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Status of Pion Decay Experiments

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Abstract. The branching ratio of pion decays, $R_{e/\mu} = \Gamma(\pi^+ \rightarrow e^+\nu + e^+\nu\gamma)/\Gamma(\pi^+ \rightarrow \mu^+\nu + \mu^+\nu\gamma)$, has provided a sensitive test of electron-muon universality in weak interactions. The uncertainty of the Standard Model prediction is at a 0.01 % level. Although a recent measurement, $R_{e/\mu} = (1.2344 \pm 0.0023(stat) \pm 0.0019(syst)) \times 10^{-4}$, reduced the experimental uncertainty by a factor of two, there is room for improvement by more than an order of magnitude. The status of two $\pi^+ \rightarrow e^+\nu$ experiments at TRIUMF and PSI as well as related pion decay experiments is presented.

1. Introduction

The focus of the present paper is on the measurements of the branching ratio $R_{e/\mu} = \Gamma(\pi^+ \rightarrow e^+\nu + e^+\nu\gamma)/\Gamma(\pi^+ \rightarrow \mu^+\nu + \mu^+\nu\gamma)$, which provides the best test of $e - \mu$ universality in charged-current weak interactions. As indicated in the expression of $R_{e/\mu}$, the experimental result includes radiative decays with virtual and real photons. A recent theoretical prediction, $R_{e/\mu} = (1.2352 \pm 0.0002) \times 10^{-4}$ [1, 2], included uncertainties from uncalculated two-loop effects. Model dependent effects were calculated based on the Chiral Perturbation Theory (ChPT) up to the $O(m^2/p^4)$ terms.

The experimental status till 2014 was: $R_{e/\mu} = (1.2265 \pm 0.0050) \times 10^{-4}$ (TRIUMF) [3] and $(1.235 \pm 0.005) \times 10^{-4}$ (PSI) [4]. Presently, there are two experiments, PIENU at TRIUMF [5] and PEN at PSI [6], to improve the uncertainties to a level of $<0.1\%$. The PIENU group released a result of a partial analysis in 2015, $R_{e/\mu} = (1.2344 \pm 0.0023(stat) \pm 0.0019(syst)) \times 10^{-4}$ [7]. The new result improved the test of $e - \mu$ universality to be $g_e/g_\mu = 0.9996 \pm 0.0012$. This still leaves room for experimental improvement by more than an order of magnitude in the uncertainty.

Since the uncertainty of the standard model (SM) calculation for $R_{e/\mu}$ is very small and the decay $\pi^+ \rightarrow e^+\nu$ is helicity-suppressed by the V-A structure of charged currents, the branching ratio $R_{e/\mu}$ is extremely sensitive to helicity-unsuppressed couplings such as the pseudo-scalar coupling. At the level of 0.1 % measurements, new physics beyond the SM up to the mass scale of 1000 TeV/c² may be accessed by a deviation from the precise SM expectation [2]. Possible sources of deviation include Majorons [8], charged Higgs particles and leptoquarks [9]. Also, SUSY models with and without R-parity violation [10]. or with lepton flavor violating terms [11] could cause a deviation from the SM prediction. Another example of the new physics is sterile massive neutrinos [12] which were sought in the PIENU experiment [13].

In this paper, the present status of two on-going experiments [5, 6], which aim at a precision level of $<0.1\%$ for the measurement of $R_{e/\mu}$, will be discussed, and also precision measurements of other pion decays will be reviewed in the context of $\pi^+ \rightarrow e^+\nu$ measurements.



