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Heavy-Neutrino Search Using $K_{\mu 2}$ Decay

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The muon momentum spectrum in $K_{\mu 2}$ decay has been measured by using a high-resolution magnetic spectrograph to look for a discrete muon peak associated with heavy-neutrino emission. The spectrum revealed no distinct peak, and the upper bound of the mixing ratio between the muon neutrino and a massive neutrino has been determined to be 10^{-4}–10^{-6} in the mass range of 70–300 MeV/c^2.

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Neutrinos are generally considered to be massless in the conventional theory of weak interactions. Experimentally, a finite neutrino mass cannot be excluded, especially if we take seriously the nonzero value of 14–46 eV/c^2 reported for the electron neutrino.[1] For other types of neutrinos, the present limits are $m(\nu_\mu) < 0.57$ MeV/c^2,[2] and $m(\nu_\tau) < 250$ MeV/c^2.[3]

Finite (and nondegenerate) neutrino masses imply neutrino flavor mixing since the weak neutrino eigenstates ν_e, ν_μ, and ν_τ are, in general, not mass eigenstates themselves, but linear combinations of the neutrino mass eigenstates as

$$\nu_l = \sum U_{li}\nu_i \quad (l = e, \mu, \tau, \ldots;\ i = 1, 2, 3, \ldots).$$

The current belief is that the mixing matrix is nearly diagonal, i.e., ν_e is dominantly coupled to ν_1, $\nu_\mu \cong \nu_2$, and $\nu_\tau \cong \nu_3$. In a series of papers Shrock[4] emphasized that there is a very interesting possibility that some of the neutrino mass eigenstates including unknown generations are so heavy that they may show up with probability $|U_{li}|^2$ in a two-body decay spectrum, well separated from the dominant peak. Such a possibility cannot be excluded by the presently known experimental evidences. On the other hand, neutrino-oscillation experiments[5] are only sensitive to small mass differences with relatively large mixing, and thus they cannot detect small mixing of heavy neutrinos.

A sensitive test of this interesting idea was proposed by Shrock, and involves measuring the lepton momentum spectrum in two-body leptonic decays of pseudoscalar mesons, such as K_{l2} or π_{l2}.

The signature of a heavy-neutrino emission would be a discrete peak at

$$p_l = \tfrac{1}{2}Mc[1+x^2+y^2-2(x+y+xy)]^{1/2},$$

where M is the parent mass, $x = m_l^2/M^2$, and $y = m_\nu^2/M^2$. The intensity of this extra peak $M^+ \to l^+\nu_i$, relative to that for the conventional decay $M^+ \to l^+\nu_l$, is related to the neutrino mixing ratio $|U_{li}|^2$ as

$$\Gamma(M^+ \to l^+\nu_i) = \rho\Gamma(M^+ \to l^+\nu_l)|U_{li}|^2,$$

where ρ is a kinematical factor including phase space

$$\rho = \frac{[x+y-(x-y)^2][1+x^2+y^2-2(x+y+xy)]^{1/2}}{x(1-x)^2},$$

which enhances heavy-neutrino emission with respect to helicity-suppressed massless neutrinos.

As summarized in Ref. 4, presently available data can exclude only a small region in a neutrino mixing versus mass plane; a dedicated experiment which looks for heavy-neutrino emission with high sensitivity and with a large mass window (since we do not know what values to expect) is therefore worthwhile.

Because of the larger mass window available, we decided to use the K^+ decay. In Ref. 6, we already reported on a survey experiment measuring a range spectrum in $K_{\mu 2}$ decay. Here, we report on the result of our new dedicated experiment using a high-resolution magnetic spectrograph with a wider momentum range (100–250 MeV/c) and much better momentum resolution [full width at half maximum (FWHM) ~ 1%]. Furthermore, we employed a very effective photon veto system using NaI(Tl) counters to suppress the continuum background. Thus, we increased the sensitivity and the mass range. The motivation and design aim of this experiment are also described in Ref. 7, where an argument is made that the expected ν_τ mass may fall in the mass range just covered by the present experiment (70–300 MeV/c^2).

