rangle, \tag{7b}$$

and for no coherent interference

$$A_{NC} = 1 + 12\langle\alpha^2\rangle. \tag{7c}$$

Note that the amplification can be quite large. If $\langle\alpha^2\rangle = \frac{1}{3}$, for example, the amplification factor is 3 for the Weinberg-Salam model, and larger still for the other two cases. There are corresponding effects for an initial $\bar{\nu}_\mu$ beam, but the coefficients $\langle\alpha^2\rangle$ are down by a factor of 3. Finally, we remark that the observation of an amplified cross section for accelerator neutrinos would help rule out models in which "live" neutrinos such as ν_μ oscillate into "inert," or weak-isospin-singlet, neutrinos.[8]

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[7]Footnote added: Predictions in Tables I and II apply to experiments in which $(\Delta p_\nu/\langle p_\nu\rangle)x \gg l_{osc}(\langle p_\nu\rangle)$, where Δp_ν is the momentum spread of the reactor neutrinos, $\langle p_\nu\rangle$ is their mean momentum, x is the distance between the neutrino source and the detector, and l_{osc} is the oscillation length. When x is too short to satisfy this condition, no general tables such as I and II can be given because the reaction rates become x dependent. After the present paper was written, our attention was called to a new report by V. Barger, K. Whisnant, D. Cline, and R. J. N. Phillips [Report No. UW-COO-881-148 (unpublished)], which presents some $\bar{\nu}e$ results valid for small x, although specific to the Weinberg-Salam neutral current and an illustrative oscillation scheme with specific mixing angles. These results complement those in Tables I and II, and permit a somewhat more accurate comparison between theory and small-x experiments for certain theoretical cases. If $m_1^2 - m_2^2 \approx (1\text{ eV})^2$, the experiment of Ref. 5 is one for which the condition on x given above is not well satisfied, but we hope that experiments with larger x will be done in the future.

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