PROCEEDINGS OF SCIENCE

Rare pion and muon decay measurements: the PIBETA and PEN experiments

D. Počanić,[∗,a] **M. Bychkov**,[a] **B.A. VanDevender**,[a†] **L.P. Alonzi**,[a] **V.A. Baranov**,[b] **W. Bertl**,[c] **Yu.M. Bystritsky**,[b] **E. Frlež**,[a] **N.V. Khomutov**,[b] **A.S. Korenchenko**,[b] **S.M. Korenchenko**,[b] **M. Korolija**,[d] **T. Kozlowski**,[e] **N.P. Kravchuk**,[b] **N.A. Kuchinsky**,[b] **D. Mekterović**,[d] **D. Mzhavia**,[bf] **A. Palladino**,[ac] **P. Robmann**,[g] **A.M. Rozhdestvensky**,[b] **U. Straumann**,[g] **I. Supek**,[d] **P. Truöl**,[g] **A. van der Schaaf**,[g] **E.P. Velicheva**,[b] **V.P. Volnykh**[b]

[a]*Department of Physics, University of Virginia, Charlottesville, VA 22904-4714, USA*
[b]*Joint Institute for Nuclear Research, RU-141980 Dubna, Russia*
[c]*Paul Scherrer Institut, Villigen PSI, CH-5232, Switzerland*
[d]*Institut "Rudjer Bošković," HR-10000 Zagreb, Croatia*
[e]*Instytut Problemów Jądrowych im. Andrzeja Sołtana, PL-05-400 Świerk, Poland*
[f]*Institute for High Energy Physics, Tbilisi State University, GUS-380086 Tbilisi, Georgia*
[g]*Physik-Institut, Universität Zürich, CH-8057 Zürich, Switzerland*

E-mail: pocanic@virginia.edu, mab3ed@virginia.edu

We review recent measurements of the rare decays: $\pi^+ \to \pi^0 e^+ \nu$ (pion beta decay), $\pi^+ \to e^+ \nu\gamma$ (radiative pion decay), $\mu^+ \to e^+ \nu\bar{\nu}\gamma$ (radiative muon decay), and their theoretical implications. The PIBETA experiment, with measurements recently completed at PSI, has brought about an order of magnitude improvement, or better, in the branching ratio precision for these processes. The successor PEN experiment, currently under way at PSI, aims to improve the precision of the $\pi^+ \to e^+ \nu$ (π_{e2}) decay branching ratio by about an order of magnitude. Each of these results contributes toward a better understanding of the limits on certain particles and interactions not included in the standard model, or toward improving the precision of chiral lagrangian and pion structure parameters. We finally review the near-term prospects for their further improvement.

PACS: 13.20.Cz 13.35.Bv 14.40.Aq

6th International Workshop on Chiral Dynamics, CD09
6-10 July 2009
Bern, Switzerland

∗Speaker.
†Presently at: CENPA, University of Washington, Seattle, WA 98195, USA.

PoS(CD09)009

1. Motivation

Thanks to exceptionally well controlled theoretical uncertainties, decays of light mesons, particularly of the pion, are understood at very high precision, typically a few parts per 10^4, or better (see, e.g., Refs. [1 – 3]). Hence, pion decays present fertile ground for testing predictions of the standard model (SM), as well as for setting constraints on processes and particles outside the SM. Muon decays are theoretically cleaner yet, and provide direct information regarding the symmetry properties of the weak interaction itself, e.g., departures from its $V-A$ form.

2. The PIBETA experiment

The PIBETA experiment, with measurements in 1999–2001 and 2004 at the Paul Scherrer Institute (PSI), Switzerland, was primarily designed to improve the accuracy of the π_β decay branching ratio. Pion decays at rest were detected in an detector system consisting of a large solid angle pure CsI electromagnetic calorimeter, beam and central tracking detectors[4, 5]. The apparatus is shown schematically in Fig. 1.