Figure 1 shows a schematic diagram of the spectrograph. The experiment was performed at the K3 beam channel of the 12-GeV proton synchrotron at the National Laboratory for High Energy Physics (KEK). A dc-separated 550 MeV/c K^+ beam was degraded in a 7-cm-copper degrader, and was stopped in ten layers of plastic scintillators (seven $8\times20\times0.6$ cm^3, two $8\times20\times0.2$

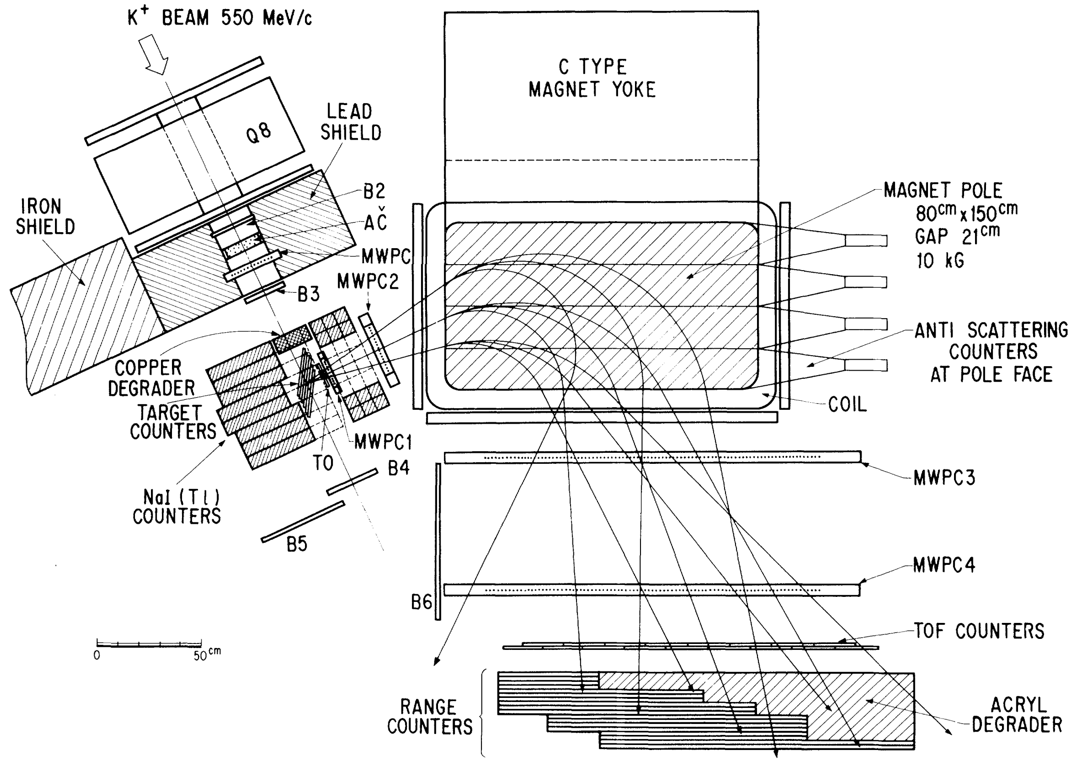

FIG. 1. Plan view of the neutrino mass spectrograph.

cm^3, and one $8\times20\times0.1$ cm^3) tilted 30° to the beam. The K/π ratio was typically 25%, and the number of stopped K^+ was about 5000 per beam spill.

Because minimum-ionizing muons lose about 1.7 MeV in each 6-mm stopping counter, misidentification of the K^+ stopping layer would lead to poor momentum resolution and a spurious shoulder in the spectrum. Therefore, the K^+ stopping layer in the stopping counters was carefully determined by using both pulse height and timing information, and ambiguous events (about 15%) were rejected.

Charged particles from K^+ decays were momentum analyzed by a magnetic spectrograph, consisting of two entrance multiwire chambers (PC1 and PC2), a 10-kG C-type rectangular-pole magnet with the dimensions shown in the figure, and two exit chambers (PC3 and PC4). The time difference between K^+ arrival and the T0 counter located at the spectrograph entrance was measured to select delayed events (2–25 nsec), since prompt events (mostly due to K^+ decay in flight) produced a broad shoulder around the 236-MeV/c peak. Time-of-flight (TOF) measurements between the T0 counter and the TOF stop counters and, in addition, range information from 46 range counters were used to identify muons.

Among the major K^+ decay modes, $K^+\rightarrow\mu^+\pi^0\nu$ (3.2%) and $K^+\rightarrow\mu^+\nu\gamma$ (0.6%) decays produce a continuous background to the muon momentum spectrum, below the 236-MeV/c main peak (63.5%). To achieve high sensitivity to small discrete peaks, these decay modes must be vetoed. We surrounded the K^+ stopping region with 112 modular NaI(Tl) counters (6.5 cm$^2\times$30 cm) with discriminator thresholds set around 1 MeV to veto π^0 and γ from these decay modes.

