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Search for heavy neutrinos in $\pi^+\to\mu^+\nu$ decay and status of lepton universality test in the PIENU experiment

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In the present work of the PIENU experiment, heavy neutrinos were sought in pion decays $\pi^+\to\mu^+\nu$. No evidence for extra peak was found in the muon kinetic energy spectrum and 90% confidence level upper limits were set on the neutrino mixing matrix $|U_{\mu i}|^2$ in the mass range of 15.7 to 33.8 MeV/c^2, improving an order of magnitude over previous experiments. Current status of lepton universality test is also reported.

KEYWORDS: Heavy neutrino, pion decay, lepton universality

1. Introduction

The PIENU experiment aims to measure the pion branching ratio $R^\pi = \Gamma[\pi^+\to e^+\nu_e(\gamma)]/\Gamma[\pi^+\to\mu^+\nu_\mu(\gamma)]$ with precision of $< 0.1\%$, which provides a stringent test of the Standard Model (SM) hypothesis of lepton universality [1]. The PIENU experiment is also sensitive to search for heavy neutrinos (ν_H) associated with the pion decay [2,3]. Some models predict the mixing of massive neutrinos with SM neutrinos. An example of a heavy neutrino model is the Neutrino Minimal Standard Model [4] that adds three massive gauge-singlet fermions to the SM.

Search for heavy neutrinos associated with the decay $\pi^+ \to \mu^+ \nu$ has been completed using the full data sets of the PIENU experiment [2]. The results of the analysis for heavy neutrinos in $\pi^+ \to \mu^+ \nu$ decay and current status of lepton universality test is presented.

2. The PIENU experiment

The decays $\pi^+ \to e^+ \nu_e$ and $\pi^+ \to \mu^+ \nu_\mu$ followed by $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$ decays ($\pi^+ \to \mu^+ \to e^+$ chain) have different energy characteristics that can be precisely measured and used to extract the pion branching ratio and search for heavy neutrinos. The muon in $\pi^+ \to \mu^+ \to e^+$ has kinetic energy $T_\mu = 4.1$ MeV and range in plastic scintillators of about 1 mm; the total energy of decay positrons has a continuous distribution from 0.5 to 52.8 MeV. The decay $\pi^+ \to e^+ \nu_e$ produces a mono-energetic positron at 69.8 MeV.

Figure 1 shows the schematic of the PIENU detector [5]. The PIENU experiment was carried out at M13 beam line in TRIUMF [6]. The beam with momentum 75 MeV/c was tracked by two multi-wire proportional chambers (WC1 and WC2). Following WC2, the beam was degraded by two thin plastic scintillators B1 and B2 to provide time and energy loss for beam pion identification. After B2, two sets of Si strip trackers (S1 and S2) were located to detect pion decay in flight events. The pion beams stopped in the center of an 8 mm plastic scintillator target (B3) and decayed at rest.

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) provided the time of decay positrons. The energy of decay positrons were measured by a NaI(Tl) calorimeter surrounded by 97 pure CsI crystals for shower leakage detection.

