Status of the PIENU experiment

T. Numao[1], A.Aguilar-Arevalo[2], M. Aoki[3], M. Blecher[4], D.I. Britton[5], D.A. Bryman[6], D. vom Bruch[6], S. Chen[7], J. Comfort[8], S. Cuen-Rochin[6], L. Doria[1], P. Gumplinger[1], A. Hussein[9], Y. Igarashi[a], S. Ito[3], S. Kettell[b], L. Kurchaninov[1], L. Littenberg[b], C. Malbrunot[6], R. Mischke[1], D. Protopopescu[5], A. Sher[1], T. Sullivan[6], and D. Vavilov[1]

[1]TRIUMF, 4004 Wesbrook Mall, Vancouver, B.C. V6T 2A3, Canada
[2] Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de Mexico, México
[3] Osaka University, Toyonaka, Osaka, 560-0043, Japan
[4] Virginia Tech., Blacksburg, VA 24061, USA
[5] University of Glasgow, Glasgow, UK
[6] University of British Columbia, Vancouver, B.C. V6T 1Z1, Canada
[7] Tsinghua University, Beijing, 100084, China
[8] Arizona State University, Tempe, AZ 85287, USA
[9] University of Northern British Columbia, Prince George, B.C. V2N 4Z9, Canada
[a] KEK, 1-1 Oho, Tsukuba-shi, Ibaraki, 305-0801, Japan
[b] Brookhaven National Laboratory, Upton, NY 11973-5000, USA

E-mail: `toshio@triumf.ca`

Abstract.
The branching ratio, $R_{e/\mu} = \Gamma(\pi \to \mathrm{e}\nu + \mathrm{e}\nu\gamma)/\Gamma(\pi \to \mu\nu + \mu\nu\gamma)$, provides a sensitive test of muon-electron universality in weak interactions. The status of the PIENU experiment at TRIUMF, which aims to improve the precision of the $R_{e/\mu}$ measurement by a factor of > 5, is presented.

1. Introduction

The branching ratio of pion decays, $R_{e/\mu} = \Gamma(\pi \to \mathrm{e}\nu + \mathrm{e}\nu\gamma)/\Gamma(\pi \to \mu\nu + \mu\nu\gamma)$, which has been precisely calculated by the Standard Model (SM) $R_{SM} = (1.2352 \pm 0.0001) \times 10^{-4}$ [1, 2], has provided one of the best tests of electron-muon universality in weak interactions. The current experimental values of the branching ratio are $R_{e/\mu} = (1.2265 \pm 0.0034(stat) \pm 0.0044(syst)) \times 10^{-4}$ (TRIUMF) [3] and $R_{e/\mu} = (1.235 \pm 0.005) \times 10^{-4}$ (PSI) [4], indicating that there is a room for improvement of almost two orders of magnitude. The goal of the PIENU experiment at TRIUMF is to improve the precision of the branching ratio measurement by a factor of > 5, confronting the SM prediction to better than 0.1 %, which allows access to new physics beyond the SM up to the mass scale of 1000 TeV. Examples of the new physics probed include the R-parity violating SUSY [5], heavy neutrino mixing [6], excited gauge bosons, leptoquarks [7], compositeness or charged Higgs bosons.

2. Experiment

In the PIENU experiment, the branching ratio $R_{e/\mu}$ is obtained from the ratio of positron yields from the $\pi^+ \to \mathrm{e}^+\nu$ decay ($E_{e^+} = 70$ MeV) and the $\pi^+ \to \mu^+\nu$ decay followed by the $\mu^+ \to \mathrm{e}^+\nu\overline{\nu}$ decay ($\pi^+ \to \mu^+ \to \mathrm{e}^+$ decay, $E_{e^+} < 53$ MeV) using stopped π^+'s.

The π^+ beam was degraded by two thin plastic scintillators, and stopped in an 8-mm thick active target at a rate of 5×10^4 π^+/s [8]. A pion was tracked by wire chambers (WC1 and WC2) at the entrance of the detector system, and by two sets of single-sided 0.3-mm thick X and Y silicon strip counters located immediately upstream of the target.

The positron calorimeter located on the beam axis consisted of two thin plastic scintillators and a 48-cm (dia.) × 48-cm (length) single-crystal NaI(Tℓ) detector [9]. Two concentric layers of 97 pure CsI crystals [10] (9 radiation lengths radially) surrounded the NaI(Tℓ) crystal to capture the electromagnetic shower. Positrons were tracked by a set of X and Y Si-strip counters immediately downstream of the target counter, and three layers of wire chambers (WC3) in front of the NaI(Tℓ) crystal.

