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Search for Massive Neutrinos in $\pi \to e\nu$ Decay

D.A. Bryman, R. Dubois,[a] T. Numao, R. Olaniyi,[b] and A. Olin
TRIUMF and University of Victoria, Vancouver, B.C., Canada V6T 2A3
and
M.S. Dixit
National Research Council of Canada, Ottawa, Canada K1A 0R6
and
J-M. Poutissou
TRIUMF and University of British Columbia
Vancouver, B.C., Canada V6T 2A3
and
J.A. Macdonald
TRIUMF, Vancouver, B.C., Canada V6T 2A3

Abstract

The positron spectrum from $\pi^+ \to e^+\nu_e$ decay has been examined for evidence of peaks arising from an admixture in the ν_e weak eigenstate of massive neutrinos. Limits on the intensity of such peaks, together with the measured $\pi \to e\nu$ branching ratio, have been used to derive constraints on the neutrino mixing parameters over the range 4 MeV $< m(\nu)$ $<$ 120 MeV.

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In the standard $SU(2)_L \times U(1)$ gauge theory of electroweak interactions the neutrinos are massless. However, massive neutrinos may occur in extensions of this framework,[1] with the neutrino mass eigenstates ν_i distinct from the weak eigenstates ν_a ($a = e, \mu, \tau, \ldots$). These states are related through the unitary transformation

$$\nu_a = \sum U_{ai} \nu_i \;,$$

where U_{ai} can be assumed to be nearly diagonal.

The effects of such mixings on the decay of pseudoscalar mesons has been investigated by Shrock.[2] In this scheme, $\pi \to e^+\nu$ decay must be considered as an incoherent sum of decay modes

$$\pi^+ \to e^+\nu_i \;, \tag{1}$$

where the decay rate is given by the product of $|U_{ei}|^2$ and a factor depending on $m(\nu_i)$. This leads to peaks in the $\pi \to e$ decay spectrum whose energy is determined by $m(\nu_i)$. Although the decay rate is helicity suppressed by a factor of $\sim 10^4$ for massless neutrinos, this suppression is not effective for massive neutrinos. The $\pi \to e$ decay is therefore an experimentally favoured reaction with which to search for subsidiary peaks due to heavy neutrinos. We have searched a large sample of $\pi \to e$ decay data, taken to measure the $\frac{\pi \to e\nu}{\pi \to \mu\nu}$ branching ratio, for evidence of such peaks.

The measurement was carried out at the TRIUMF cyclotron in Vancouver, Canada. Positive pions of 77 MeV/c were degraded and stopped in a scintillator target. Positrons from $\pi^+ \to e^+\nu$ decay and from the $\pi^+ \to \mu^+\nu_\mu$, $\mu^+ \to e^+\bar{\nu}_\mu\nu_e$ decay chain were detected in a 46 cm ϕ × 51 cm NaI(Tℓ) crystal preceded by a three-element scintillator telescope. The resolution of the crystal for 70 MeV/c electrons was measured to be 3.5% FWHM. In the experiment the positron energy and decay time relative to the pion stop were recorded together with pileup and energy loss information. A more detailed description of the experiment may be found in Ref. 3.

The analysis was performed on the positron energy spectrum recorded 2-22 ns after the pion stop in order to minimize the uncertainties arising from muon decay positrons. The shape of the muon decay spectrum was determined using positrons occurring 85-160 ns after the pion stop. The $\pi \to e\nu$ decay spectrum shown in Fig. 1(a) was obtained after subtraction of the $\mu \to e\nu\bar{\nu}$ shape. The expected $\pi \to e\nu$ shape for $m_\nu = 0$ was determined by a Monte Carlo calculation using the measured detector response function and including the effects of Bhabha scattering, Landau straggling, and internal bremsstrahlung photons emitted in the direction of the decay positrons. Figure 1(b) shows the residuals left after subtraction of the $\pi \to e\nu$ and $\mu \to e\nu\bar{\nu}$ shapes.

