Search for Massive Neutrinos in the decay $\pi^+ \rightarrow e^+ \nu$

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For the PIENU Collaboration


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Because of helicity the \( \pi^+ \to e^+ \nu \) decay is suppressed over the \( \pi^+ \to \mu^+ \nu \) decay by a factor \( (m_e/m_\mu)^2 \).

\[
R_{SM}^{e/\mu} = \frac{\Gamma(\pi \to e\nu + \pi \to e\nu\gamma)}{\Gamma(\pi \to \mu\nu + \pi \to \mu\nu\gamma)} = 1.2352(1) \times 10^{-4}
\]

The presence of a heavy neutrino changes this helicity relation and alter the value of the branching ratio.

If the heavy neutrino mass is \( M_\nu = 60\text{~to}130 \text{~MeV/c}^2 \) additional low energy positron peak would be detected in the \( \pi^+ \to e^+ \nu_e \) spectrum.

(For measurement of the pion branching ratio at TRIUMF, see Talk: C. Malbrunot - Parallel 5G - Lepton Universality and Forward Jets)
Experimental Method

- Stop pions in an active target Scintillator
- Select $\pi^+ \rightarrow e^+$ events

Required

- High purity pion beam
- Knowledge of response function of calorimeter
- Good $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ background suppression

Target

- $\pi^+$
- $\mu^+$
- $4 \text{ MeV}$
- $e^+$

Full Energy spectrum

- $\pi^+ \rightarrow \mu^+ \rightarrow e^+$
- $\pi^+ \rightarrow e^+$
- $\sim 500 \text{ ns time gate}$

Suppressed Energy spectrum

- Nal energy [MeV]
- CsI
- Nal
- CsI

Counts

07/28/2011
The PIENU detector

- Large solid angle ($\Omega/4\pi = 20\%$)
- Good statistics
- Contain shower leakage (CsI)
- Decay positron travels few material

- Silicon near target & WC
- Good tracking
- Detection of Decay In Flight

- High resolution calorimeter
  Nal : 1% $\sigma$ at 70 MeV

- Use of fast digitizers
  500 MHz
  separation between $\pi \rightarrow \mu \rightarrow e$ and $\pi \rightarrow e$
The PIENU detector (cont'd)

Monolithic NaI(Tl) crystal surrounded by 97 pure CsI crystals

PIENU II is movable and detachable from PIENU I for line shape measurement at various e+ entrance angles.
50 kHz pion stop in Target with 2% positrons and 10% muons

Triggers: 600Hz

- \( \pi \rightarrow e \nu \): Early (2-50 ns)
- \( \pi \rightarrow \mu \rightarrow e \): Prescaled (1/16)
- Monitor and calibration triggers: \( e^+ \) beam, Xe, cosmic-ray

Waveforms are recorded

A. Aguilar-Arevalo et al., Nucl. Instr. and Meth. A 609 (2009)
Target energy

4 MeV

Kink angle in \( \pi^+ \) track

Suppression of background

Target energy

\( \pi^+ \)

Total Energy deposited in Target

Downstream & Upstream tracking enables background suppression based on vertex position

Panoramic display
Suppression of background (cont'd)

Summary of cuts:
- Time cut (takes advantage of the difference in lifetimes)
- Target energy cut *
- Kink cut
- Pulse Shape cut
- Z vertex *
- CsI veto *
- Radial cut in WC3 *

Optimization of cuts by minimizing
\[ S = \frac{\sqrt{N_{<54\,\text{MeV}}}}{N_{>54\,\text{MeV}}} \]

* Cuts with energy dependence

Tighter angular cuts = better peak resolution
Only effective above 47 MeV
Analysis region divided:
1) 0-47 MeV: no angular cut
2) 47-60 MeV: 35 deg cut

<table>
<thead>
<tr>
<th>Positron energy [MeV]</th>
<th>Counts</th>
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<tbody>
<tr>
<td>0-47 MeV</td>
<td>Britton et al. Exp.</td>
</tr>
<tr>
<td>47-60 MeV</td>
<td>This analysis All cuts</td>
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<td>70-80 MeV</td>
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<tr>
<th>Angle cut: 20°, 30°, 35°, 40°, 70°</th>
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\[ S = \frac{\sqrt{N_{<54\,\text{MeV}}}}{N_{>54\,\text{MeV}}} \]
Response function of the calorimeter was measured with a positron beam at various angles. **Photo-nuclear reactions** in the NaI crystal were discovered.

Neutrons are generated by photo-nuclear reactions $I(\gamma,n)$ in NaI. If the **neutron escapes** from the crystal, the separation energy of the neutron is lost.

The lineshape spectrum is **subtracted** from the pienu data before performing the massive neutrino search.
Massive neutrino search

Search for extra peak in the suppressed spectrum

- Components of the fit:
  - $\pi-\mu-e$ (Michel spectrum for $t = 150-500$ ns)
  - $\mu\text{DIF}$ (distorted Michel spectrum)
  - $A*\exp(B*t) + C$ (to simulate background and tail)
  - Extra peak (MC generated)

Fitting regions:
- 9-62 MeV (35 degree cut)
- 9-50 MeV (No angle cut)
- 0.5 MeV steps. Peak position fixed. Fit over entire energy region.

Fit of 35 deg. spectrum without peak.
$\chi^2$/DOF = 1.00
$\pi\text{DIF}=2\%$ of pienu
$\mu\text{DIF}=3\%$ of pienu

Energy spectrum for $\mu\text{DAR}$ and $\mu\text{DIF}$

Peak shapes for 35 deg. data

Counts

Normalized counts

Positron energy [MeV]
Amplitude of the potential peaks and the associated errors converted to upper limit on the ratio $\Gamma(\pi^+ \to e+\nu_i)/\Gamma(\pi^+ \to e+\nu_e)$ as a function of positron energies (or massive $\nu$ mass).

Acceptance correction for energy dependent cuts applied

Factor of 5 improvement over prior limits on the mass range $M_\nu = 90\sim115$ MeV/c$^2$
<table>
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<tr>
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Data used for this analysis
1/2 million $\pi^+ \rightarrow e^+$ events after selection cuts
Conclusions

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6 million $\pi^+ \rightarrow e^+$ events accumulated so far