2. Experimental method

Both PIENU and PEN experiments measure pion decays at rest. A 70-MeV positron is emitted in the $\pi^+ \rightarrow e^+\nu$ decay. Since muons from $\pi^+ \rightarrow \mu^+\nu$ decays, having a short range (~ 1.4 mm) in plastic scintillator, remain in the target, the solid angle for positron detection from the subsequent muon decay $\mu^+ \rightarrow e^+\nu\bar{\nu}$ ($E_{e^+} = 0 - 52$ MeV) is almost the same as that from $\pi^+ \rightarrow e^+\nu$ decays. On the other hand, muon detection for $\pi^+ \rightarrow \mu^+\nu$ decays involving entirely different solid angles and corrections is anticipated to have larger experimental uncertainties. In both experiments, the ratio of the positron yields from $\pi^+ \rightarrow e^+\nu$ and $\mu^+ \rightarrow e^+\nu\bar{\nu}$ following $\pi^+ \rightarrow \mu^+\nu$ ($\pi^+ \rightarrow \mu^+ \rightarrow e^+$) was measured with an inorganic crystal calorimeter. No magnetic field was applied.

Events from $\pi^+ \rightarrow e^+\nu$ (decay with the pion lifetime of 26 ns) and $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ (a sharp increase with the pion lifetime and a slow decrease with the muon lifetime of 2.2 μ s) are separated at the upper end of $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ spectrum (nominally, at 52 MeV), and the time spectra for the low- and high-energy regions are fitted together with background terms. Low-energy $\pi^+ \rightarrow e^+\nu$ events below 52 MeV due to the response function of the calorimeter and radiative pion decays will be corrected. Other small corrections for energy-dependent effects are also applied. The main background for $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ decay comes from the presence of muons from previously stopped pions (“old muons”). Other backgrounds arising from various mechanisms will be discussed later.

3. PIENU experiment

The concept of the PIENU experiment [5, 14] was based on the previous TRIUMF experiment [3] with improvements in the acceptance by an order of magnitude and in the systematic uncertainties. Expected uncertainties are summarized in Table 1 together with those from the previous experiments.

A 75 MeV/c π^+ beam was degraded by two thin plastic scintillators (6 mm and 3 mm thick) and stopped in an 8-mm thick active target at a rate of 5×10^4 pions/s. Pion tracking was provided by six planes of wire chambers at the exit of the beam line, and two sets of X-Y Si-strip counters immediately upstream of the target.

In order to gain a large solid angle (~ 25 %) while reducing the variation of the amount of material along the positron path, the positron telescope consisting of two thin plastic scintillator counters and a calorimeter system was placed on the beam axis. The extension of the beam line with a capability of particle separation [15] allowed this geometry by suppressing positrons in the beam to < 2 % of pions. It also reduced (together with more shielding) the neutron rate from the pion-production target by an order of magnitude. The primary calorimeter was a 48-cm (diam.) \times 48-cm (length) single-crystal NaI(Tl) surrounded by two rings of 97 pure CsI crystals (9 radiation lengths) to reduce the shower leakage. The improvement factor of 30 in statistics was therefore expected to come from a larger solid angle and a longer running period. Positron tracking came from one set of X-Y Si-strip counters immediately downstream of the target, and three layers of wire chambers in front of the NaI crystal.

In the analysis, events with a single pion in the beam detector and a single positron in the calorimeter were selected. By requiring no preceding beam particles within a time window up to -6 μ s, the presence of “old” muons in the target region was reduced by an order of magnitude to achieve a low beam-rate condition for a clean measurement.

The “old” muon was the primary source of the background in the low-energy time spectrum. In the high-energy time spectrum, one type of the backgrounds which had the identical distribution to the low-energy one was due to the calorimeter resolution and $\mu^+ \rightarrow e^+\nu\bar{\nu}\gamma$ decays (the γ -ray also hit the calorimeter to raise the observed energy). Neutrons from the production target and calibration sources also contributed to this type of background.

Radiative pion decays $\pi^+ \rightarrow \mu^+\nu\gamma$ (the branching ratio of 2×10^{-4}) followed by a

$\mu^+ \rightarrow e^+\nu\bar{\nu}$ decay could be a background in the high-energy region when the γ -ray hit the calorimeter. Since the calorimeter energy used to separate the two regions was measured with respect to the positron time, the contribution of the extra γ -ray energy to the observed energy varied with the time difference between the two decays.

