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Precision Measurement of the $\pi^+ \to e^+ \nu_e$ Branching Ratio in the PIENU Experiment

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The PIENU experiment at TRIUMF aims to measure the branching ratio of the pion decay modes $R^\pi = [\pi^+ \to e^+ \nu_e(\gamma)]/[\pi^+ \to \mu^+ \nu_\mu(\gamma)]$ with precision of $< 0.1\%$. Precise measurement of R^π provides a stringent test of electron-muon universality in weak interactions. The current status of the PIENU experiment and future prospects are presented.

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1. Introduction

The pion branching ratio, $R^{\pi} = [\pi^+\to e^+\nu_e(\gamma)]/[\pi^+\to\mu^+\nu_\mu(\gamma)]$ is one of the most precisely calculated in the Standard Model (SM). The most recent theoretical prediction including radiative corrections [1, 2] gives $R^{\pi}_{\rm SM} = (1.2352\pm0.0002)\times10^{-4}$. The $\pi^+\to e^+\nu_e$ branching fraction is suppressed to the order of 10^{-4}, which is well known as "helicity suppression". A precise measurement of R^{π} provides a sensitive test of the SM hypothesis of electron-muon universality. The previous experimental results at TRIUMF and PSI are respectively $R^{\pi}_{\rm exp} = [1.2265\pm0.0034(\rm stat)\pm0.0044(\rm syst)]\times10^{-4}$ [3] and $R^{\pi}_{\rm exp} = [1.2346\pm0.0035(\rm stat)\pm0.0036(\rm syst)]\times10^{-4}$ [4]. Both experiments obtained comparable levels of statistical and systematic uncertainties; however there is a room for improvement by two orders of magnitude in precision to reach the precision of the theoretical result.

The goal of the PIENU experiment is to improve the accuracy of R^{π} by a factor of 5, to <0.1%, which corresponds to 0.05% for the universality test. This precision also allows access to new physics up to the mass scale of 1000 TeV/c^2 for helicity unsuppressed pseudoscalar interactions [2]. Examples of the new pseudoscalar interactions probed include R-parity violating SUSY [5], leptoquarks [6], and the effects of charged Higgs bosons [2]. The $\pi^+\to e^+\nu_e$ decay measurement is also sensitive to the existence of heavy sterile neutrino mixing [7] through the R^{π} measurement [8, 9] and a direct additional peak search [10].

2. The PIENU Experiment

Figure 1 shows the schematic of the PIENU detector and the pion decay modes of interest. The PIENU detector was located at the TRIUMF M13 beam line [11]. The beam with momentum 75 MeV/c was tracked by two multi-wire proportional chambers (WC1 and WC2) and two sets of Si strip detectors (S1 and S2). After WC2, two thin plastic scintillators B1 and B2 were placed in order to measure time and energy loss for pion identification. A plastic scintillator target B3 with thickness of 8 mm was immediately downstream of S2 and the beam pions decayed at rest in the center of the target.

In order to reconstruct the decay-positron tracks and define their acceptance, another Si strip detector (S3) and multi-wire proportional chamber (WC3) were employed. Two thin plastic scintillators (T1 and T2) were used to measure the time of decay positrons. These positrons entered a large single crystal NaI(Tl) calorimeter surrounded by two rings of pure CsI crystals (97 total) to detect shower leakage. See Ref. [12] for more details of the PIENU detector.

3. Analysis

The decays $\pi^+\to e^+\nu_e$, and $\pi^+\to\mu^+\nu_\mu$ followed by $\mu^+\to e^+\nu_e\bar{\nu}_\mu$ ($\pi^+\to\mu^+\to e^+$ decay chain) have different energy and time characteristics that can be measured precisely and used to extract the ratio R^{π}. The muon in $\pi^+\to\mu^+\to e^+$ has a kinetic energy of 4.1 MeV and a range in plastic scintillators of about 1mm; the total energy of the decay positrons have a continuous distribution from 0.5 to 52.8 MeV. The decay time spectrum of $\pi^+\to\mu^+\to e^+$ distributes as $\frac{\lambda_\pi\lambda_\mu}{\lambda_\pi-\lambda_\mu}(\mathrm{e}^{-\lambda_\mu t}-\mathrm{e}^{-\lambda_\pi t})$, where λ_π and λ_μ are the decay constants of the pion and muon, respectively. In contract, the

