Limit on the Muon Neutrino Mass from $K^0 \mu^3$ Decay Spectra

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Recent upgrades to the BNL-AGS have made it possible to make many high statistics measurements. Here we will consider the statistics and the resolution needed to improve the limit on the muon neutrino mass using $k_L^0 \rightarrow \pi^\pm \mu^\mp \nu_\mu$ decays. The method relies on the shape of the invariant mass distribution of the pion and the muon, $m_{\pi\mu}$, near the end point where the neutrino energy is low in the center of mass[1]. The use of simultaneously detected $k_L^0 \rightarrow \pi^+ \pi^-$ events to calibrate the mass scale and understand the resolution of the spectrometer reduces the sensitivity of this method to previously measured particle masses and to the magnetic field in the spectrometer. An additional check on the experimental method can be obtained by measuring the endpoint of $k_L^0 \rightarrow \pi^\pm e^\mp \nu_e$ decays in which one does not expect to observe a non-zero neutrino mass at the sensitivity level of this experiment. Finally, by comparing the end point spectra for neutrinos and antineutrinos one can obtain the most stringent limit on a neutrino-antineutrino mass difference, a non-zero value of which would violate CPT invariance. The only other method that limits a neutrino-antineutrino mass difference is the measurement of π^+ and π^- lifetimes, if one attributes the difference in the lifetimes to the dependence of the decay amplitude on neutrino mass[2,3].

The V-A theory of weak interactions predicts little dependence of the k_{i3} matrix element on the neutrino mass. The boundary of the Dalitz plot does, however, depend on the neutrino mass. In the case of zero neutrino mass the $m_{\pi\mu}$ distribution approaches m_k with the first derivative zero, and in the case of non-zero neutrino mass the same distribution terminates before approaching m_k . The measured quantity, $m_{\pi\mu}$, at the endpoint is simply related to the neutrino energy in the kaon center of mass by the following formula:

$$E_\nu = \frac{m_k^2 - m_{\pi\mu}^2 + m_\nu^2}{2m_k} \approx \frac{(m_k + m_{\pi\mu})}{2m_k} (m_k - m_{\pi\mu}) \approx m_k - m_{\pi\mu}.$$

Since m_k is effectively measured in the same experiment by using $k_L^0 \rightarrow \pi^+ \pi^-$ decays, the neutrino energy measurement is independent of the kaon mass. Furthermore, the

dependence on pion mass is only in second order, and therefore the pion mass uncertainty (0.4 keV) contributes only about 0.23 keV to the neutrino energy uncertainty.

The previous best experiment of this type achieved mass limits of 725 keV for the muon neutrino and 500 keV for the electron neutrino at 90% confidence level [1]. The experimenters collected 2130 well identified $k_L^0 \rightarrow \pi^\pm \mu^\mp \nu_\mu$ events with $m_{\pi\mu} > 493.5 \text{ MeV}$ (The fraction of the total spectrum in the Dalitz plot that is above this mass without dilution due to resolution smearing is 3.1×10^{-5}). They used the invariant mass spectrum including the non-Gaussian tails of $k_L^0 \rightarrow \pi^+ \pi^-$ events to calibrate the absolute mass scale and also to simulate the experimental resolution. The lower limit on the mass window is dictated by the need to suppress background arising from $k_L^0 \rightarrow \pi^+ \pi^-$ events in which one of the pions either decays in flight or is misidentified as a muon. Kinematically this background should not populate events with $m_{\pi\mu}$ above 489 MeV. This is seen most simply from the use of the following approximation for two body invariant mass in the laboratory frame:

$$m_{12}^2 \approx m_1^2 + m_2^2 + \frac{p_2}{p_1} m_1^2 + \frac{p_1}{p_2} m_2^2 + p_1 p_2 \theta^2$$

where p_1, p_2 , and θ are the laboratory momentum of particle 1, particle 2 and the laboratory angle between particles 1 and 2, respectively. In the extreme case that the momentum of the misidentified muon is much larger than the momentum of the pion the invariant mass will be: $m_{\pi\mu}^2 \approx m_k^2 - (m_\pi^2 - m_\mu^2)$. Errors in momentum measurements cause background events to leak out of this kinematic limit to populate the end point region.

One must collect much higher number of events with $m_{\pi\mu} > 493.5 \text{ MeV}$ with better mass resolution and muon identification to improve the muon neutrino mass limit. Experiment E871, a search for $k_L^0 \rightarrow \mu^\pm e^\mp$, at the BNL-AGS offers such a possibility [4-5]. E871 is a two arm magnetic spectrometer optimized for two body charged decays of neutral long lived kaons. Two magnets provide nearly independent measurements of the momentum of each particle. A Cerenkov counter, lead glass, and a fine grained muon range system provides redundant particle identification. The trigger and data acquisition system is built to take data at very high rates to achieve sensitivities of 10^{-12} for two body charged decays of the k_L^0 .

The estimated mass resolution for E871 is 1.13 MeV for $k_L^0 \rightarrow \pi^+ \pi^-$ events. I have computed the number of $k_L^0 \rightarrow \pi^\pm \mu^\mp \nu_\mu$ events with $m_{\pi\mu} > 493.5 \text{ MeV}$ necessary as a function of the limit on m_{ν_μ} assuming a Gaussian mass resolution with $\sigma_m = 0.5, 1.0$ and 1.5 MeV ; see Figure 1. Barring systematic error the number of events needed to achieve a sensitivity of 100 keV (a factor of 2 better than the best 90% confidence level limit of 220 keV from pion decay at rest [6]) is about 3.0×10^5 . The number of events needed increases very rapidly as the limit is lowered mainly because the V-A shape

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approaches the kaon mass with zero slope so that in the case of zero neutrino mass there are no events at the end point. Most possible systematic errors, such as variation in the spectrometer acceptance over the fitted mass range or background contamination, will either change the shape smoothly or cause the overall normalization to shift. A non-zero neutrino mass should cause a relatively abrupt change in the shape only at the endpoint, therefore the systematic errors should not be a major difficulty. This, of course, will have to be studied with actual data. I have used the geometric dimensions of the E871 spectrometer, the appropriate kaon spectrum, and the requested intensity to compute the rate of $k_L^0 \rightarrow \pi^\pm \mu^\mp \nu_\mu$ events with $m_{\pi\mu} > 493.5$ MeV to be about 300 per hour. E871 should be able to collect more than enough events in a 4000 hour run for this measurement.

Figure 1. Number of $k_L^0 \rightarrow \pi^\pm \mu^\mp \nu_\mu$ events needed with $m_{\pi\mu} > 493.5$ MeV versus the muon neutrino mass sensitivity for various mass resolutions. This was calculated assuming that the data will be binned with a binsize equal to or smaller than the mass sensitivity. A maximum likelihood method using the small event statistics at the endpoint should yield somewhat better sensitivity.

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