The peak-finding algorithm was chosen to facilitate the calculation of the probability for finding peaks in the data. It was adapted from a Fourier transform technique used in the analysis of nuclear γ-ray spectra.[5] Components of frequency higher than the detector resolution function were removed from the spectrum. The smoothed spectrum Fig. 1(c) was then searched for local maxima, and all peaks for which the relative error in the area was less than 50% were recorded. Nearby inflection points caused a peak to be treated as an unresolved multiplet.

Of interest are $P_e(A,E)$, the probability of finding a real peak of area A and energy E in the data, and $P_s(A,E,\Delta E)$, the probability of finding a spurious peak of area A in an energy region $E \pm \Delta E$. P_e determines the confidence limits where no peaks are found, while P_s is used to test the significance of any peaks found. These probabilities were obtained from our data in the following manner: First a spectrum was generated consisting of a $\pi \to e\nu$ peak and isolated additional peaks (an analytic approximation to the peak shape was used). This spectrum was randomized using statistics comparable to the experimental data, the $\pi \to e\nu$ and $\mu \to e\nu\bar{\nu}$ peaks were fitted, and then the peak-searching algorithm was applied to the residuals. The lower limit of the area of a peak that would be detected with 90% confidence is given by $P_e\ (A_{90},E) = 0.9$; it was obtained from 100 trials of this procedure at each energy. The spurious peak distribution $P_s(A,E,\Delta E)$ is similarly determined from randomized spectra including only the $\pi \to e\nu$ peak. Limits on the yield

$$\frac{\Gamma(\pi \to e\nu_i)}{\Gamma(\pi \to \mu\nu)} = \frac{A_{90}}{A(\pi \to e\nu)} \cdot \frac{\Gamma(\pi \to e\nu)}{\Gamma(\pi \to \mu\nu)} \tag{2}$$

are shown in Fig. 2.

The largest peak found in the data corresponded to a positron energy of 40 MeV and an intensity of 0.066 ± 0.020 of the $\pi \to e\nu$ peak. An examination of the spurious peak probability P_s showed that such peaks occurred in about 50% of the randomized spectra. We conclude that there is no evidence of a statistically significant peak in our data. Moreover, the upper limit for the intensity of the 40 MeV peak (at 90% confidence) is very nearly equal to the P_e limit.

It is interesting to apply these limits to a 3-generation world with $m(\nu_1) = m(\nu_2) = 0$, $m(\nu_3) > 0$, although the results can also be interpreted more generally. Shrock[2] has obtained the following expression for the branching ratio to heavy neutrinos from the spectral tests:

$$\eta_{e3} = \frac{\Gamma(\pi \to e\nu_3)}{\Gamma(\pi \to e\nu_1)} = |U_{e3}|^2\ \rho_e(\delta_3)\ , \tag{3}$$

where

$$\rho_e(\delta_3) = \frac{\left(1+\delta_e^2+\delta_3^2 - 2(\delta_3+\delta_e+\delta_3\delta_e)\right)^{1/2}\left(\delta_3+\delta_e - (\delta_3-\delta_e)^2\right)}{\delta_e(1-\delta_e)^2} , \qquad (4)$$

$$\delta_e = \frac{m_e^2}{m_\pi^2} , \quad \delta_3 = \frac{m(\nu_3)^2}{m_\pi^2} .$$

Shrock has also discussed the manner in which the branching ratio

$$R_\pi = \frac{\Gamma(\pi \rightarrow e\nu) + \Gamma(\pi \rightarrow e\nu\gamma)}{\Gamma(\pi \rightarrow \mu\nu) + \Gamma(\pi \rightarrow \mu\nu\gamma)}$$

may be used to constrain possible mixing parameter values.^{2} This must be interpreted differently from the η_{e3} constraint [Eq.(3)] because the violation could arise from causes other than massive neutrinos. In general R_π depends on both $|U_{e3}|^2$ and $|U_{\mu3}|^2$. The result using Ref. 3 is $\bar{R}_\pi = R_\pi/R_\pi^0 = 0.989 \pm 0.018$ at 90% confidence, where R_π^0 is the theoretical branching ratio assuming no mixing. In the range $0 < m(\nu_3) <$ 33 MeV we have

$$\bar{R}_\pi = \frac{1 + |U_{e3}|^2 \left(\rho_e(\delta_3) - 1\right)}{1 + |U_{\mu3}|^2 \left(\rho_\mu(\delta_3) - 1\right)} . \qquad (5)$$

