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Precision tests of electron-muon universality with pions

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Summary. — The TRIUMF PIENU experiment aims to measure the branching ratio of pion decays, $R_{e/\mu} = \Gamma(\pi \rightarrow e\nu(\gamma))/\Gamma(\pi \rightarrow \mu\nu(\gamma))$, at a precision level of $< 0.1\%$, confronting the Standard Model (SM) prediction of $R^{SM}_{e/\mu} = 1.2353(1) \times 10^{-4}$. At that level, new physics beyond the SM involving mass scales up to 1000 TeV may be heralded by an observed deviation from the precise SM expectation. Also, evidence of massive neutrinos in the $\pi^+ \rightarrow e^+\nu$ decay spectrum has been sought with the background from $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ decay chain highly suppressed. Upper limits (90% C.L.) on the neutrino mixing matrix element $|U_{ei}|^2$ in the mass region 65–130 MeV/c^2 have been set at a 10^{-8} level.

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PACS `12.15.Ff` – Quark and lepton masses and mixing.

1. – Introduction

The branching ratio ($R_{e/\mu}$) of the decays $\pi^+ \to \mathrm{e}^+\nu$ and $\pi^+ \to \mu^+\nu$, which is helicity-suppressed by a factor of $(m_e/m_\mu)^2$, provides stringent tests of e-μ universality in weak interactions. Since the observed branching ratio includes the effect of real and virtual photons, radiative corrections are important in order to extract the ratio of the weak coupling constants. The radiative correction assuming a point-like pion is of the order of $\delta = (3\alpha/\pi)\ln(m_e/m_\mu)$ [1]. Marciano and Sirlin [2] showed that lepton flavour independent QCD radiative corrections cancelled in $R_{e/\mu}$. Based on chiral perturbation theory, Cirigliano and Rosell [3] calculated to the $O(m^2/p^4)$ terms including the helicity-unsuppressed structure dependent terms and gave a prediction of $R^{th}_{e/\mu} = 1.2352(1) \times 10^{-4}$. The prediction is in agreement with the most recent experimental results:

(1) $R^{exp}_{e/\mu} = 1.2265 \pm 0.0034(\mathrm{stat}) \pm 0.0044(\mathrm{syst}) \times 10^{-4}$ TRIUMF [4], and

(2) $R^{exp}_{e/\mu} = 1.2346 \pm 0.0035(\mathrm{stat}) \pm 0.0036(\mathrm{syst}) \times 10^{-4}$ PSI [5].

Because of helicity-suppression in the standard model (SM), the $\pi^+ \to \mathrm{e}^+\nu$ decay is extremely sensitive to helicity-unsuppressed couplings. A 0.1% measurement of the $\pi^+ \to \mathrm{e}^+\nu$ branching ratio probes new physics in mass scales up to 1000 TeV for pseudoscalar interactions [6]. In the case of SUSY models, the exchange of various generations of squarks may lead to a non-universal contribution that results in an observable deviation, and the measurement of $R_{e/\mu}$ places substantial constraints on the possible size of R-parity violating effects [7]. Other candidate examples of the "new physics" probed include heavy neutrino mixing as well as high-scale four-fermion operators due to excited gauge bosons, leptoquarks, compositeness or charged Higgs bosons.

2. – Experiment

The concept of the PIENU experiment [8] is based on the previous TRIUMF experiment [4] that measured positrons from pion decays at rest. The branching ratio $R_{e/\mu}$ is obtained from the ratio of positron yields from the $\pi^+ \to e^+\nu$ decay ($E_{e^+} = 69.8\,\mathrm{MeV}$) and the $\pi^+ \to \mu^+ \to e^+$ decay ($\pi^+ \to \mu^+\nu$ decay followed by $\mu^+ \to \mathrm{e}^+\nu\overline{\nu}$ decay, $E_{e^+} = 0.5$–$52.8\,\mathrm{MeV}$). By measuring positrons, many normalization factors cancel in first order, and only small energy-dependent effects, such as those for multiple Coulomb scattering and positron annihilation, require corrections using Monte Carlo (MC) simulations. The low-energy fraction of the $\pi^+ \to \mathrm{e}^+\nu$ events below the cut-off energy for the $\pi^+ \to \mathrm{e}^+\nu$ selection is determined empirically by suppressing the dominant $\pi^+ \to \mu^+ \to \mathrm{e}^+$ component by a factor of 10^5. The uncertainties are summarized in table I.

