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Search for massive neutrinos in $\pi^+ \to \mu^+\nu$ decay

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Evidence of massive neutrinos was sought in the $\pi^+ \to \mu^+ x$ decay spectrum in the mass region $M_x = 30$–33.91 MeV/c^2. Upper limits on the branching ratio $R_{\mu x} \leq (4-6) \times 10^{-5}$ (90 % C.L.) were set for this region, which correspond to the neutrino mixing parameter $\mid U_{\mu x} \mid^2 < 10^{-3}$–$10^{-4}$.

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Recently, the KARMEN group reported an anomaly in the time spectrum of the neutrinos produced from a pulsed beam stop source [1] and suggested the possibility of the presence of a noninteracting massive neutral particle emitted in pion decay $\pi^+ \to \mu^+ x$ with mass around $M_x = 33.9$ MeV/c^2 (a detailed discussion on the constraints associated with x couplings can be found in Ref. [2]). The possibility of x being a conventional neutrino is unlikely due to the measured Z^0 width [3] and the recent upper mass bound of the τ neutrino, $M_\tau \leq 24$ MeV/c^2 [4]. However, "sterile" neutrinos such as iso-singlet neutrinos $(\nu_{\chi_1}, \nu_{\chi_2}, \ldots, \nu_{\chi_k})$ [5] may exist without affecting the Z^0 width. The weak eigenstates ν_{χ_k} of such neutrinos are related to the mass eigenstates ν_i by a unitary matrix, $\nu_l = \sum_{i=1}^{3+k} U_{li}\nu_i$, where $l = e, \mu, \tau, \chi_1, \chi_2, \cdots, \chi_k$. Such mixings would produce additional peaks in the lepton energy spectrum from two-body meson decays such as $\pi^+ \to \mu^+\nu$ [6]. The branching ratio of $\pi^+ \to \mu^+ x$ decay to the normal $\pi^+ \to \mu^+\nu$ decay can be written as

$$R_{\mu x} = \frac{\Gamma(\pi \to \mu x)}{\Gamma(\pi \to \mu\nu_2)} = \mid U_{\mu x} \mid^2 \rho_\mu(M_\pi, M_\mu, M_x), \qquad (1)$$

where ν_2 is the conventional massless neutrino and ρ_μ is a kinematic factor [6].

Previous direct searches for the production of massive neutrinos coupling to the muon in pion decay have been carried out by Abela *et al.* [7] and Daum *et al.* [8]. Because of the experimental threshold for the muon detection, these measurements did not cover the region between $M_x = 30$ MeV/c^2 and the kinematic limit 33.91 MeV/c^2. Shrock [6] estimated upper limits $\mid U_{\mu x} \mid^2 \leq 2 \times 10^{-3}$ (1σ) using the ρ parameter in the muon decay spectrum, and this has been the tightest limit available for this mass region.

The present work is based on the data taken for the branching ratio measurement of the decay $\pi^+ \to e^+\nu$ [9]. Positive pions of momentum $P_{\pi^+} = 83$ MeV/c from the TRIUMF M13 channel were degraded by a 12.7-mm-thick plastic-scintillation counter $B1$ and stopped at a rate of 10^5 s^{-1} in a 12.7-mm-thick scintillator target $B3$ sandwiched between two 1.6-mm-thick scintillation counters $B2$ and $B4$. Positrons from the decay $\pi^+ \to e^+\nu$ (branching ratio $R_{e\nu} \sim 10^{-4}$, $T_{e^+} = 69.3$ MeV) and from the decay $\mu^+ \to e^+\nu\bar{\nu}$ following the decay $\pi^+ \to \mu^+\nu$ (the $\pi^+ \to \mu^+ \to e^+$ chain, $T_{e^+} = 0$–52.3 MeV) were detected by scintillation counters with an effective diameter of 15 cm placed 22 cm from $B3$, and energy-analyzed by a 51-cm-long × 46-cm-diameter NaI (Tl) crystal TINA.

For the decay chain $\pi^+ \to \mu^+ \to e^+$, the energy in the pion stopping counter $B3$ involves three components: the kinetic energy of the stopping pion, the kinetic energy of the decay muon (normally $T_\mu = 4.12$ MeV for $M_\nu = 0$ MeV/c^2) which would vary with the neutrino mass, and a small fraction of the positron energy (~0.5 MeV). The energy resolution for the decay chain $\pi^+ \to \mu^+ \to e^+$ in $B3$ was $\Delta E = 0.6$ MeV (σ) after correcting for the pion energy loss in $B1$. A possible peak corresponding to $T_\mu = 0$ MeV would be separated from the normal decay and, thus, the energy spectrum in $B3$ can be used to search for evidence of $\pi^+ \to \mu^+ x$ decay.

