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LIMITS ON NEUTRINO-ANTINEUTRINO TRANSITIONS FROM ASTUDY OF HIGH ENERGY NEUTRINO INTERACTIONS

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In the context of gauge theories of grand unification or of lepton-quark substructure even the best established conservation laws not directly implied by the gauge structure become suspect. Indeed the search for their violation, for example in proton decay or neutrino mixing, becomes of prime importance. In addition the observation of neutrino mixing would imply massive neutrinos which could be of cosmological significance. Thus it is particularly important to investigate all possibilities of neutrino mixing.

One possibility that has been discussed theoretically from several viewpoints⁽¹⁾ is that neutrinos produced in normal decays could sometimes interact as anti-neutrinos, perhaps anti-neutrinos of a different flavour, or else oscillate into states that do so interact.

Oscillations leave the helicity of a neutrino essentially unchanged. For such a process to occur with a probability higher than $\alpha(m_\nu/E)^2$ therefore requires the presence of some right-handed leptonic charged current. Theoretically such a current arises naturally in many Grand Unified Theories and leads to neutrino mass and neutrino mixing. It could, for example, be due to a massive right-handed W boson or to mixing with mirror fermions with right-handed couplings. Experimentally it is admissible at the 10% level event in low Q^2 meson decay amplitudes⁽²⁾. A scalar coupling mediated, for example, by charged Higgs exchange could also serve and is equally admissible experimentally.

Alternatively neutrino mass may be associated with the majoron. Majoron emission at production or interaction point would change the helicity of the neutrino, thus changing the neutrino into an anti-neutrino of the same or different flavour⁽³⁾.

This letter reports new experimental limits on $\nu_\mu \rightarrow \bar{\nu}_e$ and $\bar{\nu}_e \rightarrow \bar{\nu}_e$ oscillations and transitions. The data are from BEBC filled with a 74 mole percent neon hydrogen mixture and exposed to the CERN SPS wide band neutrino beam. This beam has a small predicted flux of $\bar{\nu}_e$. The predicted ratio of $\bar{\nu}_e:\nu_e:\nu_\mu$ events is 1:30:1800 hence secondary $\nu_\mu \rightarrow \bar{\nu}_e$ or $\nu_e \rightarrow \bar{\nu}_e$ oscillations cannot be masked by a large background

Abstract

We distinguish electron and positron tracks from ν_e and $\bar{\nu}_e$ charged current interactions in a large bubble chamber filled with a neon-hydrogen mixture. No evidence is seen for an excess of $\bar{\nu}_e$ interactions from primary $\bar{\nu}_e$ sources or secondary $\nu_\mu \rightarrow \bar{\nu}_e$ or $\nu_e \rightarrow \bar{\nu}_e$ oscillations. Upper limits on oscillation parameters, majoron emission and lepton number violating π and K decays are presented.

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of primary $\bar{\nu}_e$. The same film has already been used to study $\mu^- e^+$ events (4), to measure the ν_μ total charged current cross section (5) and to search for $\nu_\mu \rightarrow \nu_e$, $\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_x$ oscillations (6). Thus the experimental details have all been reported previously excepting only the criteria used for distinguishing between ν_e and $\bar{\nu}_e$ events (i.e. between high energy e^- and e^+).

The BEBC was operated to give thin continuous tracks and maximise the spatial resolution. As a result, and because of their rapid energy loss in the heavy liquid, (X_0 about 42 cm) and the high magnetic field (3.5 Tesla), the charges of most electrons were evident on inspection. In the few cases of ambiguity due to early shower development the unambiguous part of the electron track was measured precisely and reconstructed. In 2% of the cases the electron showered so early that its track could not be followed far from the vertex unambiguously, and measurement over this short unambiguous length of track gave a sagitta value with a fractional error exceeding 70%: these tracks were considered to be of unidentified charge.

Using these criteria, 104 unpaired single e^- or e^+ events (ν_e candidates) and 18 unpaired single e^+ events ($\bar{\nu}_e$ candidates) were found on the film. These events were inside the kinematical cuts: electron energy above 1 GeV and corrected neutrino energy above 10 GeV. The same film was estimated to contain 6060 ± 440 charged current ν_μ interactions over 10 GeV, a few of which would appear as background in the ν_e or $\bar{\nu}_e$ samples if they had semi-leptonic charm decays, close compton, or asymmetric e^+e^- pairs. To remove this background, events were discarded if they contained a μ^- candidate (7) whose momentum or transverse momentum exceeded that of the electron. The loss of true ν_e and $\bar{\nu}_e$ events due to this cut was estimated as $(3 \pm 2)\%$ from the effect of this cut when interacting rather than non-interacting negative tracks were considered as μ^- candidates. The only other appreciable losses were due to event scan efficiency $(2 \pm 2)\%$, electron identification efficiency $(12 \pm 4)\%$ and confused events $(2 \pm 2)\%$. After all cuts the residual background was negligible (about 1 event) and there remained 89 ν_e candidates and no $\bar{\nu}_e$ candidates, (see table 1).

The calculated beam composition predicts 73 ± 8 ν_e events and 2 ± 1 $\bar{\nu}_e$ events inside the cuts from conventional sources, consistent with the numbers observed. Since no ν_e events from either conventional or unconventional sources were observed, upper limits on unconventional $\bar{\nu}_e$ sources are given below at a 90% confidence level corresponding to less than 2.3 observed events.

