PEN experiment: a precise test of lepton universality

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With few open channels and uncomplicated theoretical description, charged pion decays are uniquely sensitive to certain standard model (SM) symmetries, the universality of weak fermion couplings, and to aspects of pion structure and chiral dynamics. We review the current knowledge of the pion electronic decay $\pi^+ \rightarrow e^+\nu_e(\gamma)$, or $\pi e_2(\gamma)$, and the resulting limits on non-SM processes. Focusing on the PEN experiment at the Paul Scherrer Institute (PSI), Switzerland, we examine the prospects for further improvement in the near term.

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1. Introduction: pion electronic decay, $\pi^+ \rightarrow e^+\nu_e$

Charged pion decays have provided important early insight into the $V-A$ nature of the weak interaction following the failure of initial searches to observe the direct electronic decay ($\pi \rightarrow e\nu$, or $\pi_{e2}$). This led to a low branching fraction prediction of $\sim 1.3 \times 10^{-4}$ [1] as a consequence of the helicity suppression of the right-handed state of the electron, even before the decay’s discovery [2]. Further, predicted radiative corrections for the $\pi_{e2}$ decay [3, 4] received quick and decisive experimental confirmation [5, 6], establishing the process as an important theory testing ground.

Pion decays have more recently been described with extraordinary theoretical precision. Thanks to the underlying symmetries and associated conservation laws, the more complicated, and thus more uncertain, hadronic processes are suppressed. Should measurement results approach or reach the precision level of their theoretical description, pion decays offer a uniquely clean testing ground for lepton and quark couplings. A statistically significant deviation from the standard model expectations would indicate presence of processes or interactions not included in the SM, affecting $\pi$ decays through loop diagrams.

Of particular interest is the $\pi^- \rightarrow \ell\nu_\ell$ (or, $\pi^+ \rightarrow \bar{\ell}\nu_\ell$) decay which connects a pseudoscalar $0^-$ state (the pion) to the $0^+$ vacuum. At the tree level, the ratio of the $\pi \rightarrow e\nu$ to $\pi \rightarrow \mu\nu$ decay widths is given by [1, 7]

$$R_{\pi e/\mu} \equiv \frac{\Gamma(\pi \rightarrow e\nu)}{\Gamma(\pi \rightarrow \mu\nu)} = \frac{m_e^2}{m_\mu^2} \frac{(m_\pi^2 - m_e^2)^2}{(m_\pi^2 - m_\mu^2)^2} \simeq 1.283 \times 10^{-4}. \quad (1)$$

The first factor in the above expression, the ratio of squared lepton masses for the two decays, comes from the helicity suppression by the $V-A$ lepton weak couplings to the $W$ boson. If, instead, the decay could proceed directly through the pseudoscalar current, the ratio $R_{\pi e/\mu}^\pi$ would reduce to the second, phase-space factor, or approximately 5.5. A more complete treatment of the process includes $\delta R_{\pi e/\mu}^\pi$, the radiative and loop corrections, and the possibility of lepton universality (LU) violation, i.e., that $g_e$ and $g_\mu$, the electron and muon couplings to the $W$, respectively, may not be equal:

$$R_{\pi e/\mu} \equiv \frac{\Gamma(\pi \rightarrow e\nu(\gamma))}{\Gamma(\pi \rightarrow \mu\nu(\gamma))} = \frac{g_e^2 m_e^2 (m_\pi^2 - m_e^2)^2}{g_\mu^2 m_\mu^2 (m_\pi^2 - m_\mu^2)^2} (1 + \delta R_{\pi e/\mu}^\pi), \quad (2)$$