Positron events in an early time region ($5 \leq t \leq 30$ ns, with respect to the pion stop time), which are enriched in $\pi^+ \to e^+\nu$ events, were selected for a reference sample of events without muon energy. For the secondary peak search described here, events with positron energy $T_{e^+} \leq 56$ MeV in a late-time region ($100 \leq t \leq 150$ ns) were selected to suppress $\pi^+ \to e^+\nu$ events. Due to the response function of the NaI detector, however, a very small fraction (5×10^{-4}) of $\pi^+ \to e^+\nu$ events still remained at this stage, and this component was subtracted from the spectrum before the search. The normal $\pi^+ \to \mu^+ \to e^+$ chain was suppressed by using pulse-shape information from the $B3$ counter recorded by two analogue-to-digital converters (ADC's): one with a gate sampling the first 7 ns of the signal and the other with a 200-ns-wide gate to accumulate the total signal [9]. This technique allowed suppression of $\pi^+ \to \mu^+ \to e^+$ events by a factor of ~30 at a small cost of acceptance, and reduced the low-energy tail which prevented complete separation of the two peaks at $T_\mu = 0$ MeV ($\pi^+ \to e^+\nu$) and $T_\mu = 4$ MeV ($\pi^+ \to \mu^+ \to e^+$). However, this approach introduced an acceptance variation with T_μ because the detection probability of $\pi^+ \to \mu^+\nu$ decay depended on the amplitude of the second pulse. The acceptances of the above cuts were estimated to be 68% at $T_\mu = 0$ MeV and 25% at $T_\mu = 1$ MeV by comparing with the unsuppressed spectrum. The background shape due to the radiative decay $\pi^+ \to \mu^+\nu\gamma$ (≤ 0.1 of the background in the region of the search) was also distorted by the acceptance variation but the effect was still negligible at the level of this investigation. In the region of zero muon energy, the remaining events after these cuts were

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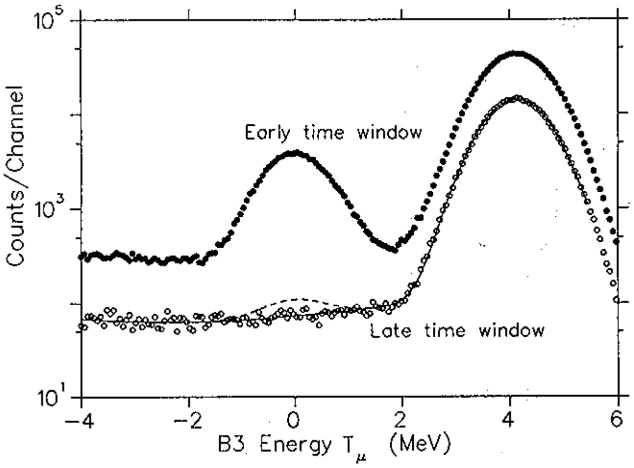

FIG. 1. Typical $B3$ energy spectrum in an early-time window 5 to 30 ns after the pion stop time (closed circles) and the same spectrum for $T_{e^+} \leq 56$ MeV in the late-time region 100–150 ns. The solid line indicates the fit at $T_\mu = 0$ MeV and the dashed line corresponds to the signal $| U_{\mu x} |^2 = 10^{-2}$ at $M_x = 33.905$ MeV$/c^2$.

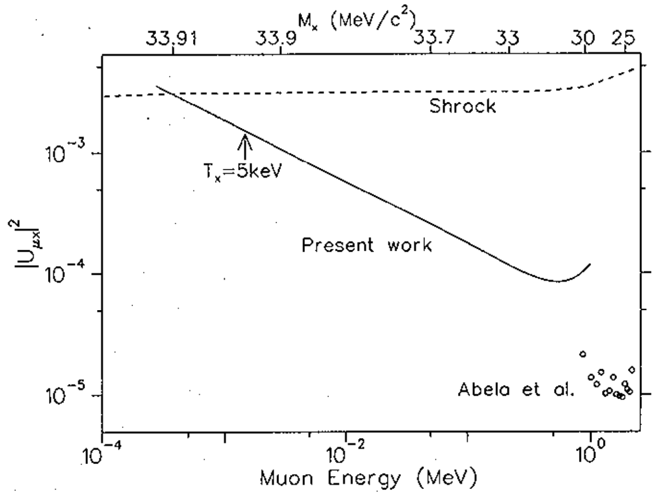

FIG. 2. Upper limits (90% C.L.) of $| U_{\mu x} |^2$ with the muon energy (lower scale) up to 2 MeV and the neutrino mass (upper scale). The results from the present experiment ($T_\mu \leq 0.8$ MeV$/c^2$) are shown by the solid line. The previous limits (90% C.L.) of Shrock [6] are shown by the dashed curve, and of Abela *et al.* [7] by the open circles.