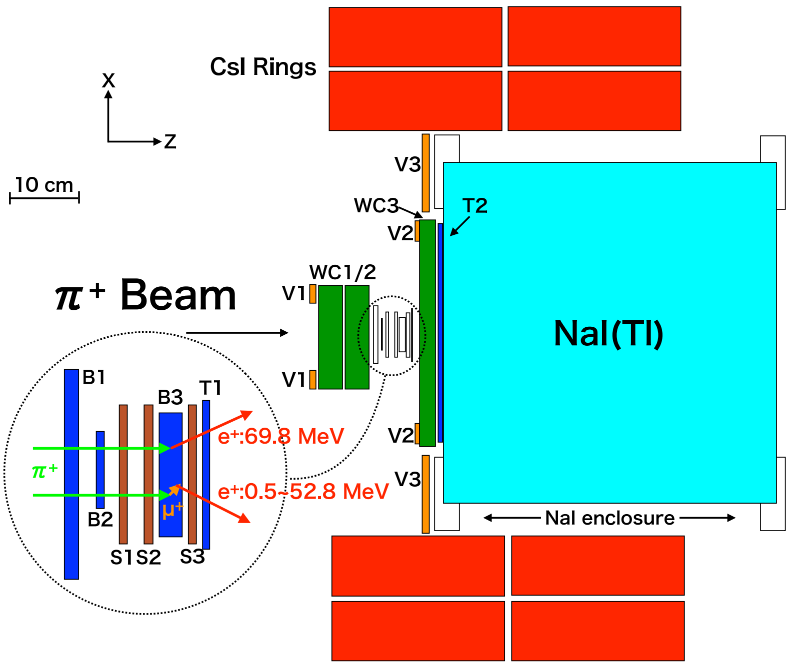

Fig. 1. Schematic of the PIENU detector [5].

3. Heavy neutrino search

The ratio of the decay rate $\pi^+ \to \mu^+ \nu_H$ to the normal decay rate $\pi^+ \to \mu^+ \nu_\mu$ can be written as [7]

$$\frac{\Gamma(\pi^+ \to \mu^+ \nu_H)}{\Gamma(\pi^+ \to \mu^+ \nu_\mu)} = |U_{\mu i}|^2 \bar{\rho}(m_H) \tag{1}$$

where $U_{\mu i}$ is the neutrino mixing matrix, m_H is the mass of the heavy neutrino ν_H, and $\bar{\rho}(m_H)$ is a kinematic factor. Heavy neutrinos can be sought by search for low energy peaks due to heavy neutrinos in the muon energy spectrum. The experimental limits of $|U_{\mu i}|^2$ in the mass range 5 – 30 MeV/c^2 have been set at a level of 10^{-2} – 10^{-5} by Abera et al. [8]. Heavy neutrinos in the mass range 30 – 33.9 MeV/c^2 have also been sought by Bryman and Numao [9], providing the upper limits 10^{-3} – 10^{-4}. Lighter mass region 1 – 20 MeV/c^2 has been searched for by Daum et al. using Germanium detector [10], and the upper limits on $|U_{\mu i}|^2$ with an order of 10^{-5} have been set.

In the PIENU experiment, the waveform of each plastic scintillator was read out by 500 MHz Flash ADC system [11]. To search for heavy neutrino in $\pi^+ \to \mu^+ \nu$ decay, a second pulse in B3 due to the muon kinetic energy should be identified. Figure 2 shows the energy spectrum of the second pulse (muon) in B3 after event selection cuts (e.g. $E_e < 55$ MeV, decay time $t > 200$ ns, triple pulse requirement in B3, and so on). Major background in $T_\mu < 3.3$ MeV is radiative pion decay ($\pi^+ \to \mu^+ \nu_\mu \gamma$). Extra peaks were sought from 1.2 to 3.3 MeV in 0.05 MeV steps.

As shown in Fig. 2, when the muon energy T_μ was below 1.2 MeV, the pulse detection logic could not efficiently identify the peak. In order to search for extra peaks in $T_\mu < 1.2$ MeV region, the wide time window gate in B3, which fully recorded the pulses due to beam pion, decay muon from pion, and decay positron from muon, was used for. The contribution from the positron pulse, which was well separated from muon pulse by requirement of late decay time $t > 300$ ns, was subtracted from the integrated charge. Then, the contribution from beam pion about 17 MeV was subtracted from the remaining energy due to pion and muon pluses. Figure 3 shows the muon energy spectrum after subtraction. The dominant background in $T_\mu < 0$ MeV region was due to pion decay in flight (πDIF) events in or near B3.

Extra peaks due to massive neutrinos associated with $\pi^+ \to \mu^+ \nu$ were searched for and no evidence was observed. 90% confidence level upper limits in the mass range of 15.7 to 33.8 MeV/c^2 were set on the mixing matrix $|U_{\mu i}|^2$. Figure 4 shows the results of the PIENU experiment and previous experiments. In the PIENU experiment, some accidental background was minimized by precise pulse analysis and πDIF events were suppressed using tracking information by wire chambers and Si strip detectors. Additionally, more than ten times higher statistics were collected over previous experiments. Thus, upper limits on $|U_{\mu i}|^2$ were improved by an order of magnitude over the previous experiments.

