NEW RESULTS IN RARE ALLOWED MUON AND PION DECAYS

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Simple dynamics, few available decay channels, and highly controlled radiative and loop corrections, make pion and muon decays a sensitive means of exploring details of the underlying symmetries. We review the current status of the rare decays: $\pi^+ \to e^+\nu$ (π_{e2}), $\pi^+ \to e^+\nu\gamma$ ($\pi_{e2\gamma}$), $\pi^+ \to \pi^0 e^+\nu$ (π_{e3}), and $\mu^+ \to e^+\nu\bar{\nu}\gamma$. For the latter we report new preliminary values for the branching ratio $B(E_\gamma > 10\,\mathrm{MeV}, \theta_{e\gamma} > 30°) = 4.365\,(9)_{\mathrm{stat}}\,(42)_{\mathrm{syst}} \times 10^{-3}$, and the decay parameter $\bar{\eta} = 0.006\,(17)_{\mathrm{stat}}\,(18)_{\mathrm{syst}}$, both in excellent agreement with standard model predictions. We review recent measurements, particularly by the PIBETA and PEN experiments, and near-term prospects for improvement. These and other similar precise low energy studies complement modern collider results materially.

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1. The physics of rare muon and pion decays

Muon decay, a pure leptonic electroweak process, serves a special role in the standard model (SM) because it calibrates the strength of the weak coupling. Its precise

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theoretical description, via the so-called Michel parameters,[1] positions it uniquely to provide constraints on possible contributions outside the $V-A$ standard electroweak model. Below we discuss new results on the radiative muon decay $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu \gamma$, or RMD, the only process that gives access to the decay parameter $\bar{\eta}$.

Pion decays constrain the SM in different ways, ever since providing early evidence for the $V-A$ nature of the weak interaction through the $\sim 10^5$ helicity suppression of direct $\pi \to e$ decay compared to the $\pi \to \mu \to e$ sequence. In recent decades the theoretical treatment of pion decays has reached unprecedented levels of precision. Of particular interest are the π_{e2}, $\pi_{e2\gamma}$, and π_{e3} decay channels.

(a) $\pi \to e\nu$ decay (π_{e2})

A series of calculations have refined the SM description to a precision better than a part in 10^4:

$$\left(R_{e/\mu}^\pi\right)^{\mathrm{SM}} = \left.\frac{\Gamma(\pi \to e\bar{\nu}(\gamma))}{\Gamma(\pi \to \mu\bar{\nu}(\gamma))}\right|_{\mathrm{calc}} = \begin{cases} 1.2352(5) \times 10^{-4} & \text{Ref. 2,} \\ 1.2354(2) \times 10^{-4} & \text{Ref. 3,} \\ 1.2352(1) \times 10^{-4} & \text{Ref. 4,} \end{cases} \tag{1}$$

where (γ) indicates that radiative decays are included. Meanwhile, experimental precision lags behind the theoretical one by almost two orders of magnitude: $\left(R_{e/\mu}^\pi\right)^{\mathrm{exp}} = 1.230(4) \times 10^{-4}$.[5] Because of the large helicity suppression of the π_{e2} decay, its branching ratio is highly susceptible to small non-$V-A$ contributions from new physics, making this decay a particularly suitable subject of study, as discussed in, e.g., Refs. 6–11. This prospect provides the primary motivation for the ongoing PEN[13] and PiENu[19] experiments. Of the possible "new physics" contributions in the Lagrangian, π_{e2} is directly sensitive to the pseudoscalar one. At the precision of 10^{-3}, $R_{e/\mu}^\pi$ probes the pseudoscalar and axial mass scales up to $1,000\,\mathrm{TeV}$ and $20\,\mathrm{TeV}$, respectively.[10,11] For comparison, CKM unitarity and precise measurements of several superallowed nuclear beta decays constrain the non-SM vector contributions to $20\,\mathrm{TeV}$, and scalar to $10\,\mathrm{TeV}$.[5] Although scalar interactions do not directly contribute to $R_{e/\mu}^\pi$, they can do so through loop effects, resulting in sensitivity to new scalar interactions up to $60\,\mathrm{TeV}$.[10,11] The subject was recently reviewed in Ref. 12. Alternatively, $(R_{e/\mu}^\pi)^{\mathrm{exp}}$ provides limits on masses of certain SUSY partners,[9] and on neutrino sector anomalies.[8]

(b) Radiative $\pi \to e\nu\gamma$ decay ($\pi_{e2\gamma}$)

