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"Evidence for Non-Standard Neutrinos"

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ABSTRACT

A review of the world sample of flux-normalized neutrino cross-sections collected over the past two decades is made in order to check for non-standard neutrino properties. This review shows evidence for such models, which have neutrino oscillations as a consequence. The world sample of neutrinos fails a test of constant slope of the cross-sections with energy at the 98% confidence level. Although this is not fatal to the standard theory, the parameterization of the cross-sections versus the length per unit energy (L/E), the "oscillation" parameter, shows that the world data are currently consistent with the existence of such oscillations for L/E values of, e.g., 5.5 or 15.5 m/GeV (or ΔM^2 of about 450 or 160 eV^2) with an amplitude of about +/- 5 percent.

PACs: 13.10.+q, 13.15.-f, 14.60.Gh and 95.30.Cq

INTRODUCTION

In the early 1970's, before the discovery of the tau lepton and the emergence of the Standard Model, the question of whether charged and neutral leptons exist in multiplets larger than doublets was raised; the Han-Nambu double-triplet models could incorporate this [1]. In addition, Majorana neutrino models that have two left-handed small mass states were advanced [2]. Early experimental attempts at resolving the first of these questions were inadequate[3]. Many flux-normalized experiments have been conducted since, and we review these here with a view to "updating" these questions. Notwithstanding the current success of the Standard Model with three families of leptons and quarks, it is the author's opinion that such possibilities be experimentally tested. Evidence supporting such possibilities is found, but proof would clearly require more statistically solid findings. As new rounds of neutrino experimentation with short- and long-baselines and high statistics are in process or envisoned for the next decade, it would seem prudent to put these non-standard hypotheses to crucial tests.

THE VARIOUS MODELS

Three examples of models leading to neutrino oscillations are:

1. the usual "flavor-changing" one,
2. the one case of Majorana neutrinos mentioned above

and 3. triplets of leptons, each with one charged lepton and two neutrinos.

As is well known, the standard neutrino oscillation formalism (for two neutrinos ν_1 and ν_2), leads to a "disappearance" probability $P = 1 - x^2y^2$ and an "appearance" probability of $p = x^2y^2$. Here $x^2 = \sin^2(2\theta)$, $y^2 = \sin^2[\pi(L/E)/(l/E)]$, where θ is the mixing angle, L is the actual flight distance (m) and $l = 2480\ E/\Delta M^2$ (m) is the standard oscillation length, for E in GeV and ΔM^2 in eV^2.

The true cross-sections, $\sigma(E,0)$, in the presence of oscillations, are given by the number of events (per unit of detector), N(t), at time t divided by the neutrino flux, F(t), at the same time t. But, the experimentally published ones assume no oscillations. Therefore the measured ones are "apparent" cross-sections, $\sigma(t)$, given by N(t) divided by F(0). Thus, $\sigma(t) = N(t)/F(0) = N(t)/[F(t)/P]$, or $\sigma(E,t) = P\,[N(t)/F(t)] = P\,\sigma(E,0)$. Allowing for different coupling strengths, in general, for ν_1 and ν_2 respectively, this leads to the "observable "cross-section for a beam of ν:

$$\sigma_1(E, L) = P\sigma_1(E, 0) + p\sigma_2(E, 0) \qquad (1a)$$

$$= \sigma_1(E, 0) - x^2y^2\{\sigma_1(E, 0) - \sigma_2(E, 0)\} \qquad (1b)$$

The flavor-changing scenario (case 1) has a small coupling, $x^2 < .005$, for muon neutrinos ν_μ, to electron or tau ones, ie ν_2, in the ΔM^2 range of a few hundred eV^2 in "appearance" experiments [4]. Here the magnitudes of $\sigma_1(E,0)$ and $\sigma_2(E,0)$ are expected to be equal. As we are looking for larger effects, as in other "disappearance" limits [4], we will not discuss this case further in this paper.

The Majorana neutrino (case 2) scenario with two light neutrinos [2], both left-handed, one in a doublet, ν ,(accompanying the muon in our case) and the other a singlet, η, leads to oscillations of the doublet neutrino to the (sterile) singlet one, that is $\sigma_1 = \sigma_\nu$ and $\sigma_\eta = 0$. Therefore, if one is looking only in the "disappearance" mode, this looks the same as the flavor-changing case. However here there is nothing to find in the "appearance" mode unlike the former.