The veto efficiency of the $\mu^+\pi^0\nu$ mode was quite high because of 2γ emission, better than 99%, while the $\mu^+\nu\gamma$ mode was difficult to eliminate. Even with 92% solid-angle coverage by the NaI counters, about 30% of the $\mu^+\nu\gamma$ photons escaped undetected for $p_\mu \lesssim 220$ MeV/c, becoming much worse toward the 236-MeV/c peak, since low-energy photons are preferentially emitted along the muon momentum direction.[8]

Much effort has been made to achieve good momentum resolution: large bending angle, first-order horizontal focusing, high-resolution two-dimensional readout of the multiwire proportional chambers, and a helium gas bag between the magnet poles to minimize multiple scattering. Momentum reconstruction was performed by numerically integrating the equation of motion,[9] and a χ^2 test was applied to eliminate spurious tracks (about 50%). The reconstructed momentum was then corrected for energy loss in the K^+ stopping counters by using the pulse-height information.

The final spectra are shown in Fig. 2. Open squares represent the overall charged-particle spectrum without photon veto; major K^+ decay modes such as $\mu^+\nu$, $\pi^+\pi^0$, $e^+\pi^0\nu$, $\mu^+\pi^0\nu$, and $\pi^+\pi^+\pi^-$ can be readily identified by distinct peaks and shoulders as indicated in the figure.

Closed squares represent the final muon momentum spectrum with photon veto and particle identification. The accidental loss through the photon veto amounted to 40%. The muon identification applied did not lose muon events but served to remove a slight $\pi^+\pi^0$ peak at 205 MeV/c. The total number of muons in the spectrum is 2.54 $\times 10^6$.

The momentum resolution at 236 MeV/c is 2.1 MeV/c FWHM (0.9%) with a perfectly Gaussian line shape, and decreases gradually toward lower momenta, as shown, because of multiple scatter-

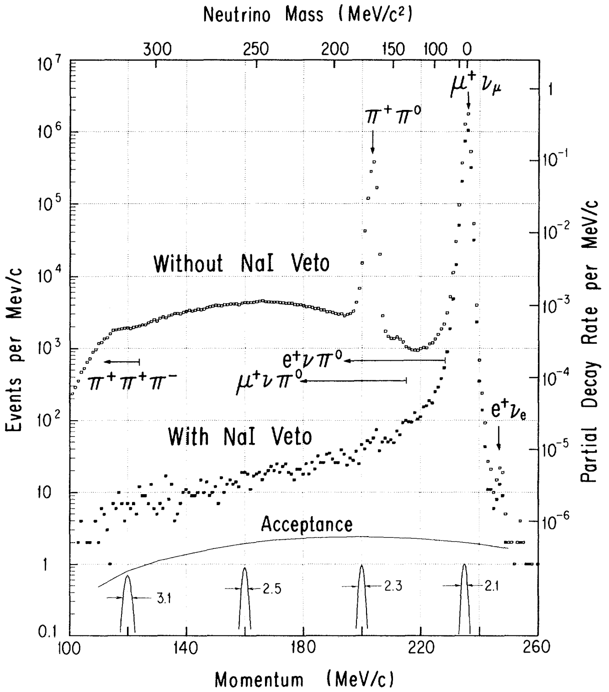

FIG. 2. The momentum spectrum of charged particles analyzed by the spectrograph is given by open squares. Closed squares represent the final muon momentum spectrum with photon veto and particle identification. The momentum dependences of the acceptance (relative) and resolution (FWHM) are also shown.

ing and energy losses.

Note that the ordinate is in a logarithmic scale, and the upper tail of the 236-MeV/c $\mu^+\nu$ peak falls quadratically over almost five orders of magnitude. Also note the wide momentum acceptance of the spectrograph, which ensures an almost flat acceptance of about 100 msr between 120 and 250 MeV/c. The continuum in the muon spectrum and the slight lower tail of the $\mu^+\nu$ peak are due to the $\mu^+\nu\gamma$ decays which evaded photon veto. This assignment was checked by Monte Carlo calculations, and was found to be consistent. To investigate the peak region, a better spectrum (FWHM ~ 0.5%) from only the thin downstream stopping layers was used.