due mostly to pion decays in-flight. Figure 1 shows the resulting $B3$ energy spectra for the early-time window (closed circles), and the late-time region (open circles). The horizontal scale of the figure does not include saturation effects in the scintillator but a correction was applied in the final results. There was a small energy shift of ~0.2 MeV (corrected in the figure) between the early- and late-time spectra because of the difference in the undetected fraction of positron energy.

The data of Fig. 1 were examined for evidence of peaks attributable to the presence of mass eigenstates x. The spectrum in the early-time region (closed circles) was first fitted to define the parameters in the fitting function: a Gaussian peak for the $\pi^+ \to \mu^+ \to e^+$ decay, another Gaussian peak for the $\pi^+ \to e^+\nu$ decay (a "training" sample for the massive neutrino peak), and a quadratic background due to decays in-flight. Using the late-time-window spectrum, the search was then carried out by changing the "$\pi^+ \to e^+\nu$" peak energy representing a shift due to $\pi^+ \to \mu^+ x$ decay and fitting the spectrum to the same function with the fixed energy and width for the "$\pi^+ \to e^+\nu$" component. The peak energy was stepped in ~ 0.06-MeV increments through the muon-energy range 0 – 0.8 MeV to find the most probable peak area at each energy. The resulting areas monotonically decreased from 24±80 to −116±88 events with increasing of muon energy. By normalizing to the unsuppressed $\pi^+ \to \mu^+ \to e^+$ decays (the total number of events was 5×10^6) and correcting for the acceptance, the peak areas were converted to branching-ratio upper limits (90% C.L.) assuming the normal probability distribution with a constraint that the physical region of a peak area be positive; only the positive-area part of the normal distribution was used to calculate the limit. The solid line in Fig. 1 shows the best fit at $T_\mu = 0$ MeV; the branching ratio obtained for the secondary peak at $T_\mu = 0$ MeV was $(0.68 \pm 2.28) \times 10^{-5}$, which corresponds to a 90% upper limit, $R_{\mu x} \leq 4.2 \times 10^{-5}$. Using Eq. (1), an upper limit on the mixing coefficient for heavy neutrinos coupling to muons was derived $| U_{\mu x} |^2 \leq 1.4 \times 10^{-3}$ at $M_x = 33.905$ MeV ($T_x = 5$ keV). For comparison, the dashed line in Fig. 1 indicates the signal that would correspond to $| U_{\mu x} |^2 = 1 \times 10^{-2}$ with the same mass. The solid curve in Fig. 2 shows the upper limits on $| U_{\mu x} |^2$ from the present work for the region $T_\mu \leq 0.8$ MeV. The dashed curve and open circles in the figure indicate the results from Refs. [6] and [7], respectively. In the figure, the upper limits obtained by Shrock (1σ) were converted to 90% C.L., which gave $| U_{\mu x} |^2 \leq 3 \times 10^{-3}$. Although the present results do not eliminate the possibility of a massive neutrino around $M_x = 33.9$ MeV$/c^2$, they provide improved constraints by a factor up to 40 in the mass region 30 to 33.91 MeV$/c^2$.

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[1] B. Armbruster *et al.*, Phys. Lett. B **348**, 19 (1995).
[2] V. Barger, R. J. N. Phillips, and S. Sarkar, Phys. Lett. B **352**, 365 (1995); **356**, 617(E) (1995).
[3] J. Steinberger, Phys. Rep. **203**, 345 (1991).
[4] D. Buskulic *et al.*, Phys. Lett. B **349**, 585 (1995).
[5] L. S. Littenberg and R. E. Shrock, Phys. Rev. Lett. **68**, 443 (1992).
[6] R. E. Shrock, Phys. Rev. D **24**, 1232 (1981); **24**, 1275 (1981).
[7] R. Abela *et al.*, Phys. Lett. **105B**, 263 (1981).
[8] M. Daum *et al.*, Phys. Rev. D **36**, 2624 (1987).
[9] D. I. Britton *et al.*, Phys. Rev. D **49**, 28 (1994); **46**, R885 (1992).