Allowing for the lepton families as triplets [1], and assigning ν_μ to pion decays and λ_μ to kaon decays, ie.

$$\pi^+ \dashrightarrow \mu^+ \nu_\mu \qquad \text{and} \qquad K^+ \dashrightarrow \mu^+ \lambda_\mu \qquad (2).$$

We obtain two "beams" of neutrinos (the kaon and pion ones). Thus (1b), applied to both beams, becomes:

$$\sigma_1(\nu N) = \sigma_\nu(E,L) = \sigma_\nu(E,0) - x^2y^2 \{ \sigma_\nu(E,0) - \sigma_\lambda(E,0) \}$$

$$\sigma_2(\lambda N) = \sigma_\lambda(E,L) = \sigma_\lambda(E,0) + x^2y^2 \{ \sigma_\nu(E,0) - \sigma_\lambda(E,0) \} \qquad (3)$$

which gives σ_ν and σ_λ oscillating 180 degrees out of phase. We distinguish case 3a (3b) as to $\sigma_\nu(E,0)$ larger (smaller) than $\sigma_\lambda(E,0)$.

THE WORLD SAMPLE

During the 1970's and through the early 1980's, many bubble chamber and counter experiments have measured the total cross-sections of neutrinos and anti-neutrinos as a function of energy. The monitoring of the neutrino fluxes was accomplished by instrumentation placed in the hadron decay space and/or in the shielding to measure the hadron and/or muon fluxes. Then the (apparent) cross-sections were given as the number of events (at time t) divided by the measured flux (at time t=0), after various corrections and systematics are taken into account. The earlier experiments had statistical errors at the same level as the systematics; later experiments were dominated by systematics. These systematics are partially of an overall character, and partially of a character dependent on energy. By taking the errors in quadrature, one likely overestimates the total error, since this does not account for point-to-point correlations.

The neutrino charged current total cross-sections used are:

GGM-PS--CERN Gargamelle Bubble Chamber at Proton Synchrotron [5],
CITFR (E21)--Cal-Tech, Fermilab, Rochester Electronic Experiment [6],
FNAL-E254--CITFR, Brookhaven, Purdue Experiment [3,7],
BEBC--CERN's Big European Bubble Chamber Experiment [8],
CDHS--CERN, Dortmond, Heidelberg, Saclay Electronic Experiment [9],
CHARM--CERN's CHARM Electronic Detector Experiment [10],
GGM-SPS--Gargamelle at the Super Proton Synchrotron [11],
BNL-7-ft BC--Brookhaven's 7-foot Bubble Chamber Experiment [12],
FNAL15-ft BC Fermilab15-ft Bubble Chamber Experiments [13,14,15]
CFRR(R)-(E616)--Fermilab's E-616 Electronic Experiment [16],
CDHSW--CDHS and Warsaw Electronic Experiment [17],
and CCFR-(E701)--Fermilab's E-701 Electronic Experiment [18].

The values of the cross-sections (σ) divided by energy (E), ie σ/E +/- $d\sigma/E$, the decay space distancess (D) and the center-to-center lengths from decay to detector (L) are found in the above references. Together with the earlier CITFR and CDHS results, these data comprise most of the Particle Data Group (PDG) set [4,19]. They are plotted versus energy in Figure 1a, and versus L/E in Figure 1b. The observed "scatter" of the higher energy data in Figure 1a takes on an "organized" form suggestive (at low L/E) of "oscillations," in Figure 1b. In order to see this more clearly, we present "weighted-averages," grouped six-at-a-time, sorted by their L/E values, in Figure 2. The confidence levels of fits to a constant value (0.655) are 2 and 0.2% for Figures 1 and 2 respectively. These values probably bracket the truth, since, as mentioned above, the errors shown of Figure 1 are likely overestimated, while the "weighted" errors of Figure 2 are probably somewhat small.

OSCILLATION ANALYSES OF THE CROSS-SECTIONS

Before doing fits to the oscillation hypotheses, we present the CITFR/CCFR and CDHS/CDHSW data sets separately in Figures 3a and 3b respectively. These data also suggest an "oscillation" scenario; we choose to treat such a possibility seriously, although it may turn out, subsequently, that it is all due to additional "systematics" [19].