Figure 1(left) shows a schematic view of the detector. A mass-separated π^+ beam at 75 MeV/c [9] is degraded by two thin plastic scintillators and stopped in an 8 mm thick active target (B3). The positron detector consists of two plastic scintillators for time measurement and a 48 cm (dia.) × 48 cm (length) single-crystal NaI(Tℓ) detector surrounded by two rings of 97 pure CsI crystals to detect leakage of the electromagnetic shower. Pion tracking is provided by wire chambers (WC1 and WC2) at the exit of the beam line, and two pairs of X-Y Si-strip counters S1 and S2 located immediately upstream of the target. Positron tracking comes from one set of X-Y Si-strip counters

TABLE I. – *Summary of experimental uncertainties* (%) *for the previous TRIUMF experiment* [4] *and estimated uncertainties for PIENU* [8].

Uncertainties (%)	Previous experiment [4]	PIENU [8]
Statistical	0.28	0.05 >
Systematical	0.44	0.06 >
Low-energy tail	0.25	0.03 >
Acceptance difference	0.11	0.03 >
Pion lifetime	0.09	0.02
Others	0.11	0.03 >

(S3) immediately downstream of the target, and three layers of wire chambers (WC3) in front of the NaI(Tℓ) crystal.

Events originating from stopped pions are selected based on their energy losses in the beam counters and the time-of-flight with respect to the primary-proton beam burst. An energy-loss cut in the positron telescope counters is applied to select decay-positrons. So far, we have accumulated 3×10^6 clean $\pi^+ \to e^+\nu$ events.

Measurements of response functions of the positron detector system to a 70 MeV/c positron beam for various entrance positions and angles, combined with radiative corrections, provide estimates of the low-energy fraction. The analysis of the beam positron data indicates that the uncertainty of the low-energy tail fraction is $< 0.1\%$. During this study, we encountered smaller peaks at 60 and 53 MeV in addition to the main 70 MeV peak. The lower energy peaks are due to escape of low-energy neutrons from the NaI crystal, which are emitted in photo-nuclear reactions of the positron shower with iodine nuclei [10].

An alternative method is to determine the low-energy tail fraction empirically from $\pi^+ \to e^+\nu$ data. In order to enhance the small $\pi^+ \to e^+\nu$ decay signal, the $\pi^+ \to \mu^+ \to e^+$ background is first suppressed by a narrow time window (2–33 ns). Figure 1(right) shows a positron energy spectrum in the time window. Since the decay $\pi^+ \to e^+\nu$ involves only two charged particles while the decay $\pi^+ \to \mu^+ \to e^+$ has three charged

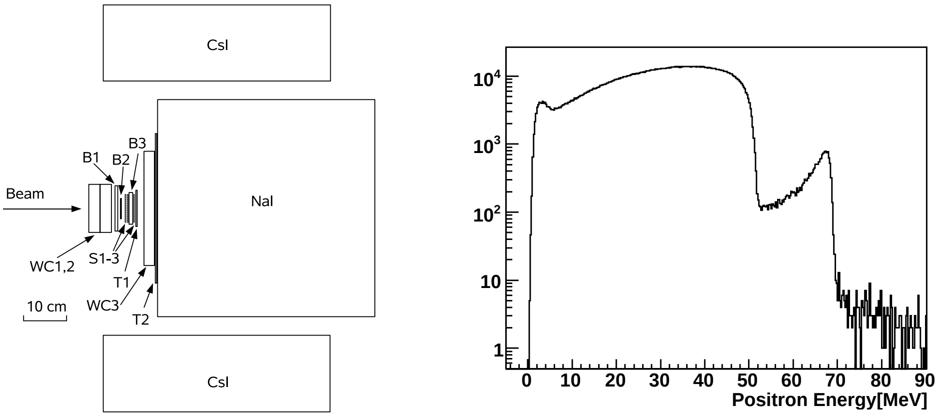

Fig. 1. – Left: schematic view of the detector. Right: positron energy spectrum.