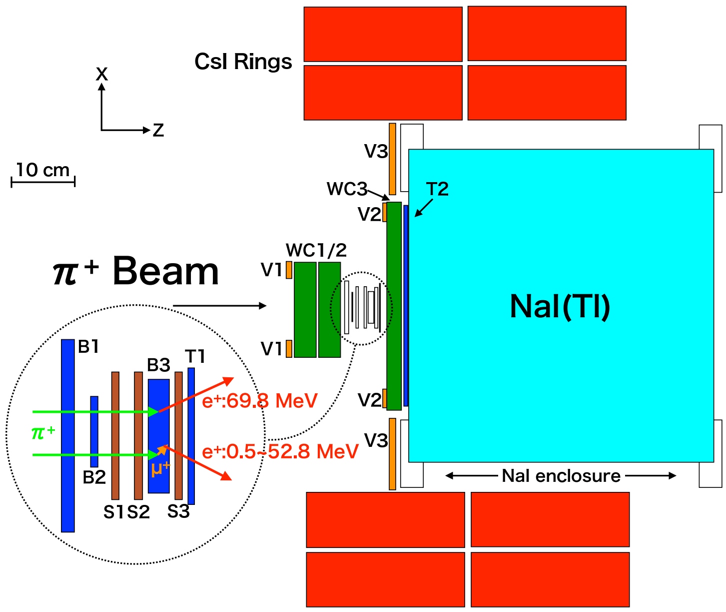

Figure 1: Schematic of the PIENU detector and pion decays.

decay $\pi^+ \to e^+ \nu_e$ produces a mono-energetic positron at 69.8 MeV, and the decay time distribution is a simple exponential curve ($\lambda_\pi e^{-\lambda_\pi t}$). R^π can be obtained from the ratio of the positron yields from $\pi^+ \to e^+ \nu_e$ decays and $\pi^+ \to \mu^+ \to e^+$ decays by taking advantage of these differences.

Figure 2 shows the energy spectrum of decay positrons in the NaI(Tl) plus CsI detectors. Two energy regions, above and below the vertical dashed black line in Figure 2 were used to distinguish the two pion decay modes. The time spectra in these two energy regions were fitted simultaneously to a fitting function including backgrounds to extract raw branching ratio ($R^\pi_{\rm raw}$), to which corrections were applied.

The most important correction for $R^\pi_{\rm raw}$, which dominated the systematic uncertainties, was the $\pi^+ \to e^+ \nu_e$ low-energy tail due to shower leakage from the calorimeters. The amount of the $\pi^+ \to e^+ \nu_e$ low-energy tail below 52 MeV was estimated using two ways. First, the dominant $\pi^+ \to \mu^+ \to e^+$ events were suppressed in the energy spectrum, and the $\pi^+ \to e^+ \nu_e$ low-energy tail was estimated by subtracting the remaining $\pi^+ \to \mu^+ \to e^+$ suppressed spectrum. Second, a special measurement of the energy spectrum using a mono-energetic positron beam was performed in order to obtain the low-energy tail empirically.

Additionally, the difference of the positron acceptance between $\pi^+ \to e^+ \nu_e$ and $\pi^+ \to \mu^+ \to e^+$ events also required a significant correction. The uncertainty of the acceptance correction was much improved compared to the previous TRIUMF experiment because the PIENU detector solid angle was about ten times larger than the previous experimental setup [3, 12]. See Refs. [8, 13] for more details of the analysis.