We proceed to fit the oscillation scenario. The flight paths of the neutrinos vary considerably because of the length of the decay spaces (D). In addition, there is a spread in the energy of the neutrinos at each data point. Therefore, the "oscilllations" will "smear" out as the neutrinos "travel" a longer or shorter L/E; the average $D/(12^{1/2} L)$ for the various experiments is 0.12. The pion and kaon neutrinos also have different "smearing"

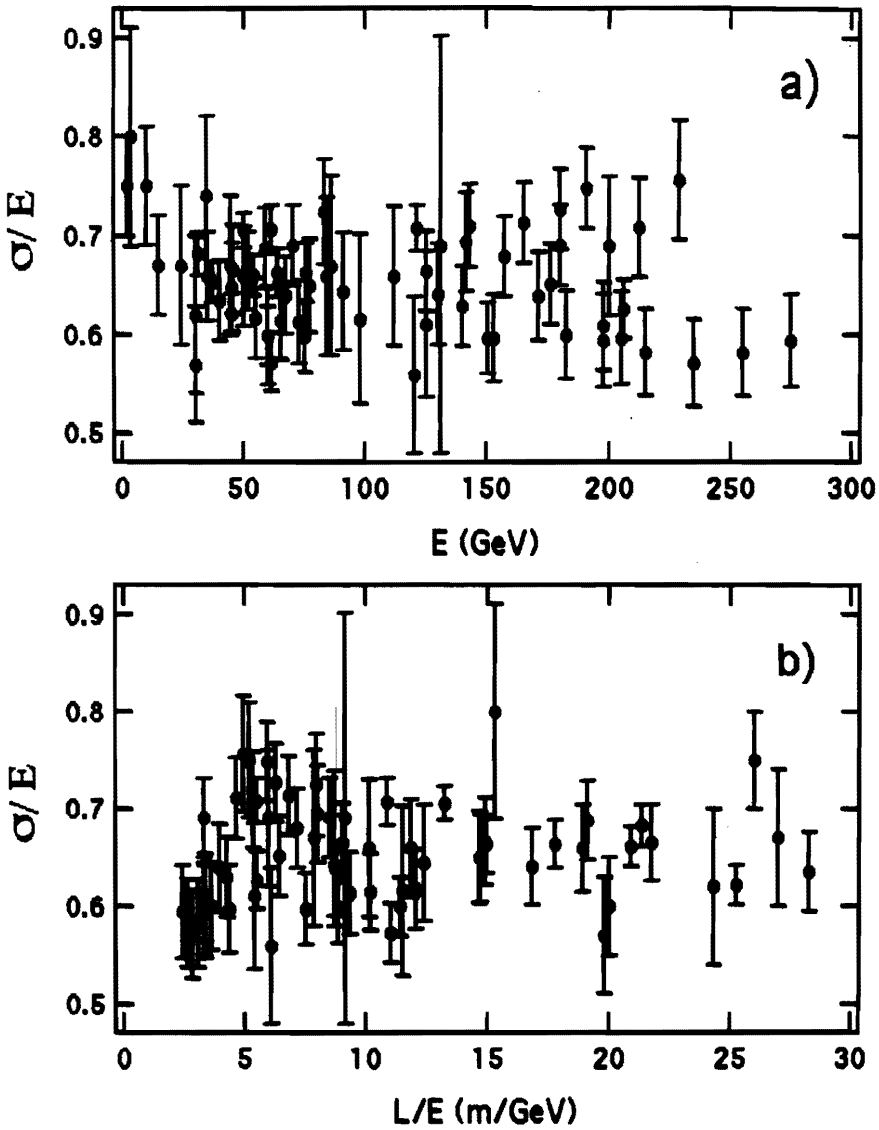

Figure 1. Neutrino cross-section slopes (σ/E in units 10^{-38} cm^2/GeV) versus a) energy (GeV) and b) L/E (m/GeV), the "oscillation" parameter.