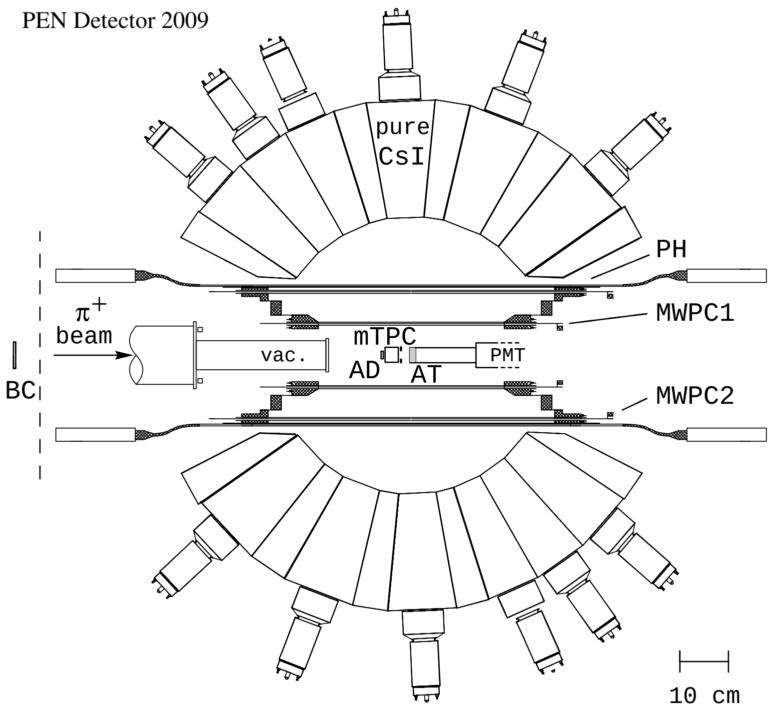

Figure 1: Schematic cross section of the PIBETA/PEN apparatus, shown here in the 2009 PEN run configuration, with its main components: beam entry with the upstream beam counter (BC), 5 mm thick active degrader (AD), mini time projection chamber (mTPC) followed by a passive Al collimator, and active target (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.

2.1 Pion beta decay $\pi^+ \to \pi^0 e^+ \nu$

The pion beta decay, with the prompt follow-on decay $\pi^0 \to \gamma\gamma$, produces a highly distinctive signal with virtually no background. We used the number of observed $\pi^+ \to e^+\nu$ (π_{e2}) decays (shown in Fig. 2), for normalization, and determined the branching ratio value $B^{\text{ex}-\text{n}}(\pi^+ \to \pi^0 e^+ \nu) = 1.036(4)_{\text{stat}}(4)_{\text{syst}}(3)_{\text{e2}} \times 10^{-8}$, where the first uncertainty is statistical, the second systematic, and the third arises from $\Delta B(\pi_{\text{e2}})$, experimental π_{e2} branching ratio uncertainty[6] . Normalizing instead to the more precise theoretical value of $B(\pi_{\text{e2}})$[3] yields $B^{\text{th}-\text{n}}(\pi^+ \to \pi^0 e^+ \nu) =$

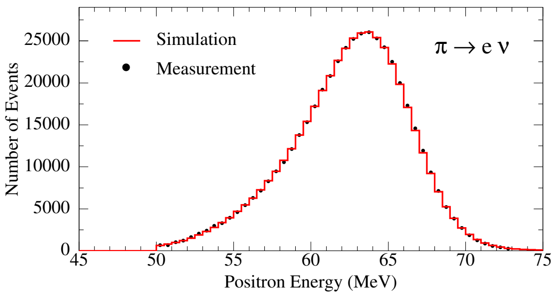

Figure 2: Background-subtracted $\pi^+ \to e^+\nu$ energy spectrum acquired with a dedicated one-arm calorimeter trigger. This decay mode was used for normalization of the $\pi^+ \to \pi^0 e^+\nu$ and $\pi^+ \to e^+\nu\gamma$ decay branching ratios. We note the near-perfect agreement between data and simulation.

$1.040(4)_{\rm stat}(4)_{\rm syst} \times 10^{-8}$. Both results agree well with the SM prediction, and represent the best test to date of vector current conservation (CVC) in a meson. This result is presented in more detail in Ref. [6].