Thanks to the radiated photon, the $\pi_{e2\gamma}$ decay provides information on the structure of the pion. Two sets of amplitudes contribute to RPD: the inner-bremsstrahlung, IB, fully described by QED, and the structure-dependent, SD. Standard $V-A$ electroweak theory requires only two pion form factors, F_A, axial vector, and F_V, vector, to describe the SD amplitude; the CVC hypothesis fixes $F_V = 0.0259(9)$. In a series of measurements at the Paul Scherrer Institute (PSI), the PIBETA project, discussed below, has improved the experimental precision of the $\pi_{e2\gamma}$ differential branching ratio as well as F_A and F_V by over an order of magnitude, and set new limits on the putative tensor term, F_T.[14,15]

(c) Pion beta decay: $\pi^+ \rightarrow \pi^0 e^+ \nu$ (π_{e3})

The extremely rare, $\mathcal{O}(10^{-8})$, pure vector $0^- \rightarrow 0^-$ pion beta decay is the theoretically cleanest process to measure the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix element V_{ud} and test quark-lepton universality. The PIBETA project has improved the experimental precision of the branching ratio by an order of magnitude.[16] This result represents the most stringent test of CVC and Cabibbo universality in a meson. The urgency of a further improvement was considerably reduced by the BNL E865 result[17] and the subsequent renormalization of V_{us} that removed a longstanding $2 - 3\sigma$ shortfall in CKM matrix unitarity.

2. Experimental method: the PEN and PIBETA projects

The PEN[13] and its predecessor PIBETA[18] experiments were designed to optimize the detection of pion and muon decays at rest. The apparatus, shown in Fig. 1, comprises an active target with beam tracking, two concentric cylindrical multiwire proportional chambers, a thin 20-element hodoscope, and a $\sim 3\pi$ sr electromagnetic calorimeter made of pure CsI. The apparatus and its performance are described in detail in Ref. 20. PIBETA focused on the π_{e3}, $\pi_{e2\gamma}$ and RMD decays in four long runs between 1999 and 2004. PEN, which started in 2007 and has conducted its main data runs in 2008–10, is focused on π_{e2}, but will produce important updates
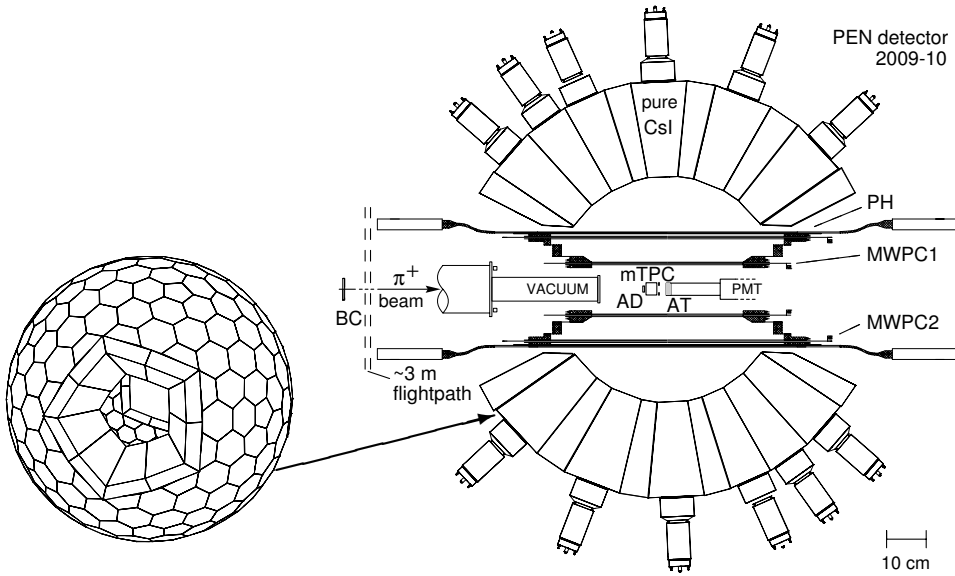

Fig. 1.   Schematic cross section of the PIBETA/PEN apparatus, shown in the 2009 PEN configuration, with its main components: beam entry with the upstream beam counter (BC), 5 mm thick active degrader (AD), mini time projection chamber (mTPC) followed by a passive Al collimator, and active target (AT), cylindrical multiwire proportional chambers (MWPC's), plastic hodoscope (PH) detectors and photomultiplier tubes (PMT's), 240-element pure CsI electromagnetic shower calorimeter and its PMT's. BC, AD, and PH detectors are made of plastic scintillator.

to the PIBETA $\pi_{e2\gamma}$ and RMD results. Key to both experiments is the simultaneous precise treatment of all of these decay processes, along with the dominant $\pi \to \mu \to e$ chain, as each presents significant backgrounds to the others.