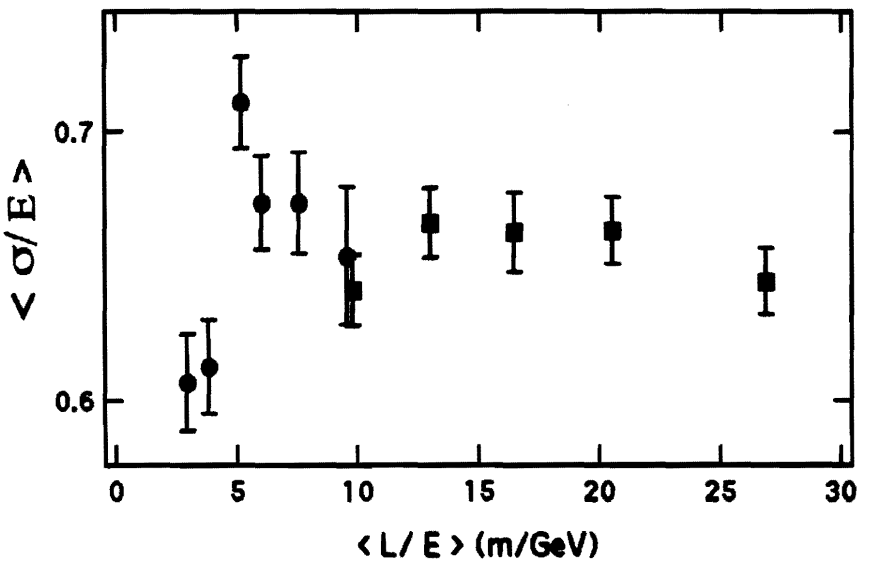

Figure 2. Cross-section slope versus L/E for data of Fig. 1b grouped by a weighted-averaging of the data taken six-at-a-time (see text; dots/squares are kaon/pion neutrinos respectively).

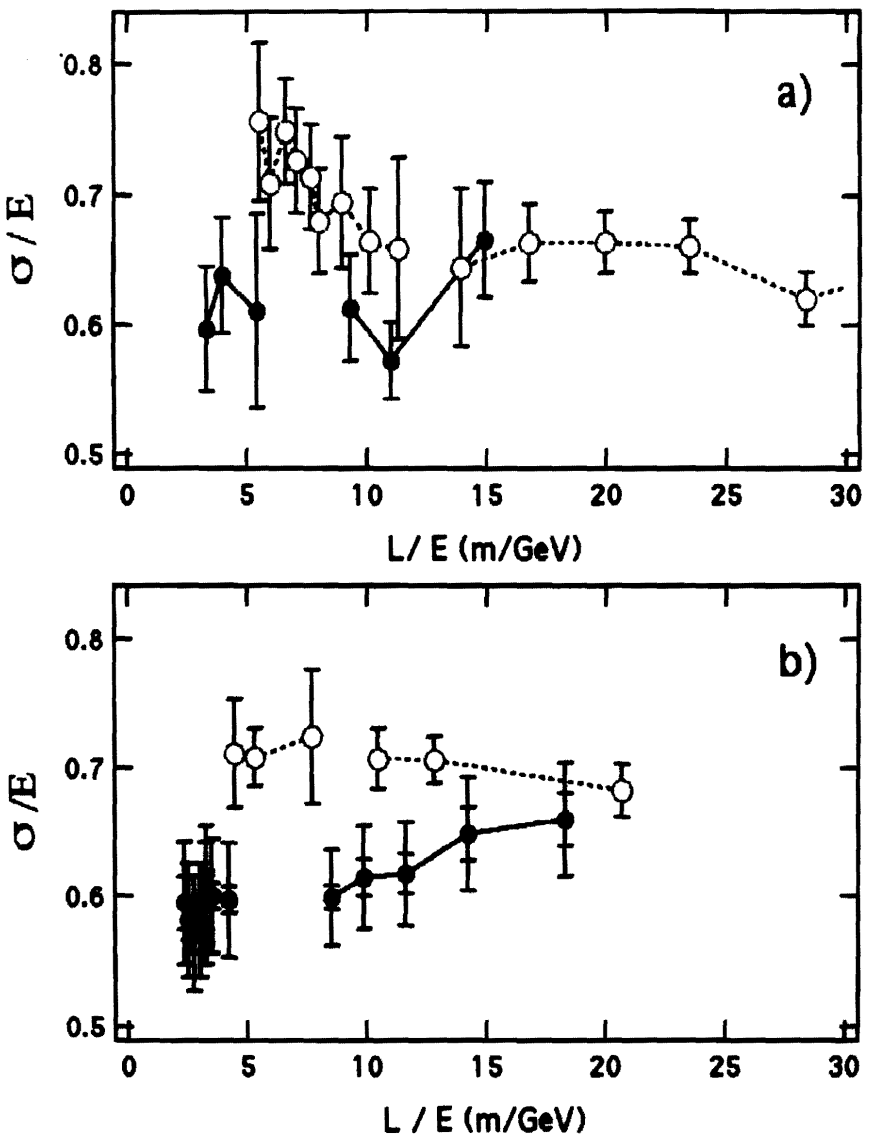

Figure 3. a) Fermilab (E-21 and E-616) and b) CERN (CDHS and CDHSW) neutrino data separately (dots/open are earlier/later experiments respectively).