where the “$(\gamma)$” indicates that radiative decays are fully included in the branching fractions. Steady improvements of the SM description of the $\pi_{e2}$ decay have reached the precision level of 8 parts in $10^5$: $R_{e/\mu}^{\pi, \text{SM}} = 1.2352(1) \times 10^{-4}$ [8, 10]. Comparison with equation (1) indicates that the radiative and loop corrections amount to almost 4% of $R_{e/\mu}^{\pi}$. The current experimental precision lags behind the above theoretical uncertainties by a factor of $\sim 23$: $R_{e/\mu}^{\pi, \text{exp}} = 1.2327(23) \times 10^{-4}$, dominated by measurements from TRIUMF and PSI [11, 14].
Because of the large helicity suppression, the $\pi\to e^2$ decay branching ratio is highly susceptible to small non-$\left(V-A\right)$ contributions from new physics, making this decay a particularly suitable subject of study, as discussed in, e.g., Refs. [15–20]. This sensitivity provides the primary motivation for the ongoing PEN [21] and PiENu [22] experiments. Of all the possible “new physics” contributions in the Lagrangian, $\pi\to e^2$ is directly sensitive to the pseudoscalar one, while other types enter through loop diagrams. At the precision of $10^{-3}$, $R_{\pi/e/\mu}^\pi$ probes the pseudoscalar and axial vector mass scales up to 1,000 TeV and 20 TeV, respectively [19,20]. For comparison, unitarity tests of the Cabibbo-Kobayashi-Maskawa (CKM) matrix and precise measurements of several superallowed nuclear beta decays constrain the non-SM vector contributions to $> 20$ TeV, and scalar ones to $> 10$ TeV [23]. Although scalar interactions do not directly contribute to $R_{\pi/e/\mu}^\pi$, they can do so through loop diagrams, resulting in a sensitivity to new scalar interactions up to 60 TeV [19,20]. The subject was recently reviewed in Refs. [24,25]. In addition, $R_{\pi/e/\mu}^{\pi,\exp}$ provides limits on the masses of certain SUSY partners [18], and on anomalies in the neutrino sector [17]. Recent intriguing indications of LU violation in B-meson decays make the subject additionally interesting (for a recent review see [26]).

2. The PEN experiment

PEN is a measurement of $R_{\pi/e/\mu}^\pi$ carried out in three runs in 2008–2010 at the Paul Scherrer Institute (PSI) by a collaboration of seven US and European institutions [21], with the aim to reach

$$\Delta R_{\pi/e/\mu}^\pi/R_{\pi/e/\mu}^\pi \simeq 5 \times 10^{-4}. \quad (3)$$

The PEN experiment uses the key components of the PIBETA apparatus with additions and modifications suitable for a dedicated study of the $\pi\to e^2$ and $\pi\to e^2\gamma$ decay processes. The PIBETA detector has been described in detail in [27], and used in a series of measurements of rare allowed pion and muon decay channels [25,28–30]. The major component of the PEN apparatus, shown in Figure 1, is the spherical large-acceptance ($\sim 3\pi\text{sr}$) electromagnetic shower calorimeter. The calorimeter consists of 240 truncated hexagonal and pentagonal pyramids of pure CsI, 22 cm or 12 radiation lengths deep. The inner and outer diameters of the sphere are 52 cm and 96 cm, respectively. Beam particles entering the apparatus with $p \simeq 75\text{MeV/c}$ are first tagged in a thin upstream beam counter (BC) and refocused by a triplet of quadrupole magnets. Following a $\sim 3\text{m}$ long flight path they pass through a 5 mm thick active degrader (AD) and a low-mass mini time projection chamber (mTPC), to reach a 15 mm thick active target (AT) where the beam pions stop and decay at rest. Decay particles are tracked non-magnetically in a pair of concentric cylindrical multiwire proportional chambers (MWPC1,2) and an array of twenty 4 mm thick plastic hodoscope detectors (PH), all surrounding the active target. The BC, AD,
Figure 1: Schematic cross section of the PEN apparatus, shown in the 2009-10 running configuration. See text for explanation of abbreviations, and [27] for details concerning the detector performance.

AT and PH detectors are all made of fast plastic scintillator material and read out by fast photomultiplier tubes (PMTs). Signals from the beam detectors are sent to waveform digitizers, running at 2 GS/s for BC, AD, and AT, and at 250 MS/s for the mTPC.

Measurements of pion decay at rest, as in the PEN experiment, must deal with the challenge of separating the $\pi \rightarrow e\nu$ and $\pi \rightarrow \mu \rightarrow e$ events with great confidence. Hence, a key source of systematic uncertainty in PEN is the hard to measure low energy tail of the detector response function. The tail is caused by electromagnetic shower leakage from the calorimeter, mostly in the form of photons. In addition, if not properly identified and accounted for, other physical processes can contribute events to the low energy part of the spectrum, as well as higher energy events above the muon beta decay (“Michel”) endpoint. One such process is the ordinary pion decay into a muon in flight, before the pion is stopped, with the resulting muon decaying within the time gate accepted in the measurement. Another is the unavoidable physical process of radiative decay. The latter is measured and properly accounted for in the PEN apparatus, as was demonstrated in PIBETA analyses [30]. Shower leakage and pion decays in flight can be appropriately characterized only if the $\pi \rightarrow \mu \rightarrow e$ chain can be well separated from the direct $\pi \rightarrow e$ decay in the target. Methods used by PEN to separate the two decay paths are discussed in [25,31] and references therein.
Figure 2: Data points: decay time spectra for the clean samples of $\pi \to e\nu$ (red) and $\pi \to \mu \to e$ (blue) events from the 2010 PEN data set. Curves: PEN Geant4 simulation of the same processes. Agreement demonstrates clean separation of the two processes.