Search for massive neutrinos in $\pi^+ \to e^+ \nu$ decay has also been completed. Upper limits on the neutrino mixing matrix $|U_{ei}|^2$ in the neutrino mass range 60 – 135 MeV/c^2 were set and are an order of magnitude improvement over previous results. Details of the analysis are described in Ref. [3].

4. Test of lepton universality

The $\pi^+ \to e^+ \nu_e$ branching fraction is suppressed to the order of 10^{-4}, which is well known as “helicity suppression” in the SM. The most recent theoretical prediction including radiative corrections gives $R^\pi_{\rm SM} = (1.2352 \pm 0.0002) \times 10^{-4}$ [12, 13]. A precise measurement of R^π provides a sensitive test of the SM hypothesis of lepton universality. The goal of the PIENU experiment at TRIUMF is to improve the accuracy of the branching ratio measurement to < 0.1% resulting in 0.05% precision in the universality test.

The PIENU experiment collected about 10^7 $\pi^+ \to e^+ \nu_e$ events during run periods from 2009 to 2012. The initial analysis using about 10% statistics has been completed in 2015 resulting $R^\pi_{\rm exp}$ =

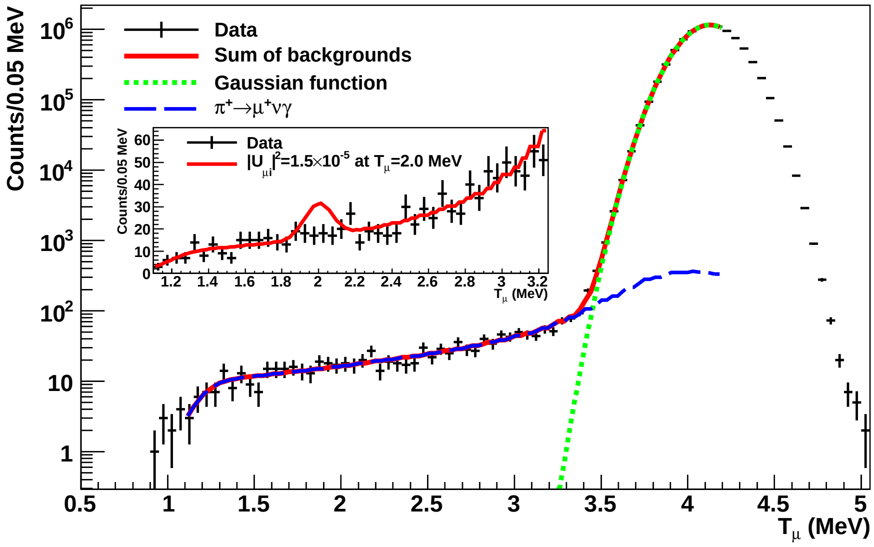

Fig. 2. Energy spectrum of the second pulse in B3 and fit results [2]. The dotted green line represents the 4.1 MeV Gaussian peak and the dashed blue line indicates radiative pion decay background. The solid red line shows the sum of those two functions. The insert box shows a hypothetical signal at $T_\mu = 2$ MeV for $|U_{\mu i}|^2 = 1.5\times10^{-5}$.