parameters, since the energy spread dE/E is about 0.25 (0.15) for pion (kaon) neutrinos. This gives standard deviations of 0.28 (0.19) of the central L/E value for each pion (kaon) data point. We assume a Gaussian smearing, subdivided into eight sections to characterize the different oscillation distances that occur as the neutrinos propagate from their origin to their interaction point. These eight sections, which are defined by cuts at -3,-2,-1,-0.5, 0, 0.5, 1, 2 and 3 standard deviations relative to midpoint of the decay space D, have "median area" points at -2.3, -1.34, -.72, -.24, .24, 1.34, and 2.3 standard deviations respectively. The eight oscillation waves, for each pre-assigned given (standard) L/E, corresponding to a given ΔM^2, are summed with the appropriate Gaussian"weights (0.023,0.137, 0.15, 0.19, 0.19, 0.15, 0.137 and 0.023 respectively). A χ^2 of these weighted oscillation waves, weighted additionally by the strength of the oscillation relative to the total crossection (generally 2.5, 5, 7.5 and 10 percent), are calculated; from a table of these χ^2 values, "probability" contour plots (not shown) can be constructed, giving "best" solutions. Curves for these "best" solutions can then be shown on the data.

For the "doubling" of neutrinos (case 3) oscillation scenario, the pion and kaon neutrinos oscillate oppositely (eqn. 3), so that there is an apparent "discontinuity" in the curves as the data goes from kaon neutrinos (at low L/E's) to pion neutrinos. We find solutions exist for both cases of this "doubling" hypothesis (for simplicity we have taken $x^2 = 1$) and for the Majorana scenario (case 2). Curves corresponding to three such solutions are shown in Fig. 4a,b along with the "averaged" data of Fig. 2. Using the standard formula (for y^2 above), these L/E values of 5.5 and 15.5 m/GeV correspond to ΔM^2 of about 450 and 160 eV^2 respectively.

OTHER DATA

We note that the Fermilab "two-detector" Stockdale, et al, disappearance oscillation experiment [20] can be re-interpreted to cover the case 2 and 3 hypotheses also. The data are given in Figure 2b of reference 20 and we have performed the above mentioned analysis on this data also. Since there are two detectors at different distances, the theory curves must be done twice, and the ratio of the cross-sections taken. The cross-section of the far (Lab-E) detector's prediction is divided by that of the near detector and plotted against L/E of the near detector; this is compared to the Stockdale, et al, measurements versus L/E of the near detector. Although the null hypothesis is not ruled out, we find that some contour-plot solutions (not shown) match those from the neutrino cross-sections above, and are plotted