In all, PEN has accumulated well over $2 \times 10^7$ raw $\pi \to e\nu$ events and well over $10^8$ raw $\pi \to \mu \to e$ events, allowing for generous data quality selections. The quality of PEN data is best illustrated in figures 2 and 3 which show the representative decay time (time following $\pi$ stop in AT) and energy spectra for the two classes of events.

The experimental branching ratio $R_{e/\mu}^{\pi,\text{exp}}$ is determined as follows:

$$R_{e/\mu}^{\pi,\text{exp}} = \frac{N_{\text{peak}}^{\pi \to e\nu}(1 + \epsilon_{\text{tail}})}{N_{\pi \to \mu\nu}} \cdot \frac{f_{\pi \to \mu \to e}(T_e)}{f_{\pi \to e\nu}(T_e)} \cdot \frac{\epsilon(E_{\mu \to e\nu})_{\text{MWPC}}}{\epsilon(E_{\pi \to e\nu})_{\text{MWPC}}} \cdot \frac{A_{\pi \to \mu \to e}}{A_{\pi \to e\nu}}$$  \hspace{1cm} (4)

$$= \frac{N_{\text{peak}}^{\pi \to e\nu}}{N_{\pi \to \mu\nu}} \cdot (1 + \epsilon_{\text{tail}}) \cdot r_f \cdot r_\epsilon \cdot r_A,$$  \hspace{1cm} (5)

where $\epsilon_{\text{tail}}$ is the low energy tail fraction of the $\pi \to e\nu$ response buried under the $\pi \to \mu \to e$ signal, $r_f$ is the ratio of the decay fractions for the two processes in the observed decay time gates, $r_\epsilon$ is the ratio of the MWPC efficiency for the two processes (not $\equiv 1$ because of the positron energy dependence of the energy deposited in chamber gas), and $r_A$ is the ratio of the geometrical acceptances for the two processes, evaluated.

Figure 3: Low energy tail of the calorimeter response (green), evaluated as a difference between the $\pi \rightarrow e\nu$ (black) and $\pi \rightarrow \mu \rightarrow e$ (red) dominated events, collected in 2010 using a dedicated “tail” trigger, designed to maximize $\pi \rightarrow e\nu$ over $\pi \rightarrow \mu \rightarrow e$ yield.
Table 1: Uncertainty budget for the determination of the $\pi \rightarrow e\nu(\gamma)$ branching ratio in PEN, including the dominant sources of systematic and statistical uncertainties. Label “DIF” denotes decay in flight of the particle so marked.

| Type          | Observable                          | Value                  | $\Delta R_{e/\mu}^\pi / R_{e/\mu}^\pi$ |
|---------------|-------------------------------------|------------------------|------------------------------------------|
| Systematic:   | $\Delta \epsilon_{\text{tail}}$    | $\simeq 0.025$         | $\begin{cases} \simeq 0.001^{\text{exp}} \\ 2 \times 10^{-4}^{\text{MC}} \text{goal} \end{cases}$ |
|               | $r_f$                               | $0.046$                | $1.8 \times 10^{-4}$                     |
|               | $r_\epsilon$                        | $\simeq 0.99$          | $< 10^{-4}$                              |
|               | $r_A$                               | $\simeq 1$             | $\leq 10^{-4}$                           |
|               | $N_{\pi\text{DIF} \rightarrow e\nu}/N_{\pi \rightarrow e\nu}$ | $< 2 \times 10^{-3}$  | $10^{-6} - 10^{-5}$                      |
|               | $N_{\pi\text{DIF} \rightarrow \mu\nu}/N_{\pi \rightarrow \mu\nu}$ | $2.3 \times 10^{-3}$  | $10^{-6} - 10^{-5}$                      |
|               | $N_{\mu\text{DIF} \rightarrow e\nu}/N_{\mu \rightarrow e\nu}$ | $1.4 \times 10^{-4}$  | $10^{-6} - 10^{-5}$                      |
| Statistical:  | $\Delta N_{\pi \rightarrow e\nu}/N_{\pi \rightarrow e\nu}$ | $\simeq 2.9 \times 10^{-4}$ |                                            |
| Overall goal  | $5 \times 10^{-4}$                  |                        |                                            |

