Improved Search for Heavy Neutrinos and a Test of Lepton Universality in the Decay $\pi \rightarrow e\nu$

Precision Physics at High Intensities
CIPANP18

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for the PIENU collaboration
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Introduction

• Today’s presentation will include two recently published results from the PiENu Experiment:

  • Limits on heavy neutrinos coupling to electrons
    – A. Aguilar-Arevalo et al., Phys. Rev. D 97, 072012 (2018)
  • Test of Lepton Universality in pion decay
    – A. Aguilar-Arevalo et al., Phys. Rev. Lett. 115, 071801 (2015)

• Plus the status of the full analysis for the $\pi \rightarrow e\nu$ branching ratio
The PiENu Experiment and Heavy Neutrinos

PiENu stops pions to make a precise measurement of the rate for the rare decay $\pi \rightarrow e\nu$.

It is also sensitive to $\pi \rightarrow ev_h$ for $60 < M_\nu < 135$ MeV/c$^2$ and sets impressive limits on the coupling of a $\nu_h$ to the electron ($|U_{ei}|^2$)

A. de Gouvêa and A. Kobach

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D. I. Britton et al., Phys. Rev. D 46, R885 (1992).
Importance of Heavy Neutrino Searches

Many extensions of the Standard Model include additional massive neutrinos. The νMSM includes three sterile neutrinos, two of which may have masses in the range probed by meson decays.[1]

Other models (such as dark matter or thermalization) also have neutrino masses in the MeV/c\(^2\) range.[2]

[1] A. Boyarsky, O. Ruchayskiy and M. Shaposhnikov, Ann.Rev. Nucl. Part. Sci. 59, 191 (2009).
[2] B. Bertoni, S. Ipek, D. McKeen, and A. Nelson, JHEP, 04, 170 (2015).
  B. Batell, T. Han, D. McKeen, and B. Haghi, arXiv:1709.07001, (2015).
  T. Appelquist, M. Piai, and R. Shrock, Phys. Rev. D 69, 015002 (2004).
The PiENu Experiment at TRIUMF

**Beam:**
60kHz pions @ 75 MeV/c
π : μ : e = 85 : 14 : 1

**Detector:** [1]
Acceptance: 20%
Plastic Scintillators
NaI(Tl) + CsI Calorimeter
Wire Chambers
Silicon Strips

**Energy resolution:**
2.2% FWHM @ 70MeV

**Temperature Stabilization**

**Data taking:**
2009-2012

[1] A. Aguilar-Arevalo et al., Nucl. Instrum. Methods Phys.Res., Sect. A 791, 38 (2015).
Ideal and observed spectra

two-body decay:
monoenergetic positron
\( \pi \rightarrow e \nu \) \( E_e = 69.8 \text{ MeV} \)

for \( m_h = 90 \text{ MeV}/c^2 \)
\( \pi \rightarrow e \nu_h \) \( E_e \approx 40 \text{ MeV} \)

Simulation of
spectrum including
detector response

Add positrons from
\( \pi \rightarrow \mu \rightarrow e \) decay chain
Suppressed spectrum

Suppress $\pi \rightarrow \mu \rightarrow e$ events with cuts including timing (ns), target energy, and Z vertex.

Simulation of spectrum including effects of detector.

$\pi \rightarrow \mu \rightarrow e$ decay chain suppressed.
Search for heavy neutrinos

Start with suppressed spectrum
Search for heavy neutrinos

Start with suppressed spectrum

Fit known components prior to neutrino search

Extrapolation of $\pi \rightarrow ev$ tail from simulation
Search for heavy neutrinos

Start with suppressed spectrum
Fit known components prior to neutrino search
Extrapolation of $\pi \rightarrow ev$ tail from simulation
Include $\pi \rightarrow \mu \rightarrow e$ shape from late-time events
Search for heavy neutrinos

Fit known components prior to neutrino search

Extrapolation of $\pi \rightarrow ev$ tail from simulation

Include $\pi \rightarrow \mu \rightarrow e$ shape from late-time events

Add component for muon decay-in-flight
Search for heavy neutrinos

Extrapolation of $\pi \to ev$ tail from simulation

Include $\pi \to \mu \to e$ shape from late-time events

Add component for muon decay-in-flight

Background fit over 4 – 56 MeV
Search for heavy neutrinos

Include $\pi \rightarrow \mu \rightarrow e$ shape from late-time events

Add component for muon decay-in-flight

Background fit over 4 – 56 MeV

Residuals from background fit shown in insert
Search for heavy neutrinos

Step signal shape for candidate $\pi \rightarrow e \nu_h$ decay across positron energy spectrum

Sample test signal for $\pi \rightarrow e \nu_h$ at 40 MeV shown

Shape of test signal at each energy follows detector response
Search for heavy neutrinos: Result

\[
\frac{1}{\text{Acc}(E_{e^+})} \frac{N(\pi \to e\nu_i)_{UL}}{N(\pi \to e\nu)} = |U_{ei}|^2_{UL} \rho_e(E_{e^+})
\]