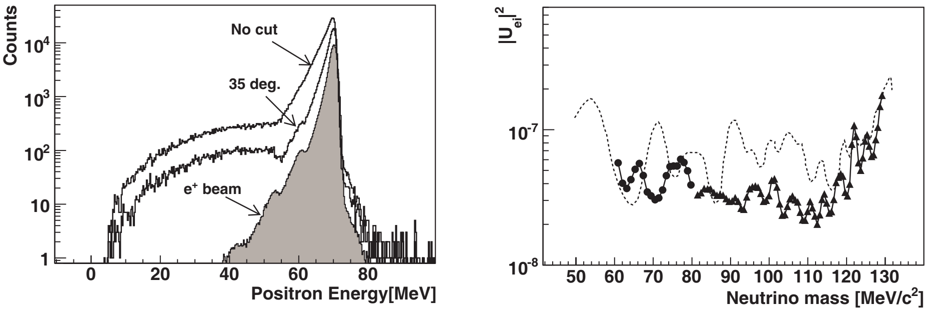

Fig. 2. – Left: positron energy spectrum with and without the angle cut, together with beam positron spectrum (shaded). Right: combined 90% C.L. upper limits obtained from the 35° spectrum (circles) and no-cut spectrum (triangles) together with the previous limits (dashed line) [11].

particles with an extra kinetic energy of 4.1 MeV from the $\pi^+ \to \mu^+\nu$ decay in the target counter, pulse shape discrimination based on the likelihood for two and three pulses, and the total energy in the beam counters are very effective in background suppression. After these cuts, the major low-energy background is from decay-in-flight (DIF) of pions near the target, in which the muon from the $\pi^+ \to \mu^+\nu$ decay stops in the target and deposits the same kinetic energy as the initial pion [4]. Beam tracking near the target allows detection of a DIF kink in the "pion" track. This suppresses the background by a factor of two.

Based on the background-suppressed spectrum and the expected statistical improvement, it seems to be possible to reduce the uncertainty of the low-energy fraction of the $\pi^+ \to \mathrm{e}^+\nu$ peak to a level of $< 0.03\%$. A summary of uncertainties is shown in table I. Together with further improvement in statistics, the PIENU experiment is expected to measure the branching ratio at a precision level of $< 0.1\%$.

3. – Massive neutrino

The background-suppressed positron spectrum obtained for the low-energy tail analysis allows a sensitive search for additional peaks due to massive neutrinos arising from extensions of the SM, *e.g.* sterile neutrinos mixing with the ordinary neutrinos [12]. The weak eigenstates ν_{χ_k} of such neutrinos are related to the mass eigenstates ν_i by a unitary matrix, $\nu_\ell = \Sigma_{i=1}^{3+k} U_{\ell i}\nu_i$, where $\ell = e, \mu, \tau, \chi_1, \chi_2 \cdots \chi_k$.

The $\pi^+ \to \mu^+ \to \mathrm{e}^+$ background is further suppressed by consistency tests of the "pion" and positron tracks based on the closest approach of the two tracks, which are not applied in the analysis of the branching ratio measurement. The energy resolution and low-energy tail of the $\pi^+ \to \mathrm{e}^+\nu$ peak are improved by restricting the positron emission angle as shown in fig. 2(left). However, using spectra with the angle cut at 35° is statistically effective only above 47 MeV where the impact of the resolution is higher. The 60 MeV peak, enhanced with the angle cut in the suppressed spectrum, is consistent with the response function of the NaI(Tℓ) crystal [10], and the beam positron spectrum is subtracted from the spectra before the fitting search.