Another type of background occurred when a positron from an “old” muon deposited extra energy into the calorimeter in addition to the true event. The one-hit requirement in the positron telescope usually protected against this type of background, but if one of the positrons was emitted to a large angle to avoid detection the protection logic did not function. Also, if two decays occurred during the two-pulse resolution of the telescope, the events were kept. These types of the backgrounds were suppressed by reducing the “old” muon component. All the backgrounds described above were included in the fitting function.

When the muon from $\pi^+ \rightarrow \mu^+\nu$ decayed in flight, the Lorentz boosting might raise the positron energy above 52 MeV. This contribution has a time distribution of the pion decay. The effect was estimated by simulation to be 0.2 % of the branching ratio and included in the branching ratio obtained by the time-spectrum fit.

The validity of the background shape and amplitude was confirmed by enhancing each type of the backgrounds by changing the related selection criteria.

Table 1. Comparison of uncertainties (%) in $R_{e/\mu}$ for PIENU [5], 2015 analysis [7] and the previous TRIUMF result [3].

Sources	PIENU	2015 analysis	Previous exp.
Statistical error	0.05	0.19	0.28
Tail correction	0.03	0.12	0.25
Acceptance difference	0.03	0.03	0.11
Others	0.03	0.08	0.14
Total	0.06	0.24	0.45

The correction for the fraction of low-energy $\pi^+ \rightarrow e^+\nu$ events was estimated with two methods. The response function of the calorimeter to 70-MeV/c positrons was measured with a positron beam directly injected into the calorimeter. The effects of hadronic interactions, which were not reproduced accurately enough in the simulation for the present condition, were parametrized based on the measured spectra at various angles, and the response function for positrons from the $\pi^+ \rightarrow e^+\nu$ decay including the radiative mode was generated by simulation. Since the amount of the contamination of low-energy positrons in the beam was not estimated, the present tail correction was considered to be an upper bound.

In order to further constrain the amount of the low-energy tail, $\pi^+ \rightarrow e^+\nu$ events were enhanced by suppressing the dominant $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ background using the decay time, the total charge deposited in the target ($\pi^+ \rightarrow \mu^+ \rightarrow e^+$ decays involve extra 4 MeV) and tracking information (to suppress background from decays-in-flight of pions). Assuming that the lowest energy area of the suppressed spectrum did not contain the low-energy tail of $\pi^+ \rightarrow e^+\nu$ events, the number of events in the area was scaled to the whole background region using the shape of the known $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ background spectrum and the background was subtracted from the background-suppressed spectrum. This method might result in over-subtraction of the background due to the presence of actual signal in the lowest energy area, and the correction obtained by this method was considered to be a lower bound.

The PIENU experiment completed the data taking stage with about 1×10^7 clean $\pi^+ \rightarrow e^+\nu$ events at the end of 2012. The result of the partial analysis of 2010 data was published in 2015 [7]. A full analysis based on ten times more event statistics with reduced background

and additional improvements in systematics is in progress. In the full analysis of the low-energy tail estimation, additional positron-beam data taken with various extreme slit and magnetic-field combinations will be analyzed, and hopefully the measured response function could be taken as the tail correction itself. Also, the uncertainty of the lower bound limited by statistics in the partial analysis will be reduced. The lower bound could be further improved by including the well-known electro-magnetic shower contribution instead of the assumption of no $\pi^+ \rightarrow e^+\nu$ events in the lowest energy area.

4. PSI experiment

In the new PSI experiment (PEN) [6], ~ 70 MeV/c pions were tagged by a counter in the beam line, slowed down by a 5-mm thick active plastic-scintillator degrader, tracked by a 40-mm \times 40-mm \times 50-mm mini-TPC (for pion tracking), and stopped in a 15-mm thick fast-scintillator target at a rate of 20 k/s.

Positrons from the $\pi^+ \rightarrow e^+\nu$ and $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ decays were measured by two sets of cylindrical wire chambers, a thin 20-element plastic-scintillator hodoscope, and 240 12-radiation-length thick pure CsI detectors that covered a solid angle of $\sim 3\pi$ sr.