A coincidence of pion and positron signals with a time window of –300 ns to 540 ns with respect to the pion signal from the beam counters was the basis of the main trigger logic. This was prescaled by a factor of 16 to form an unbiased trigger. Selecting events in the early time window (2–40 ns) with respect to a pion stop or events with $E_{e^+} > 48$ MeV in the calorimeter provided enhanced triggers of $\pi^+ \to \mathrm{e}^+\nu$ decays. The pulse shapes from the plastic counters, the CsI crystals, the Si-strip detectors, and the NaI(Tℓ) crystal were recorded, and time information from the wire chambers and logic signals were recorded with a time window of -4 to 4 μs.

The response function of the calorimeter to 70 MeV positrons for $\pi^+ \to \mathrm{e}^+\nu$ was measured with a positron beam. The calorimeter was rotated to inject the beam at various entrance angles up to 48° with respect to the beam axis.

3. Analysis

Events originating from stopped pions are selected based on their energy losses in the beam counters. Any events with extra activity in the beam counters in the time region of –7 to 1 μs with respect to the pion stop are rejected. A fiducial cut, limiting one of position tracks at WC3 to be within 60 mm from the beam axis, is imposed to minimize the thickness variation of the material along the positron path and reduce the low energy tail of the $\pi^+ \to \mathrm{e}^+\nu$ peak due to shower leakage from the NaI(Tℓ) crystal.

Events passing the above criteria are divided into two energy regions separated at $\mathrm{E}_{cut} = 52$ MeV in the summed energies of the NaI and CsI. The positron time with respect to the pion for the time region from -300 to 540 ns is separately histogrammed for the fit. Figure 1 shows the time spectra of positrons for (a) the low energy region and (b) the high energy region.

In the low-energy time spectrum, the components are from $\pi^+ \to \mu^+ \to \mathrm{e}^+$ decays and $\mu^+ \to \mathrm{e}^+\nu\overline{\nu}$ (about 1 % of $\pi^+ \to \mu^+ \to \mathrm{e}^+$) decays after decay-in-flight of a pion (πDIF), both starting at the pion stop, and $\mu^+ \to \mathrm{e}^+\nu\overline{\nu}$ decays of "old" muons originating from the previous pion stops in the target area.

The main component in the high energy region is the $\pi^+ \to \mathrm{e}^+\nu$ decay ($\lambda_\pi e^{-\lambda_\pi t}$). All backgrounds in the high-energy region originate from the same sources as in the low energy with additional effects that raise the observed energy. A scaled low-energy time spectrum comes from muon decays through the energy resolution of the detector, radiative muon decays in which the γ-ray raises the observed calorimeter energy, and a pile-up in the calorimeter with a flat time distribution (*e.g.* from neutrons from the production target). A combination of $\pi^+ \to \mu^+ \to \mathrm{e}^+$ and "old" muon decays is another indispensable source of high-energy background. Radiative pion decays $\pi^+ \to \mu^+\nu\gamma$ (the branching ratio of 2×10^{-4}) followed by a $\mu^+ \to \mathrm{e}^+\nu\overline{\nu}$ decay can also contribute to the high-energy spectrum when the γ-ray hits the

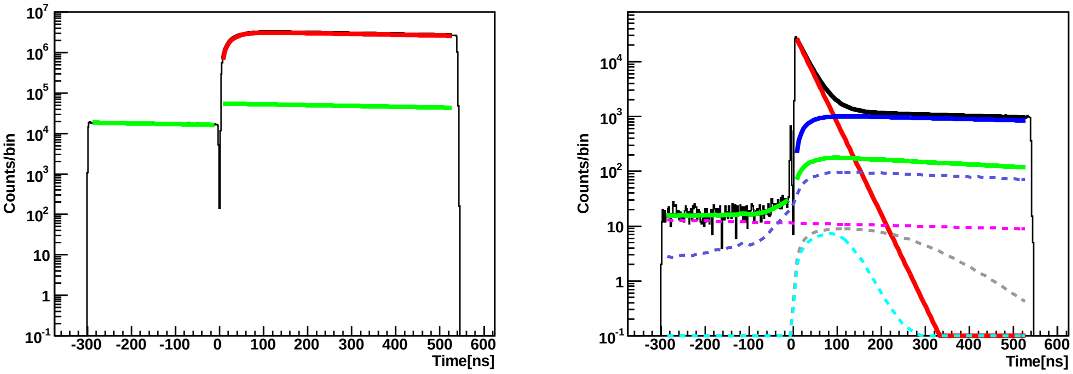

Figure 1. Time spectra of positrons for (a) low-energy and (b) high-energy regions. The full lines (red) indicate the signal components and other lines indicate various backgrounds.

calorimeter. The latter two contributions are estimated by Monte Carlo (MC) simulation using the observed pulse shapes.

A raw branching ratio is obtained by simultaneously fitting the low- and high-energy time spectra (the time region near the pion stop is excluded) to the expected time spectra.