2.2 Radiative pion decay $\pi^+ \to \mathrm{e}^+\nu\gamma$

Concurrently with the π_{e3} decay, the PIBETA collaboration has measured the $\pi^+ \to \mathrm{e}^+\nu\gamma$ (RPD) branching ratio over a wide region of phase space (Fig. 3). Two sets of amplitudes contribute to RPD: the inner-bremsstrahlung, IB, fully described by QED, and the structure-dependent amplitude, SD. The 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 gives $F_V = 0.0259(9)$.

Minimum-χ^2 fits to the measured (E_{e^+}, E_γ) energy distributions result in the weak form factor

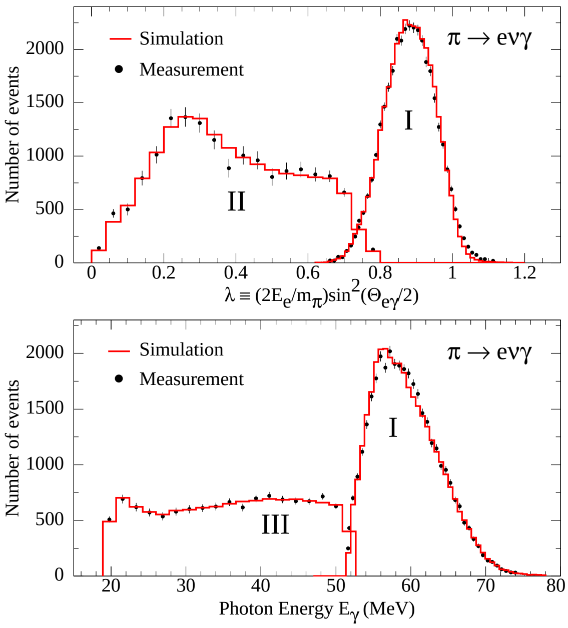

Figure 3: Data points: background-subtracted $\pi^+ \to \mathrm{e}^+\nu\gamma$ differential yields in three distinct kinematic regions, as a function of positron (top) and photon energy (bottom). Red lines: `GEANT3` calculations with the best-fit values of F_V, F_A, and a.

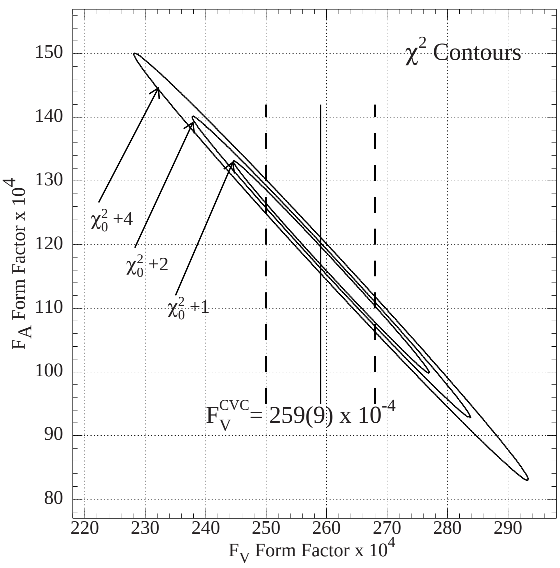

Figure 4: Contour plot of loci of constant χ^2 for the minimum value χ_0^2 plus 1, 2, and 4 units, respectively, in the F_A-F_V parameter plane, keeping the parameter $a = 0.041$. The range of the CVC prediction, $F_V = 0.0259(9)$ is indicated.