Fast wave-form digitizers (2 GHz) were employed for the beam and target counters, which were effective in suppressing the background by identifying two-pulse events ($\pi^+ \rightarrow e^+\nu$) from three-pulse events ($\pi^+ \rightarrow \mu^+ \rightarrow e^+$).

Table 2. Expected uncertainties (%) in $R_{e/\mu}$ for PEN [6].

Sources	Uncertainties
Statistical	0.02
Systematic	0.03
π/μ discri.	0.01
$E_e < E_{threshold}$	0.01
Acceptance	
Radiative decay	0.01>
Photo-nuclear int.	0.01
T0 variation	0.02>
Total	0.05

The data taking stage was over in 2010. About 2×10^7 $\pi^+ \rightarrow e^+\nu$ events (before cuts) were accumulated. Because of the large solid angle for positron detection and the method for the low-energy tail correction, the PEN experiment has different systematic uncertainties from the PIENU experiment. Expected uncertainties are summarized in Table 2, which include corrections for pion and muon event discrimination, positrons below the detection threshold for $\mu^+ \rightarrow e^+\nu\bar{\nu}$ decays, acceptance difference between $\pi^+ \rightarrow e^+\nu$ and $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ events, effects of radiative decays, photo-nuclear interactions, and the knowledge of the time zero for both decay modes. The analysis is in progress.

5. Related pion decay experiments

In this section, other pion decay experiments especially which are related to the $R_{e/\mu}$ measurement through radiative corrections are briefly summarized.

Precision measurements of other pion decay modes were used for inputs of ChPT calculations as well as for the confirmation of the ChPT predictions. The amplitudes of structure-dependent radiative decays in the $\pi^+ \rightarrow e^+\nu\gamma$ decay, which are not helicity-suppressed, are parametrized

by the vector and axial-vector form factors, F_V and F_A , respectively. The structure-dependent radiative correction for $R_{e/\mu}$ came from the ratio F_A/F_V . The PIBETA group [16], using the CsI crystal calorimeter measured $F_V = 0.0258(17)$ and $F_A = 0.0117(17)$ —they also set a tight bound for the presence of the tensor form factor, $F_T = (-0.6 \pm 2.8) \times 10^{-4}$. While in the PIBETA experiment the data was collected at a high beam rate to precisely measure the rare branching ratio of the $\pi^+ \rightarrow \pi^0 e^+ \nu$ decay ($\text{BR} \sim 10^{-8}$), the PEN experiment [6] collected data at a low beam rate together with the $\pi^+ \rightarrow e^+ \nu$ decay data. This allowed an access to the energy combination of the positron and γ -ray which was sensitive to $F_V - F_A$. The data analysis is in progress.

The vector form factor F_V in the $\pi^+ \rightarrow e^+ \nu \gamma$ decay is related to the lifetime of the π^0 through the Conserved-Vector-Current theory. A recent result $(8.32 \pm 0.15 \pm 0.18) \times 10^{-17}$ s by the PrimEx group at JLAB [18], being consistent with the previous measurements [17] though slightly off from the direct measurement, improved the uncertainty by a factor of two. Another approach to the π^0 lifetime is expected through the measurement of $e^- e^+ \rightarrow \pi^0$. The KLOE-2 group is planning to improve the measurement in the near future [19].

There are other exotic rare π^0 decay modes being sought. Since the NA62 experiment [20] is a “tagged π^0 factory” via copious $K^+ \rightarrow \pi^+ \pi^0$ decays, it is expected to improve related measurements, such as $\pi^0 \rightarrow \nu \bar{\nu}$ [21], together with a better photon vetoing capability.

6. Conclusion

Although the decay $\pi^+ \rightarrow e^+ \nu$ was discovered 50 years ago, it still remains one of the topical subjects. Precision measurements of $R_{e/\mu}$ provide the best test of e - μ universality in weak interactions. It is also sensitive to the presence of pseudo-scalar interactions arising from physics beyond the SM.

The two on-going experiments at TRIUMF and PSI are expected to finish the analysis at a level of <0.1 % uncertainty in a few years. At this level of precision, new physics up to 1000 TeV/ c^2 could be surveyed.

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