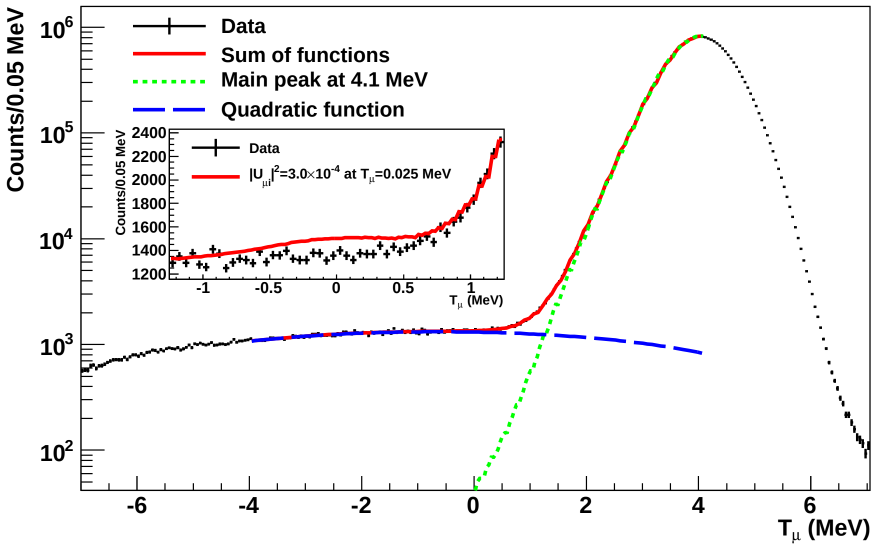

Fig. 3. Energy spectrum of the second pulse in B3 for $T_\mu < 1.2$ MeV [2]. The dotted green line represents the main peak and the dashed blue line indicates quadratic function. The solid red line shows the sum of those two functions. The insert box shows a hypothetical signal at $T_\mu = 0.025$ MeV for $|U_{\mu i}|^2 = 3.0\times10^{-4}$.

$[1.2344\pm0.0023(\text{stat})\pm0.0019(\text{syst})]\times10^{-4}$ [1], which is consistent with the SM and previous works [14, 15]. This result improved the test of lepton universality compared to previous experiments by a factor of two; $g_e/g_\mu = 0.9996\pm0.0012$ where g_e and g_μ are weak interaction coupling constants for electron and muon, respectively.

The analysis of the full data set for the PIENU experiment is in the final stages. The value of the

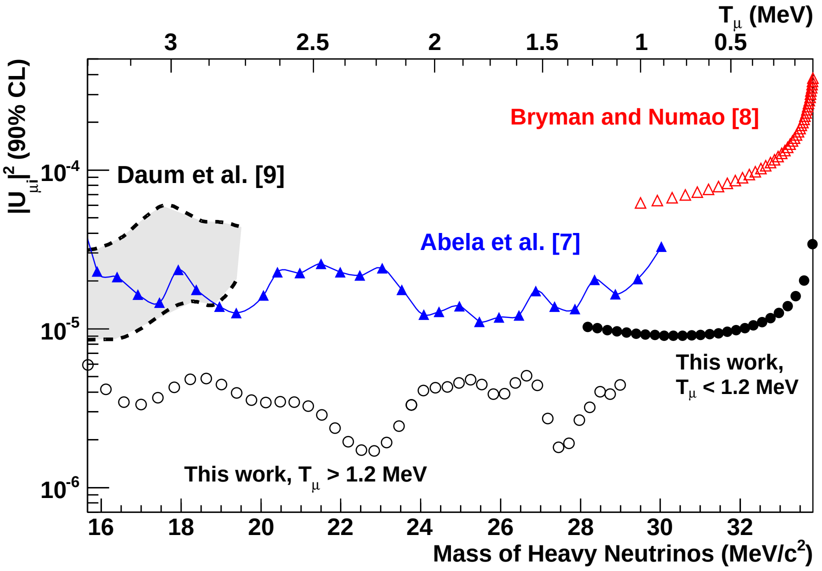

Fig. 4. 90% confidence level upper limits on $|U_{\mu i}|^2$ in the PIENU experiment [2] and previous experiments [8–10].

branching ratio is still blinded but systematic studies are almost finalized. The expected uncertainty will be close to about 0.1% for the pion branching ratio.

5. Conclusion

Massive neutrino analysis using full data sets of the PIENU experiment has been completed. No evidence was observed and upper limits on the neutrino mixing matrix $|U_{\mu i}|^2$ were set in the mass range 15.7 – 33.8 MeV/c^2, improving by an order of magnitude over the previous works.

Analysis for the pion branching ratio using full data sets is in the final stage. The uncertainty on the branching ration is expected to be about 0.1%, which corresponds to 0.05% precision in test of lepton universality.

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