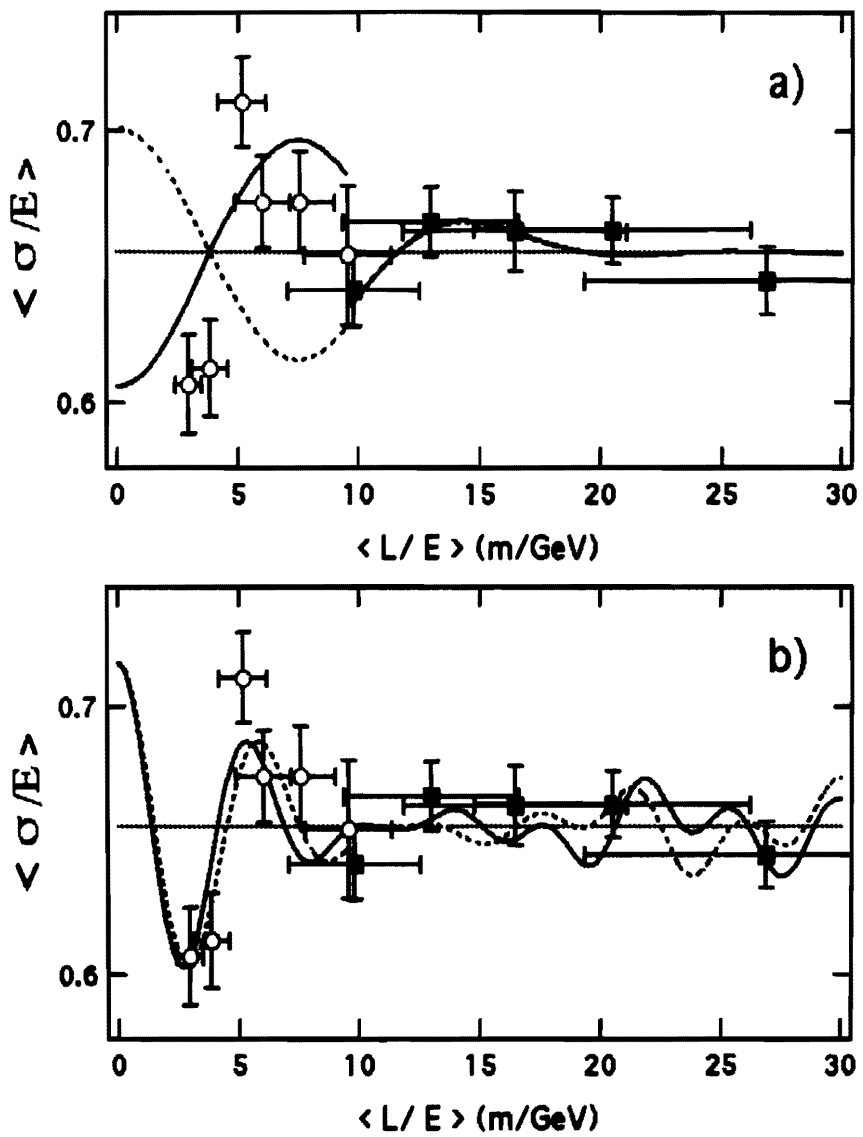

Figure 4. Examples of oscillation fits (see text) to the data of Fig. 2. a) Cases 2 (3a) for 1/E - 15.5 (15.5) m/GeV (the case 2 "curve" is unacceptable, ie not a fit). b) Cases 2 (3b) for 1/E- 6 (5.5) m/GeV. (Case 2 (3) dashed (solid)). The constant line has a χ^2 of 29 for 10 degrees-of-freedom (0.2% C.L.).

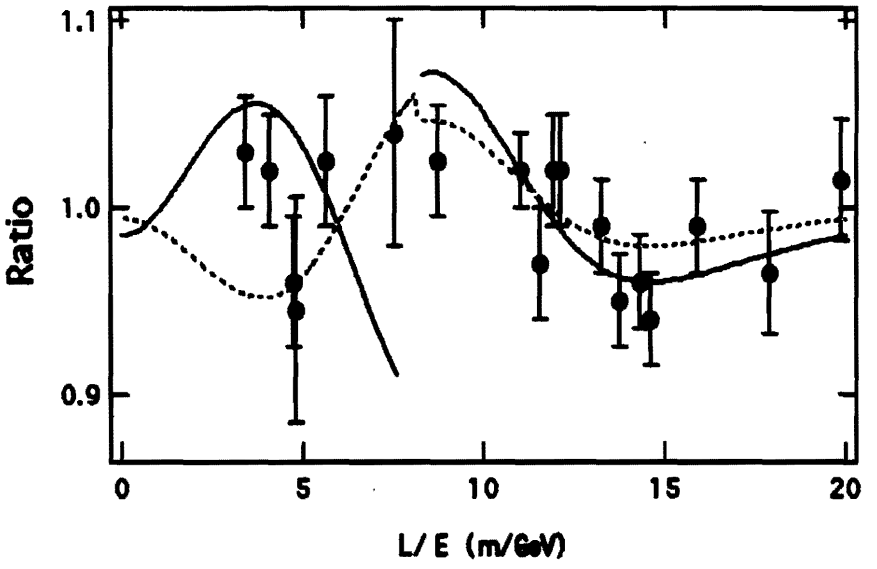

Figure 5. Examples of oscillation fits to the data of Stockdale, et al (ref. 20), for l/E = 16 m/GeV (case 2, dashed) and for l/E = 15.5 m/GeV (case 3a, solid).

with the Stockdale, et al, ratio in Figure 5. This result is independent of the total cross-section one and was unexpected.