There is no distinct peak in the muon momentum spectrum except for the normal one at 236 MeV/c. From a χ^2 test assuming a fictitious peak, we set the upper limit on the mass and mixing of heavy neutrinos as shown in Fig. 3. In terms of the mixing ratio $|U_{\mu i}|^2$, where i is presumably 3 in the ordinary $\nu_e \cong \nu_1$ and $\nu_\mu \cong \nu_2$ assignment, the 90%-confidence-level limit is about 10^{-5} for $m_{\nu_i} = 100$ MeV/c^2 and 10^{-6} for $m_{\nu_i} = 200$–300 MeV/c^2. The limit becomes exceedingly loose for lighter masses as shown, 10^{-4} for $m_{\nu_i} = 70$ MeV/c^2 for instance, because of the $\mu^+\nu\gamma$ background and the finite momentum resolution of the spectrograph.

In the same figure, bounds given by other experiments are also shown. Marked "KEK" is the result of our previous $K_{\mu 2}$ range measurement,[6] and "LBL" is from the rare decay experiment $K^+ \to \mu^+\nu\bar{\nu}\nu$.[10] The bound on $|U_{\mu i}|^2$ in a different mass range can be obtained by using $\pi_{\mu 2}$ decay. Recent results are reported by Calaprice *et al.*[11] and by Abela *et al.*,[12] of which the latter gives the best limit, as shown in the figure ("SIN"). The wavy line is the bound from the result of a ν_μ-ν_τ oscillation experiment,[13] which is relevant to the $U_{\mu 3}$ mixing in our terminology.

The figure shows how sensitive the present method is in comparison with neutrino-oscillation experiments. The only mass range that is not accessed by either $K_{\mu 2}$ or $\pi_{\mu 2}$ is <5 MeV and 30–70 MeV. A similar plot on the bound of $|U_{ei}|^2$ can be made by using the K_{e2} result[14] and the recent result from the π_{e2} measurement.[15]

So far there is no positive evidence for the existence of heavy neutrinos in the mass range 5–300 MeV/c^2, but such a possibility still cannot be excluded. Further experiments with improved momentum resolution and background suppression aimed at increased sensitivity to small mixing are under way.

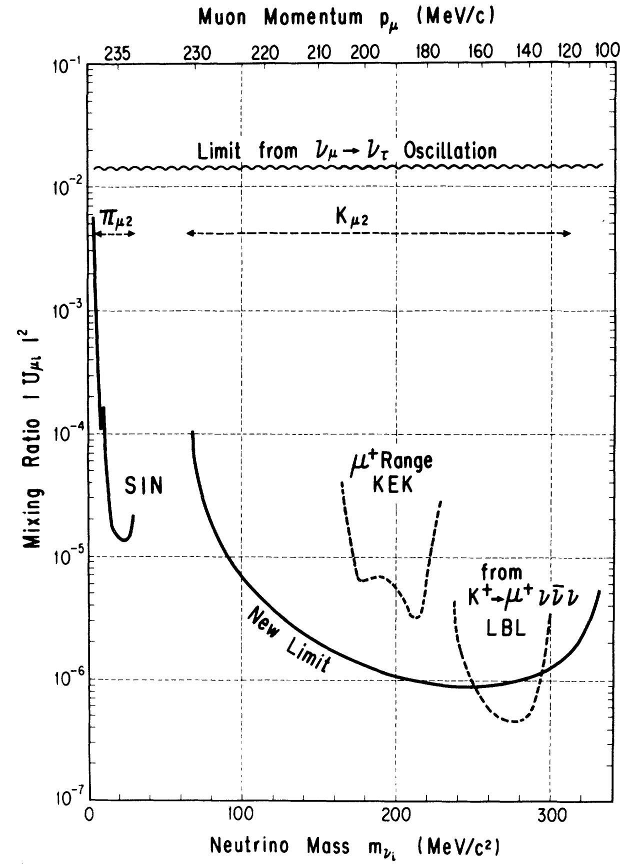

FIG. 3. On a neutrino mass vs mixing plane, the new limit (90% confidence level) obtained by the present work is indicated. Other bounds shown in the figure are from $K_{\mu 2}$ range measurement (Ref. 6), $K^+ \to \mu^+\nu\bar{\nu}\nu$ decay experiment (Ref. 10), and recent $\pi_{\mu 2}$ heavy-neutrino search (Ref. 12). A wavy line shows the limit from the result of a neutrino-oscillation measurement (Ref. 13).

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