4. Status and Conclusion

The PIENU experiment completed data taking in 2012, and the result of the partial data set

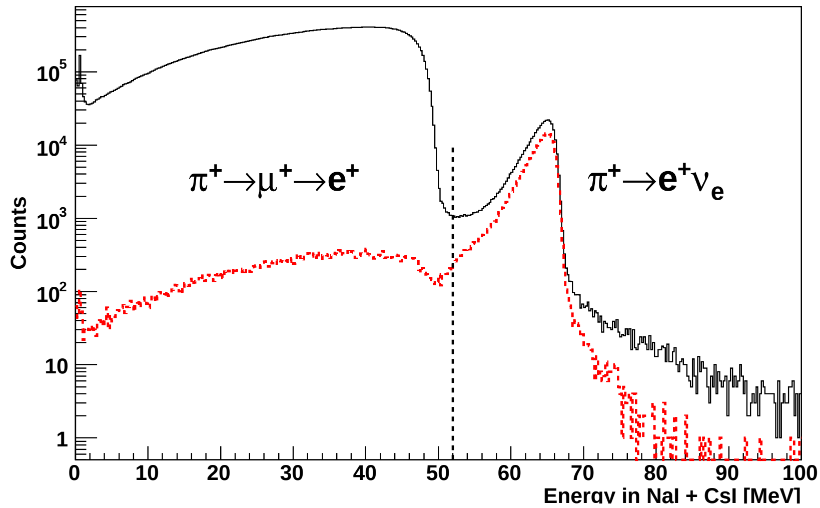

Figure 2: Measured energy spectrum of decay positrons without (solid black line) and with (dashed red line) $\pi^+ \to \mu^+ \to e^+$ suppression. Dashed vertical line shows energy threshold at 52 MeV.

analysis taken in 2010 was published in Ref. [8]. For this data set, the value of R^π including all corrections is $R^\pi = [1.2344 \pm 0.0023(\text{stat}) \pm 0.0019(\text{syst})] \times 10^{-4}$, which is consistent with the SM prediction. This result improves the test of electron-muon universality to $g_\mu / g_e = 1.0004 \pm 0.0012$ for the charged current.

A search for massive neutrino in the mass range of $0-130$ MeV/c^2 was also performed using the 2009 and 2010 data sets. This analysis improved the 90% confidence-level limits on the neutrino mixing parameter U_{ei} between the weak electron-neutrino eigenstate and a hypothetical massive eigenstate m_{ν_i} by a factor of up to four. Details of this analysis are described in Refs. [8, 9, 10].

At present, analysis of the remaining data is in progress, and the 2011 data set was also analyzed. By combining results of the 2010 and 2011 data sets, the uncertainty of R^π is improved to $\Delta R^\pi = [0.0014(\text{stat}) \pm 0.0013(\text{syst})] \times 10^{-4}$, which corresponds to 0.15% in precision, an improvement by a factor of 3 [13]. Full data set analysis is expected to improve the precision of R^π to $< 0.1\%$ and will be finished in a few years.

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PoS(KMI2017)034

References

[1] V. Cirigliano and I. Rosell, JHEP. 10 (2007) 005.

[2] D. A. Bryman, W. Marciano, R. Tschirhart, and T. Yamanaka, Annu. Rev. Nucl. Part. Sci. 61, 331 (2011).

[3] D. I. Britton et al., Phys. Rev. Lett. 68, 3000 (1992) and Phys. Rev. D 49, 28 (1994).

[4] G. Czapek et al., Phys. Rev. Lett. 70, 17 (1993).

[5] M. J. Ramsey-Musolf et al., Phys. Rev. D76, 095017, (2007).

[6] O. Shanker. Nuclear Physics B, 204(3):375-386. (1982).

[7] T. Asaka et al., JHEP 05, 030 (2009).

[8] A. Aguilar-Arevalo et al., Phys. Rev. Lett. 071801, 115 (2015).

[9] S. Ito et al., Hyperfine Interact. 238 (2017) no.1, 1.

[10] M. Aoki et al., Phys. Rev. D 052002, 84 (2011).

[11] A. Aguilar-Arevalo et al., Nucl. Instrum. Methods. A609, 102 (2009).

[12] A. Aguilar-Arevalo et al., Nucl. Instrum. Methods. A791, 38 (2015).

[13] S. Ito, Ph.D thesis, Osaka University (2016).