The anti-neutrino and forward differential cross-sections, neutral-to-charged current ratios, as well as further details about the analysis reported here, are being reported elsewhere [21], including commentary on the high statistics 800 GeV Fermilab E-744/E-770 data [22,23].

CONCLUSIONS

Although the above does not prove either the Majorana or the triplet hypotheses, it seems prudent that further experimental work should be undertaken to prove or dispell it. Two decades of flux-normalized cross-sections have given only few percent results; they were necessary to establish the basic linearity of neutrino cross-sections. Higher accuracy is required to establish higher order effects, such as those of various possible oscillation scenarios. The two detector method [20] is the most appropriate, as it provides the cross-section by measuring the events in one versus the "flux" from the events in the other. Fermilab is currently in position to do this, if the current Lab-E detector is partitioned into two and redeployed. This should not seriously compromise the total statistics to be obtained and would allow for cross-checking and reduction of systematic errors, enhancing significantly the physics results being pursued.

It is possible that some non-standard properties of neutrinos are on the verge of discovery. We hope that the evidence presented here provides the incentive to undertake the task of proving or dispelling these alternate possibilities in the coming decade.

ACKNOWLEDGEMENTS

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The following 3 Tables

I, II and III

will not appear in "Rapid Communications"

BUT

will appear in PRD1 submission along with another 9 Figures or so, and more discussion.

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Table I--World Kaon Neutrino Data.
(See text for references regarding Experiment names)
Cross-sections (and errors) in 10^{-38} cm^2/GeV

E(GeV)	D(m)	L(m)	S/E	dS/E	L/E(m/GeV)	Experiment
10	60	52	0.75	0.06	5.20	GGM-PS
125	350	675	0.610	0.074	5.40	CITFR (E21)
171	350	675	0.639	0.044	3.95	
205	350	675	0.597	0.048	3.29	
86	350	675	0.67	0.09	7.85	FNAL-E254
140	304	594	0.63	0.04	4.24	BEBC
180	304	594	0.69	0.04	3.30	
152.5	304	662	0.597	0.044	4.34	CDHS
197.5	304	662	0.610	0.045	3.35	
182.5	304	662	0.600	0.044	3.63	
197.5	304	662	0.595	0.047	3.35	
215	304	662	0.582	0.045	3.08	
235	304	662	0.572	0.044	2.82	
255	304	662	0.582	0.045	2.60	
275	304	662	0.595	0.047	2.41	
84	304	730	0.66	0.08	8.69	GGM-SPS
120	304	730	0.56	0.08	6.08	
131.1	400	1200	0.69	0.21	9.15	FNAL-15-ft.BC(K)
200	400	1200	0.69	0.07	6.00	FNAL-15-ft.BC(B)
111.7	350	1130	0.659	0.07	10.12	CCFR(R) (E616)
124.8	350	1130	0.665	0.040	9.05	
141.2	350	1130	0.695	0.050	8.00	
157.4	350	1130	0.680	0.040	7.18	
165.1	350	1130	0.714	0.040	6.84	
179.8	350	1130	0.727	0.040	6.28	
190.8	350	1130	0.749	0.040	5.92	
212.5	350	1130	0.709	0.050	5.32	
229.1	350	1130	0.756	0.060	4.93	
83	304	662	0.724	0.052	7.98	CDHSW
121	304	662	0.708	0.023	5.47	
143	304	662	0.711	0.042	4.63	
98	350	1130	0.616	0.086	11.53	CCFR (E701)
130	350	1130	0.642	0.051	8.69	
150	350	1130	0.597	0.037	7.53	
176	350	1130	0.651	0.040	6.42	
206	350	1130	0.627	0.030	5.49	

Table II--World Pion Neutrino Data.
(See text for references regarding Experiment names)
Cross-sections (and errors) in 10^{-38} cm^2/GeV