The amplitude of the $\pi^+ \to \mu^+ \to \mathrm{e}^+$ background, for which the spectrum is obtained with a late time window (150–500 ns), is a free parameter in the fit. The muon-DIF spectrum is obtained by applying a Lorentz transformation and corrections to the $\pi^+ \to \mu^+ \to \mathrm{e}^+$ spectrum. The amplitude of this component ($\sim 1/3$ of the remaining background) is a free parameter of the fit. In order to accommodate unforeseen backgrounds, the amplitude and the decay constant of an exponential function and an additional constant term are free parameters of the fit. The template peak spectrum for each peak energy is obtained from a MC simulation. The search for extra peaks is conducted with 0.5 MeV steps in the positron energy regions, $E_{e^+} = 10$–$47\,\mathrm{MeV}$ for the spectrum without the angle cut and $E_{e^+} = 47$–$60\,\mathrm{MeV}$ with the 35° cut to take advantage of improved energy resolution obtained using the cut. The entire spectrum (9–50 MeV for the no-cut data and 9–62 MeV for the data with the 35° cut) is fitted to a background function plus a possible peak. The χ^2/DOF's are 0.97 without the angle cut and 1.00 with the angle cut for the fits without the extra peak. The most significant positive "signature" is 2.0 σ at $E_{e^+} = 16.5\,\mathrm{MeV}$ ($122\,\mathrm{MeV}/c^2$ in neutrino mass).

The amplitudes and associated errors are converted to 90% C.L. upper limits on $|U_{ei}|^2$, assuming a Gaussian probability distribution with a constraint that the physical region of a peak area be positive. Figure 2(right) shows the combined results for the fits with the 35° angle cut (below $80\,\mathrm{MeV}/c^2$ in neutrino mass), and without the angle cut (above $80\,\mathrm{MeV}/c^2$) [13]. For comparison, the 90% C.L. upper limits obtained in ref. [11] are also plotted by a dashed curve. The present experiment improves the upper limits on the neutrino mixing matrix element $|U_{ei}|^2$ by a factor of up to four in the mass region 90–110 MeV/c^2.

4. – Conclusion

The PIENU experiment at TRIUMF is expected to produce measurements of the $\pi^+ \to \mathrm{e}^+\nu$ branching ratio at a level of $< 0.1\%$ uncertainty in a few years. Another experiment with similar goals is in progress at PSI [14]. At this level of precision, new physics up to $1000\,\mathrm{TeV/c}^2$ could be revealed.

REFERENCES

[1] Berman S. M., *Phys. Rev. Lett.*, **1** (1958) 468; Kinoshita T., *Phys. Rev. Lett.*, **2** (1959) 477.
[2] Marciano W. J. and Sirlin A., *Phys. Rev. Lett.*, **36** (1976) 1425.
[3] Cirigliano V. and Rosell I., *Phys. Rev. Lett.*, **99** (2007) 231801; Cirigliano V. and Rosell I., *JHEP*, **10** (2007) 005.
[4] Britton D. I. *et al.*, *Phys. Rev. Lett.*, **68** (1992) 3000; Britton D. I. *et al.*, *Phys. Rev. D*, **49** (1994) 28.
[5] Czapek G. *et al.*, *Phys. Rev. Lett.*, **70** (1993) 17.
[6] Campbell B. A. and Ismail A., CERN-PH-TH/2008-212 and arXiv:09104918v1 (2008).
[7] Ramsey-Musolf M. J., Su S. and Tulin S., *Phys. Rev. D*, **76** (2007) 095017.
[8] PIENU experiment, TRIUMF Proposal S1072 (2005).
[9] Aguilar-Arevalo A. *et al.*, *Nucl. Instrum. Methods A*, **609** (2009) 102.
[10] Aguilar-Arevalo A. *et al.*, *Nucl. Instrum. Methods A*, **621** (2010) 188.
[11] Britton D. I. *et al.*, *Phys. Rev.*, **46** (1992) R885.
[12] Kusenko A., *Phys. Rep.*, **481** (2009) 1 and references therein.
[13] Aoki M. *et al.*, *Phys. Rev. D*, **84** (2011) 052002.
[14] PEN experiment, PSI Proposal R-05-01 (2006).