Using the data of Abela <u>et al</u>.^{4} on $\pi \rightarrow \mu\nu$ to constrain $|U_{\mu3}|^2$ we find that the denominator does not vary from 1 by $O(10^{-5})$ over the range 4 MeV $< m(\nu_3) <$ 30 MeV, giving $|U_{e3}|^2 < 0.01/\left(\rho_e(\delta_3) - 1\right)$.

In the range 35 MeV $< m(\nu_3) <$ 55 MeV the $\pi \rightarrow \mu\nu_3$ decay is kinematically forbidden, while the $\pi \rightarrow e\nu_3$ electrons lie above the $\mu \rightarrow e\nu\bar{\nu}$ edge Here,

$$\bar{R}_\pi = \frac{1 + |U_{e3}|^2\left(\rho_e(\delta_3) - 1\right)}{1 - |U_{\mu3}|^2} , \qquad (6)$$

and, since $\rho_e(\delta_3) > 1$, the limits $|U_{\mu3}|^2 < 0.01$ and $|U_{e3}|^2 < 0.01/\left(\rho_e(\delta_3) - 1\right)$ are obtained. This imposes a stronger limit than the spectral test in the region where two peaks are not well resolved. The upper bounds on η_{e3} and $|U_{e3}|^2$ are presented in Table I and Fig. 2.

Finally in the range $m(\nu_3) > 55$ MeV we have

$$\bar{R}_\pi = \frac{1 - |U_{e3}|^2}{1 - |U_{\mu 3}|^2} \, . \tag{7}$$

The spectral test then constrains $|U_{e3}|^2$, and we find $|U_{\mu 3}|^2 < 0.01$. This is the only limit on $|U_{\mu 3}|^2$ in the 30-70 MeV range. A strong limit on $|U_{\mu 3}|^2 < {\sim}10^{-3}$-$10^{-6}$ in the 70-310 MeV range has been obtained recently by Hayano et al.[6] from a $K^+ \to \mu^+\nu$ decay measurement. Thus the R_π constraint implies $|U_{e3}|^2 < 0.01$ in this range. Shrock[2] has estimated a limit of $|U_{e3}|^2 \sim 10^{-5}$ for the range 80-160 MeV from existing K decay data. Finally we note the limit $m(\nu_3) < 250$ MeV obtained directly from τ decay.[7]

Cosmological arguments have been used to establish a limit of 30 eV for the mass of stable neutrinos.[8] However, in the class of theories that we are considering the heavy neutrino is not stable, so that those limits do not apply directly.[9]

Predictions for neutrino masses and mixings arise, for example, in horizontal[10] and left-right symmetric gauge models.[11] An estimate of the τ-neutrino mass in these models is given by $m_{\nu_\tau} = m_\tau^2/m_R$, where m_R is a right-handed Majorana neutrino mass. The bound $m_R > 300$ GeV obtained from charged and neutral current phenomena corresponds to $m_{\nu_\tau} < 18$ MeV.[11] The mixings are estimated to be of order $|U_{e3}|^2 \simeq m_e/m_\tau = 3\times10^{-4}$ and $|U_{\mu 3}|^2 \simeq m_\mu/m_\tau \simeq 6\times10^{-2}$, in analogy with Cabibbo mixing in the quark sector. These limits fall within the region excluded by our measurement.

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(a) Present address: Stanford Linear Accelerator Center, Stanford, CA 94305.

(b) Present address: University of Ife, Ile-Ife, Nigeria.