value of $F_A = 0.0119(1)$ with a fixed value of $F_V = 0.0259$. An unconstrained fit yields $F_V = 0.0258(17)$ and $F_A = 0.0117(17)$ in a tightly correlated band shown in Fig. 4 and defined by

$$F_A = (-1.0286 \cdot F_V + 0.03853) \pm 0.00014\,. \tag{2.1}$$

In addition, we have measured $a = 0.10(6)$ for the dependence of F_V on q^2, the $e^+\nu$ pair invariant mass squared, parametrized as $F_V(q^2) = F_V(0)(1 + a \cdot q^2)$ [7–9]. The branching ratio for the kinematic region $E_\gamma > 10\,\mathrm{MeV}$ and $\theta_{e^+\gamma} > 40^\circ$ is measured to be $B^{\mathrm{exp}} = 73.86(54) \times 10^{-8}$. Earlier deviations we found in the high-E_γ/low-E_{e^+} kinematic region [10] are completely resolved (witness the excellent agreement of data and calculation in Fig. 3), affirming full compatibility with CVC and standard $V-A$ calculations without a tensor term. For the latter we find $-5.2 \times 10^{-4} < F_T < 4.0 \times 10^{-4}$ with 90% condidence. We also derive new values for the pion polarizability at leading order, $\alpha_E = 2.78(10) \times 10^{-4}\,\mathrm{fm}^3$, and neutral pion lifetime, $\tau_{\pi^0} = (8.5 \pm 1.1) \times 10^{-17}\,\mathrm{s}$.

2.3 Radiative muon decay $\mu^+ \to e^+\nu\bar{\nu}\gamma$

Radiative muon decay (RMD) offers a particularly sensitive means for testing the $V-A$ nature of the weak interaction through $\bar{\eta}$, the only Michel parameter not accessible in ordinary μ decay. RMD events with energetic photons are required to evaluate $\bar{\eta}$. Along with other Michel parameters, $\bar{\eta}$ sets limits on departures from the $V-A$ weak interaction form ($\bar{\eta}_{SM} \equiv 0$).

With more than 4×10^5 RMD events, our 2004 PIBETA data (Fig. 5) yield the preliminary result: $B(E_\gamma > 10\,\mathrm{MeV},\, \theta_{e\gamma} > 30^\circ) = 4.40(2)_{\mathrm{stat}}(9)_{\mathrm{syst}} \times 10^{-3}$, 14 times more precise than the previous world average[12]. The best fit for B is obtained for $\bar{\eta} = -0.084 \pm 0.050(\mathrm{stat.}) \pm 0.034(\mathrm{syst.})$, yielding upper limits on the allowed value of $\bar{\eta} \leq 0.033$ and $\bar{\eta} \leq 0.060$, with 68% and 90% confidence, respectively. Combined with previous measurements of $\bar{\eta}$, this reduces the known upper limit by a factor of 2.5 to $\bar{\eta}_{\mathrm{WORLD\ AVG}} \leq 0.028$, with 68% confidence [13]. This is a work in progress. A remaining task is to improve the small-angle bremsstrahlung simulation, primarily responsible for the relatively large systematic uncertainty in the quoted preliminary branching fraction result.

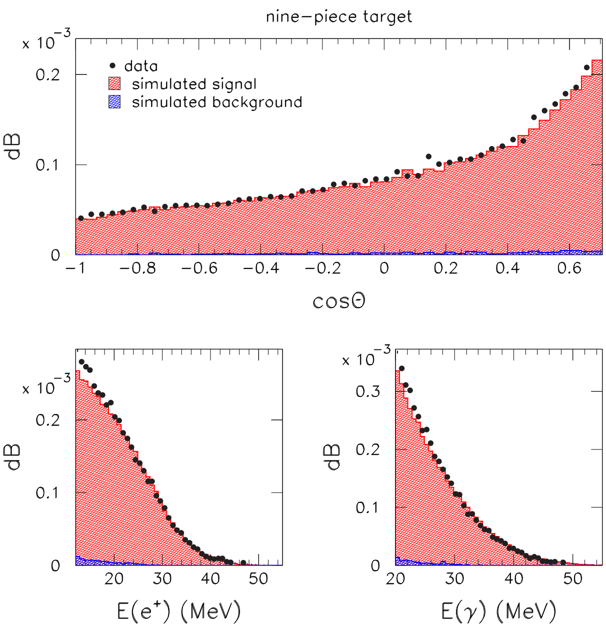

Figure 5: Data points: measured preliminary differential branching ratio values for radiative muon decays, for approximately one half of the 2004 PIBETA data set (taken with the nine-piece target), displayed as functions of $\theta_{e\gamma}$, the positron–photon opening angle, E_{e^+}, positron energy, and E_γ, photon energy. Red hatched histograms represent results of `GEANT3` Monte Carlo simulations based on the standard $V-A$ theory. Blue filled histograms: Monte Carlo simulated background. The evident discrepancies between data and simulations are primarily due to the inadequate description of small-angle bremsstrahlung in `GEANT3`; this aspect of the analysis will be improved.