Perhaps the toughest nut to crack among the leading systematic uncertainties relates to $\epsilon_{\text{tail}}$, the infamous low energy tail correction to the branching ratio in equation 5 caused by shower leakage outside the CsI electromagnetic calorimeter. To begin with, the low energy “tail” cannot be measured with sufficient accuracy concurrently with the branching ratio measurement, due to the $\sim 5$ orders of magnitude higher background of Michel positrons emanating from the $\pi \rightarrow \mu \rightarrow e$ decay chain. This is illustrated in figure 3 which shows the experimentally determined low energy “tail” evaluated through subtraction of a Michel background dominated event sample from a $\pi \rightarrow e\nu$ dominated event sample. The events shown were collected during the 2010 run by means of a specially constructed “tail” trigger, designed to suppress the yield of Michel background events. Thus obtained experimental “tail” is in excellent agreement with the Monte Carlo simulated PEN detector response, as seen in the figure. However, the last factor of 3–5 in precision must be provided by the simulation, because it is not available from the data.

The principal complication in simulating the PEN low energy tail response stems from the presence of photonuclear reactions in the calorimeter material. The greatest distortion of the purely electromagnetic shower response comes about when an energetic shower photon is absorbed by a Cs or I nucleus with subsequent emission of one
Figure 4: Data points and curves: experimental and cascade model calculated photonuclear cross sections, respectively, used as input for calculations of the PEN CsI calorimeter low energy response tail. Further model improvements of both \((\gamma, n)\) and \((\gamma, 2n)\) are under way. or more neutrons. The emitted neutrons, in turn, have a significant probability of escaping the calorimeter volume without depositing their full energy in it, and thus shifting “peak” energy events down into the low energy “tail.” Unfortunately, the situation with the relevant \((\gamma, n)\) and \((\gamma, 2n)\) cross sections is not satisfactory on two counts, as illustrated in figure 4 and discussed below. First, the \((\gamma, n)\) cross section data sets, especially that for \(^{127}\text{I}\), are not in full internal agreement. Second, the various cascade model calculations, especially for the \((\gamma, 2n)\) cross sections, used in the Geant4 Monte Carlo package have been in dramatic disagreement with measured values (by about a factor of 2), and have changed significantly from one Geant4 release version to another. After much interaction with the authors and maintainers of Geant, we have found ways to modify and correct the cascade model calculations of \((\gamma, 2n)\) cross sections, as shown in figure 4. As of this writing, members of the PEN collaboration are actively working on bringing the model calculations of photonuclear cross sections fully in line with measured data, and on quantifying the impact of the existing ambiguities in the \((\gamma, n)\) cross sections on the PEN \(\epsilon_{\text{tail}}\) correction. Once this task is completed, the branching ratio will be ready for evaluation.
3. Summary

During three production runs, in 2008, 2009 and 2010, the PEN experiment recorded more than $2 \times 10^7 \pi \rightarrow e\nu$, and over $10^8 \pi \rightarrow \mu \rightarrow e$ events, including significant numbers of pion and muon hard radiative decay events. A comprehensive blinded analysis to extract a new experimental value of $R^{\pi}_{e/\mu}$ is nearing completion, with expected precision of $\Delta R/R < 10^{-3}$. PiENu, a similar experiment at TRIUMF [22] with significantly different systematics has a similar precision goal. The near term future will thus bring about a substantial improvement in the limits on $e$-$\mu$ lepton universality, and in the related limits on non-SM, non-(\(V-A\)) processes and couplings.

In addition, new results will be forthcoming in the analysis, not discussed here in detail, of radiative $\pi^+ \rightarrow e^+\nu_e\gamma$ and $\mu^+ \rightarrow e^+\nu_e\nu_\mu\gamma$ decays in the PEN data set. The former will bring about new constraints on the pion weak form factors, the $SD^-$ term $\propto (F_V - F_A)^2$, with attendant improvement of the chiral low-energy constants. The muon radiative decay analysis will sharpen existing constraints on the $\eta$ Michel parameter, and on non-(\(V-A\)) weak interaction couplings [32,33].

However, even subsequent to the completion of the current PEN and PiENu data analyses, there will remain considerable room for improvement of experimental precision of $R^{\pi}_{e/\mu}$, with high payoff in terms of limits on physics not included in the present standard model. This work remains relevant and complementary to direct searches on the energy frontier, underway at particle colliders, providing valuable theoretical model cross checks.

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