In general, events from unconventional sources would not have the same energy spectrum as the ν_e events nor the same y distribution, and would consequently not have quite the same probability of being detected within the kinematical cuts. Monte Carlo simulations were used to evaluate these effects.

In order to express the results in terms of neutrino oscillations we assume that only two neutrinos have significant mixing. The mixing probability $P(\nu_\alpha, \nu_\beta)$ of two observed weak charged current eigenstates (ν_α, ν_β) is then related to their flight path l in metres and energy E in MeV by $P(\nu_\alpha, \nu_\beta) = \sin^2 2\theta \sin^2(1.27 \Delta E/E)$ where Δ_{ij} is the difference of the squared masses of the mass eigenstates i and j and θ_{ij} their mixing angle (8). We therefore suppose that an initial left-handed $\nu_{\mu L}$ beam may contain, after some flight path l , a fraction of left-handed anti-neutrinos $\bar{\nu}_{eL}$. The charged current interaction cross section for such $\bar{\nu}_L$ would be zero if V-A were exact. We further suppose a V+A current enables the $\bar{\nu}_{eL}$ to interact with the usual cross section for ν_μ times a factor α^2 where α could be as high as about 0.1 (2). The results are shown in table 2 and figure 1. Allowance for a possible V+A component in the neutrino production process would tighten the limits quoted.

The upper bound for production by ν_μ of an e^+ instead of a μ^- , $\sigma(\nu_\mu + N \rightarrow e^+ + X)/\sigma(\nu_\mu + N \rightarrow \mu^- + X)$ is 5×10^{-4} at 90% confidence level for events with neutrino energy above 10 GeV, electron energy above 1 GeV and a mean beam energy for observed ν_μ events of 46 GeV. From this a limit on the majoron coupling $g_{\nu e}^2$ can be deduced. After allowing for the factor 0.8 loss in acceptance due to the missing energy carried by the majoron we found, following Barger et al (3), $g_{\nu e}^2$ is less than 0.03 for a common neutrino mass m_ν of 10 eV, and $m_\chi = 100$ KeV.

The absence of any excess $\bar{\nu}_e$ interactions may also be used to set limits on any π or K decays producing these neutrinos. The ratio of primary $\pi \rightarrow \mu + \bar{\nu}_\mu$ and $K \rightarrow \mu + \bar{\nu}_\mu$ decays responsible for the observed $\bar{\nu}_\mu$ charged current events is 7:3. The limits on various decays of the parent π and K mesons which would violate normal lepton number conservation rules are given in table 3, assuming here that any losses of $\bar{\nu}_e$ and ν_e due to oscillations are negligible.

In conclusion we see no evidence for neutrino-antineutrino oscillations in the CERN SPS wide band neutrino beam. $\alpha \sin^2 \theta$ for $\nu_\mu \rightarrow \bar{\nu}_{eL}$ and $\nu_e \rightarrow \bar{\nu}_{eL}$ are less than 0.7 eV^2 and 7 eV^2 respectively at the 90% confidence level. We place limits on majoron emission and limits on some π and K decays which do not conserve usual lepton numbers.

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TABLE 1

The numbers of events with unpaired electron tracks found on the film with electron momentum over 1 GeV and neutrino energy over 10 GeV. P_t and P_L are the transverse and longitudinal momentum of the electron (e) and $\bar{\nu}_e$ candidate (L) with respect to the ν beam direction.

	e^- and e^+	e^+
All events found	104	18
Events with $P_{te} > P_{tL}$ or $P_{Le} > P_{LL}$	93	1
Events with $P_{te} > P_{tL}$ and $P_{Le} > P_{LL}$	89	0

TABLE 2

Upper limits on the oscillation parameters for small and large mass squared differences Δ (at the 90% confidence level). See also Figure 1.

	$(\nu_e, \bar{\nu}_{eL})$	$(\nu_\mu, \bar{\nu}_{eL})$
$P(\nu, \bar{\nu}_{eL})$	< 0.03	< 0.0005
$\alpha \Delta \sin 2\theta$	$< 7 \text{ eV}^2$	$< 0.7 \text{ eV}^2$
		small
$P(\nu, \bar{\nu}_{eL})$	< 0.03	< 0.0005
$\alpha^2 \sin^2 2\theta$	< 0.05	< 0.001
(Δ large)		large

TABLE 3

Upper limits on lepton number violating π and K decays, (at the 90% confidence level).

Decay mode	limit on branching fraction
$\pi^+ \rightarrow \pi^+ + \bar{\nu}_e$	< 0.0015
$\pi^+ \rightarrow \mu^+ + \nu_e$	< 0.008
$K^+ \rightarrow \mu^+ + \bar{\nu}_e$	< 0.0033
$K^+ \rightarrow \mu^+ + \nu_e$	< 0.012
$K^+ \rightarrow e^+ + \pi^0 + \bar{\nu}_e$	< 0.003

FIGURE CAPTION

Figure 1: The 90% confidence limits showing the allowed regions (below the curves) for the mixing angle and mass squared differences for the oscillations shown.

Fig. 1