NA62 Collaboration, Phys. Lett. B 778, 137 (2018)
Precise prediction for the $\pi \to e\nu$ decay rate

Pion Decay Rate:  
\[
\Gamma_{\pi \to l\nu_l} = G^2 m_\pi f_\pi^2 m_l^2 \left(1 - \frac{m_l^2}{m_\pi^2}\right)^2
\]

Branching Ratio (assuming **LEPTON UNIVERSALITY**):

\[
R_0 = \frac{\Gamma_{\pi \to e\nu_e}}{\Gamma_{\pi \to \mu\nu_\mu}} = \frac{m_e^2}{m_\mu^2} \left(\frac{m_\pi^2}{m_\mu^2} - \frac{m_e^2}{m_\pi^2}\right)^2 = 1.28336(2) \times 10^{-4}
\]

**With Radiative and Structure Corrections:**

\[
R = R_0 \times \left[1 + \frac{\alpha}{\pi} \left\{F\left(\frac{m_e}{m_\pi}\right) - F\left(\frac{m_\mu}{m_\pi}\right) + \frac{m_\mu^2}{m_\pi^2}\left(c_2 \ln \frac{m_\rho^2}{m_\pi^2} + c_3\right) + c_4 \frac{m_\pi^6}{m_e^2 m_\rho^4}\right\} + c_5 \left(\frac{\alpha}{\pi} \ln \frac{m_\mu}{m_e}\right)^2 + ..\right]
\]

S. Berman: Phys.Rev.Lett. 1(12), 468 (1958)
T. Kinoshita: Phys.Rev.Lett. 2(11), 477 (1959)
T. Goldman, W.Wilson: Phys.Rev.D 14(9), 2428 (1976)
W. Marciano, A. Sirlin: Phys.Rev.Lett. 36(24), 1425 (1976)

M. Terent’ev: Yad. Fiz. 18(870) (1973)
V.Cirigliano, I.Rosell: Phys.Rev.Lett. 99(23), 231801 (2007)

\[
R_{e/\mu}^{exp} = \frac{\Gamma(\pi^+ \to e^+\nu(\gamma))}{\Gamma(\pi^+ \to \mu^+\nu(\gamma))}
\]

\[
R_{e/\mu}^{Th} (10^{-4}) = 1.2352(2)
\]
Analysis: $\pi \rightarrow e\nu$ decay

$E < 52\text{MeV}$

$E > 52\text{MeV}$

Low Energy time (ns)

High Energy time (ns)

Simultaneous fit of both time spectra with all components

$\chi^2/\text{dof} = 1.02$
Low Energy Tail (LET)

• Largest correction
• From data: MC does not reproduce hadronic reactions (photoinuclear with neutron escape)[1]
• Positron beam (0°)

Estimated LET: (3.06 +/- 0.10) %

Combine LET estimate from positron beam with estimate from suppressed spectrum

[1] A. Aguilar-Arevalo et al., Nucl. Instrum. Methods Phys. Res., Sect. A 621, 188 (2010).
Initial Result: $\pi \to ev$ decay

Based on one month (~12% of data)

Result blinded until:
- all cuts finalized
- stability checks OK
- syst. uncertainties set
Lepton Universality Summary

\[ \frac{\Gamma(\pi \to e\nu)}{\Gamma(\pi \to \mu\nu)} = \frac{g_e^2}{g_\mu^2} R_{e/\mu}^{th} \]
\[ \frac{g_e}{g_\mu} = 0.9996 \pm 0.0012 \]

Complementary to tests with heavy quarks

The ensemble of B decay results appear to violate lepton universality [1]

[1] See recent summary in CERN Courier, 58, 23 (2018)
In this conference: G. Onderwater, A. Datta, O. Witzel, ...
Status of full analysis for $R_{e/\mu}^{exp}$

All data have been processed
~8 times more data than for 2015 result
$10^7 \pi \rightarrow ev$ events

Value of branching ratio is blinded
Final review of cuts underway
Statistical uncertainty

<0.1% in $R_{e/\mu}^{exp}$
dependent on cut for solid angle acceptance

2012 data
40% of total
$2.5 \times 10^6$ $\pi \rightarrow ev$ events
Status of full analysis for $R_{e/\mu}^{\text{exp}}$

- Systematic uncertainties under evaluation
  - approx. equal to statistical uncertainty
  - two examples of improved study of backgrounds

- pion stops upstream of target
- pion interacts in target

- select “positron” in tgt
- good events
- false triggers

- cut ?
- positron
- proton

- Time in tgt (ns)
- $E$ in downstream counters
Thank You
on behalf of the
PiENu Collaboration

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Extra slides
Energy dependent acceptance

- Correction for heavy neutrino limits