3. Radiative muon decay: $\mu^+ \to e^+ \nu \bar{\nu} \gamma$

We have recently analyzed a set of $\sim$0.5 M RMD events; the relevant measured and Monte Carlo simulated spectra, including backgrounds, are shown in Fig. 2, showing excellent agreement within the design acceptance of the spectrometer. The analysis
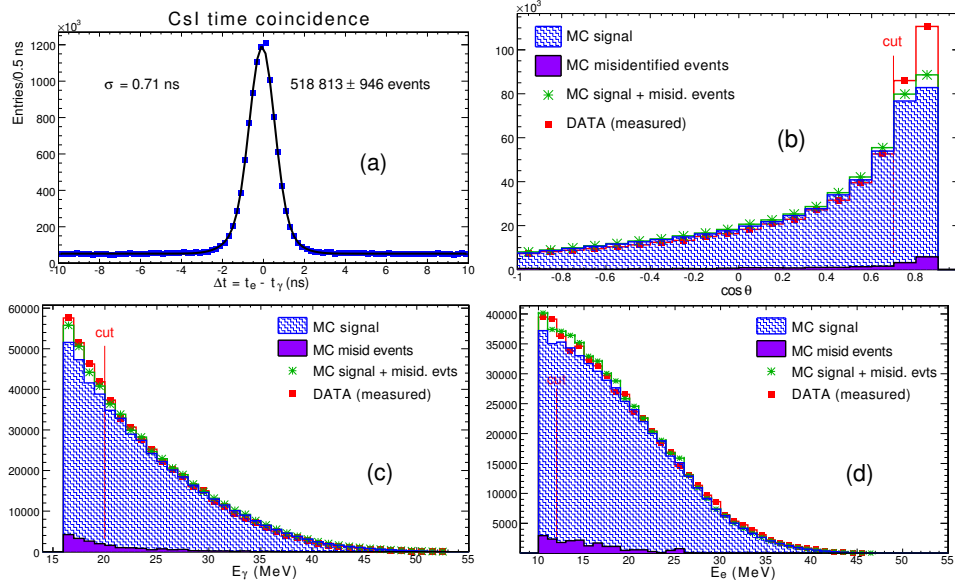

Fig. 2.   Measured and simulated RMD distributions of: (a) $\Delta t_{e\gamma}$, (b) $\cos\theta_{e\gamma}$, (c) E_γ, and (d) E_{e^+}. Also shown are the misidentified Monte Carlo events (split-off secondary neutral showers), as well as bounds of cuts applied in the branching ratio analysis.

yields a preliminary branching ratio for $E_\gamma > 10\,\mathrm{MeV}$, and $\theta_{e\gamma} > 30°$:

$$B^{\mathrm{exp}} = 4.365\,(9)_{\mathrm{stat}}\,(42)_{\mathrm{syst}} \times 10^{-3}\,, \tag{2}$$

which represents a 29-fold improvement in precision over the previous result, and is in excellent agreement with the SM value: $B^{\mathrm{SM}} = 4.342\,(5)_{\mathrm{stat\text{-}MC}} \times 10^{-3}$. Minimum-$\chi^2$ analysis of the most sensitive data subset (with roughly balanced systematic and statistical uncertainties) yields a preliminary value for the $\bar{\eta}$ parameter ($\bar{\eta}^{\mathrm{SM}} \equiv 0$):

$$\bar{\eta} = 0.006\,(17)_{\mathrm{stat}}\,(18)_{\mathrm{syst}}, \qquad \mathrm{or} \qquad \bar{\eta} < 0.028 \quad (68\%\mathrm{CL})\,, \tag{3}$$

a 4-fold improvement over previous limits.[21] Details of this analysis, including a comprehensive discussion of the uncertainties, are given in Refs. 22 and 23.

4. Prospects for the near future

During the 2008-10 production runs the PEN experiment accumulated some 23 M $\pi \to e\nu$, and > 150 M $\pi \to \mu \to e$ events, as well as significant numbers of pion and muon radiative decays. A comprehensive blinded maximum likelihood analysis is under way to extract a new experimental value of $R^\pi_{e/\mu}$. The PEN goal is $\Delta R/R \simeq 5 \times 10^{-4}$. The competing PiENu experiment at TRIUMF has a similar precision goal. The near to medium future will thus bring about a substantial improvement in the limits on e-μ lepton universality, and the attendant SM limits.

Once completed, analysis of the PEN $\pi_{e2\gamma}$ data is expected to yield improvements in the SD$^-$ structure dependent amplitude, which constrains $F_V - F_A$, thus improving on the PIBETA result for F_V.[15] In a similar vein, analysis of the PEN $\mu^+ \to e^+ \nu\bar{\nu}\gamma$ data is expected to improve the present value of the Michel parameter $\bar{\eta}$, leading to a new global analysis of the fundamental weak couplings.

Acknowledgments

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