3. The PEN experiment: $\pi^+ \to e^+\nu$ decay

Historically, the $\pi\to e\nu$ (or π_{e2}) decay, provided an early strong confirmation of the $V-A$ nature of the electroweak interaction. At present, its branching ratio is understood at the level of better than one part in 10^4 [3]. Experimental precision, however, lags behind by over an order of magnitude. Because of the large helicity suppression of the π_{e2} decay, its branching ratio is highly susceptible to even slight non-$V-A$ contributions from new physics, making this decay a particularly suitable subject of study.

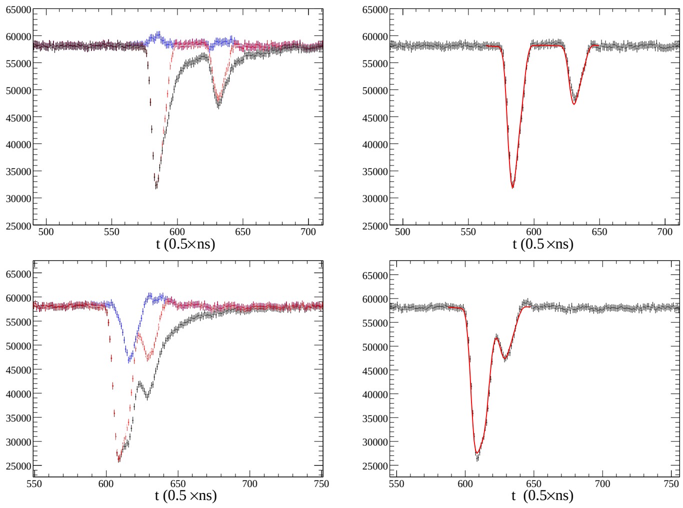

Figure 6: Sample target waveforms (wf) for a $\pi\to e\nu$ decay event (top), and a $\pi\to\mu\to e$ sequential decay event (bottom). Left panels: full original wf's (black), wf's after digital filtering (red), and wf's after subtraction of predicted π^+ and e^+ signals. Right panels: filtered wf's (black) for the same two events, with superimposed full fit (red). The $\pi\to\mu\to e$ sample wf features relatively close π, μ, and e pulses, thus highlighting the challenge of reliable extraction of strongly overlapping signals.

The PEN experiment [14] uses a modified PIBETA detector apparatus to carry out a measurement of $B(\pi_{e2})$ to an accuracy of $\Delta B/B \leq 5\times10^{-4}$ at PSI. Because of its extreme goal accuracy, PEN requires more complete specification of the stopping pion and positron track geometry than did the PIBETA measurements. High-rate waveform digitization is required for all beam detector signals, particularly for the target (Fig. 6). Beam pion tracking is required in order to suppress in-flight decay events. We illustrate the resolving power of our target waveform analysis in Fig. 7.