4. Corrections

When a muon from $\pi^+ \to \mu^+\nu$ decays in flight (μDIF), Lorentz boosting may raise the positron energy above E_{cut}. Since this contribution has a time distribution of the pion decay, it is included in the raw branching ratio obtained by the time-spectrum fit. The amplitude of this component (about 0.2 %) is well estimated by the MC simulation.

A relative acceptance difference of of low- and high-energy positron events due to small energy dependent effects in the energy-loss processes is estimated by a MC simulation. A series of systematic studies based on the measured uncertainties of the detector geometry indicate the acceptance correction can be estimated significantly better than that (0.11 %) of the previous experiment.

The largest correction to the raw branching ratio is for $\pi^+ \to e^+\nu$ events below the cut-off energy, which arise from the response function of the calorimeter and radiative pion decays. Because of the bump structure in the response function of the NaI detector [11] due to hadronic interactions, which cannot be reproduced by pure MC simulation at a satisfactory level, empirical measurements are required.

Special data taken with a 70-MeV/c positron beam are used for the study of the response function of the calorimeter. The effects of the geometry change in the measurement, the $\pi^+ \to e^+\nu$ angle distributions and radiative pion decays are corrected by MC. The fraction of the events below E_{cut} is obtained to be 3 % of the total events. Since the contribution from the low-energy tail of the positron beam cannot be ruled out completely, the tail correction obtained is treated as an upper bound.

In order to empirically estimate the lower bound, $\pi^+ \to e^+\nu$ events are enhanced by selecting the early decay-time region and using the target activity information. The contribution of πDIF to the background is further reduced by detection of a kink in the pion track when πDIF happens upstream of the target counter. Assuming that the background-suppressed spectrum in the low energy region contains a negligible $\pi^+ \to e^+\nu$ contribution, the area of the low-energy region can be scaled to the full background region ($< \mathrm{E}_{cut}$) using the known background distribution. Due to the no-tail assumption, subtraction of this scaled sum from the total count in the suppressed spectrum below E_{cut} yields a lower bound on the tail. Since the target energy cut used in the suppression method tends to remove $\pi^+ \to \mathrm{e}^+\nu$ events with Bhabha scattering which results in a larger energy deposit in the target, a correction to the effects estimated by the MC simulation is added to the tail correction. Combining all factors, the lower bound is also 3 %.

5. Status

Data taking of the PIENU experiment was completed in 2012, and the analysis of partial data taken in 2010 (representing 4×10^5 clean $\pi^+ \to \mathrm{e}^+\nu$ events) is in progress.

Consistency of the measured branching ratio has been tested by changing various conditions in the analysis. When a variation beyond the statistical fluctuation is observed the source is sought until the cause is identified and corrected. Many cuts, which would potentially influence the background shape and amplitude in the present fitting function, are varied and the validity of the background functions and effectiveness of the cuts have been confirmed. This includes the energy threshold cuts and the pile-up rejection cuts for the incoming pion, which largely affect the amplitudes and/or shapes of the "old" muon background and other backgrounds in the high energy region. Also, E_{cut} has been varied to confirm the tail and μDIF corrections.

The next step is to fix all the cuts and analysis procedures and obtain all necessary correction factors before unblinding the branching ratio (shifted by a hidden value within 1 %). Following the completion of the 2010 analysis, a full data analysis will take place with further studies of backgrounds and corrections to a level of 0.01 % of the branching ratio.

6. Conclusions

The partial analysis of 2010 data by the PIENU experiment has confirmed the validity of the method and is expected to soon improve the measurement of $R_{e/\mu}$ by nearly a factor of two. The goal of the experiment is to improve the precision of the branching ratio measurement to a level of < 0.1 %.

References

[1] W.J. Marciano and A. Sirlin, Phys. Rev. Lett. **71**, 3629 (1993).
[2] V. Cirigliano and I. Rosell, JHEP **0710**, 005 (2007).
[3] D.I. Britton *et al.*, Phys. Rev. Lett. 68, 3000 (1992); and D.I. Britton *et al.*, Phys. Rev. D49, 28 (1994).
[4] G. Czapek *et al.*, Phys. Rev. Lett. 70, 17 (1993).
[5] M.J. Ramsey-Musolf, S. Su and S. Tulin, Phys. Rev. **D76**, 095017 (2007).
[6] H. Lacker and A. Menzel, JHEP 07, 006 (2010).
[7] S.Davidson, D. Bailey and B. Campbell, Z. Phys. C61, 613 (1994).
[8] A. Aguilar-Arevalo *et al.*, to be published.
[9] G. Blanpied *et al.*, Phys. Rev. Lett. **76** (1996) 1023.
[10] I-H. Chiang *et al.*, IEEE **NS-42** (1995) 394.
[11] A. Aguilar-Arevalo *et al.*, Nucl. Instrum. Method A621, 188 (2010).