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Table I. *Bounds on the yield and mixing parameters of massive neutrinos in $\pi \rightarrow e\nu$ decay.*

$m(\nu)$ MeV	η_{ei}	$\lvert U_{ei}\rvert^2 \times 10^6$ (spectral test)	$\lvert U_{ei}\rvert^2 \times 10^6$ (branching ratio)
4	-	-	163
6	-	-	73
10	-	-	27
15	-	-	12
20	-	-	6.8
25	-	-	4.5
29	0.35	120	3.4
35	0.055	13	2.4
43	0.019	3.2	1.7
48	0.013	1.9	1.5
54	0.010	1.2	1.2
63	0.024	2.5	-
71	0.10	9.7	-
78	0.11	9.7	-
84	0.10	9.3	-
90	0.11	10.0	-
96	0.09	9.1	-
101	0.09	10	-
106	0.09	11	-
111	0.08	12	-
116	0.07	13	-
120	0.07	19	-

Figure captions

1. Spectrum of electrons from pion decay. (a) Spectrum after subtraction of μ-decay electrons; (b) spectrum of residuals after subtraction of the calculated line shape; (c) residuals after application of the Fourier smoothing algorithm.
2. Limits (at 90% c.l.) for the yield of a pion decay branch to a neutrino of mass $m(\nu_3)$, and on the mixing parameter of the electron weak eigenstate with the neutrino. Curve (a) Limit obtained from search for monoenergetic peaks. Curve (b) Limit obtained from π → eν branching ratio.

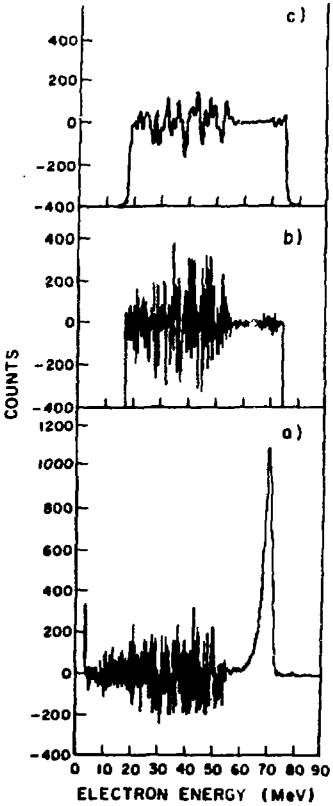

Fig. 1

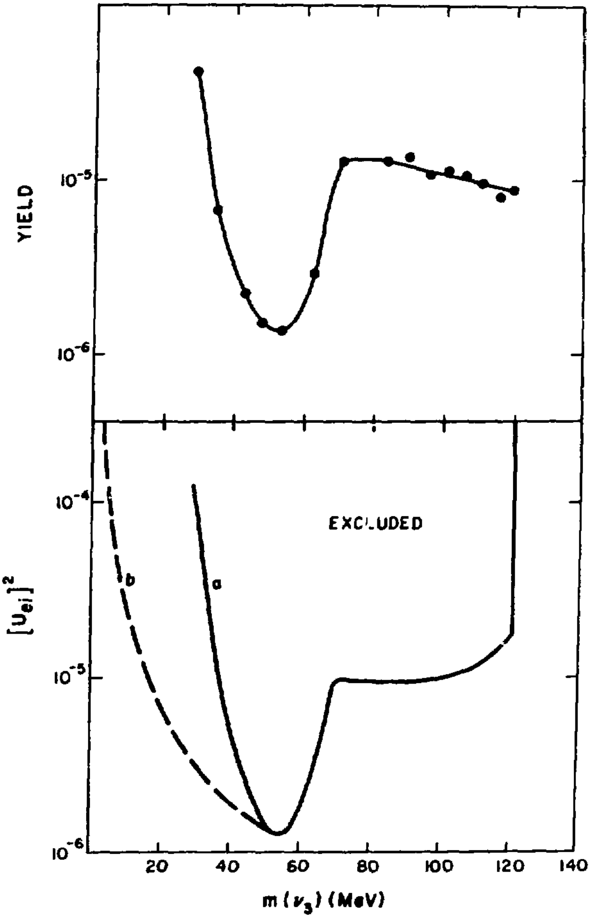
YIELD
10⁻⁵
10⁻⁶
10⁻⁴
EXCLUDED
b
a
[U_ei]²
10⁻⁵
10⁻⁶
20
40
60
80
100
120
140
m (ν₃) (MeV)

Fig. 2