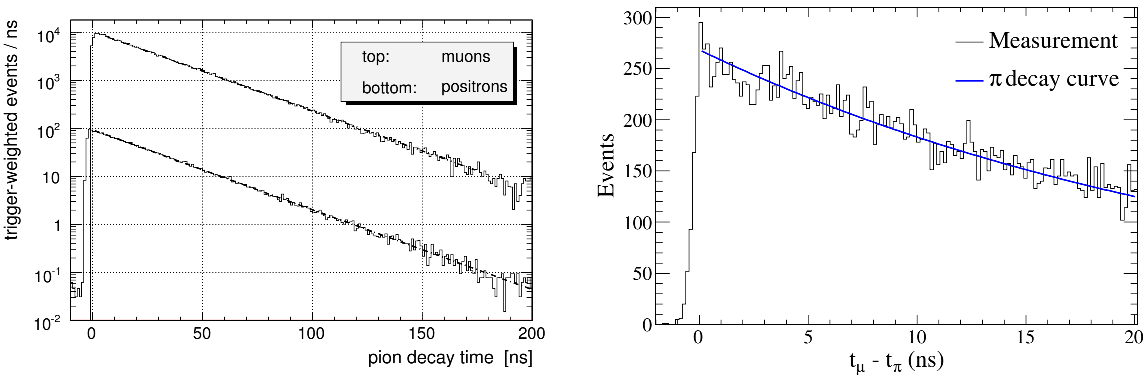

Figure 7: Left: distributions of pion decay time for μ^+ and e^+ final states. For $\pi\to\mu\nu$ events a subsequent $\mu\to e\nu\bar{\nu}$ decay was required within 5 – 25 ns after the pion decay. The observed life times agree well with the world average value. Right: spectrum of π–μ pulse time differences obtained in fits of $\pi\to\mu\to e$ event target waveforms, demonstrating the ability to separate the two processes down to time zero.

During engineering runs in 2007 in 2008 the collaboration developed the required intense low energy pion beam tunes and upgraded key detector components, including a mini time projection chamber to map the beam. To date, the experiment has observed over 7×10^{10} tagged pion stops in the target, and recorded over 4×10^6 π_{e2} decays before cuts. PEN will run in 2009-10 in order to complete the required event statistics and key systematic studies.

4. Summary

In conclusion, the PIBETA experiment has improved by an order of magnitude, or better, the accuracy of the pion beta (π_{e3}), radiative pion ($\pi_{e2\gamma}$), and radiative muon decays. In doing so, PIBETA has verified CVC and SM predictions at new levels in a meson, and significantly improved the precision of pion structure parameters (F_V, F_A, F_T form factors, polarizability, closely related to low-energy effective QCD lagrangian parameters $L_9^r + L_{10}^r$). Through the $B(\mu \to e\nu\bar{\nu}\gamma)$ and $\bar{\eta}$ measurement we have made possible new tests of the $V-A$ nature of the weak interaction. PEN, the successor experiment, is well on its way to improving the precision of the π_{e2} branching ratio, with the prospect of setting new limits on light lepton universality, and on a variety of non-SM processes manifested primarily through pseudoscalar contributions. The PEN data set will more than double our 2004 PIBETA run statistics for RPD and RMD events, leading to further improvements in their precision, while the π_β event statistics will increase only slightly.

The PIBETA and PEN experiments have been supported by the U.S. National Science Foundation, U.S. Department of Energy, the Paul Scherrer Institute, and the Russian Foundation for Basic Research.

References

[1] W. Jaus, Phys. Rev. D **63** (2001) 053009.

[2] W.J. Marciano and A. Sirlin, Phys. Rev. Lett. **96** (2006) 302002.

[3] V. Cirigliano and I. Rosell, Phys. Rev. Lett. **99** (2007) 231801.

[4] E. Frlež, D. Počanić, K.A. Assamagan, et al., Nucl. Inst. Meth. A **526** (2004) 300.

[5] `http://pibeta.phys.virginia.edu/` and links therein.

[6] D. Počanić, E. Frlež, V.A. Baranov, et al., Phys. Rev. Lett. **93** (2004) 181803.

[7] J. Bijnens and P. Talavera, Nucl. Phys. B **489** (1997) 387.

[8] C.Q. Geng, et al., Nucl. Phys. B **648** (2004) 281.

[9] H. Pichl and R. Unterdorfer, Eur. Phys. J. C **55** (2008) 273.

[10] E. Frlež, D. Počanić, V.A. Baranov, et al., Phys. Rev. Lett. **93** (2004) 181804.

[11] M. Bychkov, D. Počanić, B.A. VanDevender, et al., Phys. Rev. Lett. **103** (2009) 051802.

[12] C. Amsler et al. (Particle Data Group), Phys. Lett. **B667** (2008) 1.

[13] B.A. VanDevender, Ph.D. thesis, Univ. of Virginia (2005).

[14] `http://pen.phys.virginia.edu/` and links therein.