E(GeV).	D(m)	L(m)	S/E	dS/E	L/E(m/GeV)	Experiment
2	60	52	0.750	0.050	26.00	GGM-PS
45.2	350	675	0.666	0.044	14.93	CITFR (E21)
61.3	350	675	0.573	0.029	11.01	
72.4	350	675	0.613	0.041	9.32	
30	304	594	0.57	0.06	19.80	BEBC
50	304	594	0.66	0.05	11.88	
70	304	594	0.69	0.04	8.49	
35	304	662	0.660	0.044	18.91	CDHS
45	304	662	0.649	0.044	14.71	
55	304	662	0.618	0.040	12.04	
65	304	662	0.615	0.039	10.18	
75	304	662	0.599	0.037	8.83	
60	304	686	0.600	0.030	11.43	CHARM
30	304	730	0.62	0.08	24.33	GGM-SPS
3.2	50	65	0.80	0.11	20.31	BNL 7-foot BC
14.8	400	1200	0.67	0.05	81.08	FNAL-15-ft.BC(K)
24.4	400	1200	0.67	0.08	49.18	
34.5	400	1200	0.74	0.08	34.78	
44.5	400	1200	0.67	0.07	26.97	
60	400	1200	0.60	0.05	20.00	FNAL-15-ft.BC(B)
37.1	350	1130	0.654	0.020	30.46	CCFR(R) (E616)
44.7	350	1130	0.621	0.020	25.28	
54	350	1130	0.661	0.020	20.93	
63.5	350	1130	0.664	0.024	17.80	
75.4	350	1130	0.664	0.030	14.99	
91	350	1130	0.644	0.060	12.42	
31	304	662	0.682	0.021	21.35	CDHSW
50	304	662	0.706	0.018	13.24	
61	304	662	0.707	0.024	10.85	
40	350	1130	0.635	0.040	28.25	CCFR (E701)
52	350	1130	0.665	0.039	21.73	
59	350	1130	0.688	0.041	19.15	
67	350	1130	0.641	0.039	16.87	
77	350	1130	0.650	0.047	14.68	

Table III--World Anti-Neutrino Data.
(See text for references regarding Experiment names)

Cross-sections (and errors) in 10^{-38} cm^2/GeV

E(GeV)	D(m)	L(m)	S/E	dS/E	L/E(m/GeV)	Experiment
			Pion Anti-Neutrinos			
2	60	52	0.30	0.025	26.00	GGM-PS
45.9	350	675	0.288	0.015	14.71	CITFR (E21)
60	350	675	0.282	0.013	11.25	
65.7	350	675	0.275	0.017	10.27	
30	304	594	0.28	0.03	19.80	BEBC
50	304	594	0.32	0.03	11.88	
70	304	594	0.31	0.02	8.49	
35	304	662	0.319	0.019	18.91	CDHS
45	304	662	0.297	0.017	14.71	
55	304	662	0.303	0.018	12.04	
65	304	662	0.285	0.016	10.18	
75	304	662	0.297	0.016	8.83	
60	304	686	0.30	0.02	11.43	CHARM
30	304	730	0.29	0.04	24.33	GGM-SPS
50	400	1200	0.34	0.029	24.00	FNAL-15-ft.BC(T)
36.9	350	1130	0.361	0.018	30.62	CCFR(R) (E616)
45	350	1130	0.352	0.014	25.11	
54	350	1130	0.350	0.014	20.93	
63.8	350	1130	0.332	0.017	17.71	
75.6	350	1130	0.331	0.022	14.95	
89.3	350	1130	0.333	0.035	12.65	
31	304	662	0.327	0.009	21.35	CDHSW
50	304	662	0.332	0.008	13.24	
61	304	662	0.338	0.014	10.85	
58	350	1130	0.307	0.018	19.48	CCFR (E701)
			Kaon Anti-Neutrinos			
129	350	675	0.395	0.057	5.23	CITFR (E21)
168	350	675	0.325	0.034	4.02	
188	350	675	0.337	0.046	3.59	
140	304	594	0.31	0.03	4.24	BEBC
180	304	594	0.29	0.03	3.30	
107.5	304	662	0.294	0.025	6.16	CDHS
122.5	304	662	0.271	0.023	5.40	
137.5	304	662	0.274	0.021	4.81	
152.5	304	662	0.287	0.022	4.34	
167.5	304	662	0.302	0.023	3.95	
182.5	304	662	0.303	0.029	3.63	
110.3	350	1130	0.314	0.042	10.24	CCFR(R) (E616)
126.5	350	1130	0.341	0.036	8.93	
150	350	1130	0.339	0.026	7.53	
174.4	350	1130	0.321	0.026	6.48	
201.9	350	1130	0.303	0.032	5.60	
83	304	662	0.346	0.023	7.98	CDHSW
121	304	662	0.337	0.014	5.47	
143	304	662	0.306	0.025	4.63	
147	350	1130	0.334	0.020	7.69	CCFR (E701)