PEN experiment: a precise measurement of the $\pi^+ \to e^+\nu$ decay branching fraction

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Abstract. A new measurement of $B_{\pi e2}$, the $\pi^+ \to e^+\nu(\gamma)$ decay branching ratio, is currently under way at the Paul Scherrer Institute. The present experimental result on $B_{\pi e2}$ constitutes the most accurate test of lepton universality available. The accuracy, however, still lags behind the theoretical precision by over an order of magnitude. Because of the large helicity suppression of the π_{e2} decay, its branching ratio is susceptible to significant contributions from new physics, making this decay a particularly suitable subject of study.

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MOTIVATION

Historically, the $\pi \to e\nu$ decay, also known as π_{e2}, provided an early strong confirmation of the $V-A$ nature of the electroweak interaction. At present, thanks to exceptionally well controlled theoretical uncertainties, its branching ratio is understood at the level of better than one part in 10^4. The most recent independent theoretical calculations are in very good agreement and give:

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

where (γ) indicates that radiative decays are included. Marciano and Sirlin [1] and Finkemeier [2] took into account radiative corrections, higher order electroweak leading logarithms, short-distance QCD corrections, and structure-dependent effects, while

Cirigliano and Rosell [3] used the two-loop chiral perturbation theory. A number of exotic processes outside of the current standard model (SM) can produce deviations from the above predictions, mainly through induced pseudoscalar (PS) currents. Prime examples are: charged Higgs in theories with richer Higgs sector than the SM, PS leptoquarks in theories with dynamical symmetry breaking, certain classes of vector leptoquarks, loop diagrams involving certain SUSY partner particles, as well as non-zero neutrino masses and their mixing (Ref. [4] gives a recent review of the subject). In this sense, π_{e2} decay provides complementary information to direct searches for new physics at modern colliders.

The two most recent measurements of the branching ratio are mutually consistent:

$$B^{\pi e2}_{\rm exp} = \begin{cases} 1.2265\,(34)_{\rm stat}\,(44)_{\rm syst} \times 10^{-4} & \text{Ref. [5]}, \\ 1.2346\,(35)_{\rm stat}\,(36)_{\rm syst} \times 10^{-4} & \text{Ref. [6]}, \end{cases} \tag{2}$$

and dominate the world average of $1.2300\,(40) \times 10^{-4}$, which, however, is less accurate than the theoretical calculations by a factor of 40. The PEN experiment [7] is aiming to reduce this gap and, in doing so, to set new limits on the above non-SM processes.

EXPERIMENTAL METHOD

The PEN experiment uses an upgraded version of the PIBETA detector system, described in detail in Ref. [8]. The PIBETA collaboration performed a series of rare pion and muon decay measurements [9, 10, 11]. The PEN apparatus consists of a large-acceptance ($\sim 3\pi$ sr) electromagnetic shower calorimeter (pure CsI, 12 radiation lengths thick) with non-magnetic tracking in concentric cylindrical multi-wire proportional chambers (MWPC1,2) and plastic scintillator hodoscope (PH), surrounding a plastic scintillator active target (AT). Beam pions pass through an upstream detector (BC), have their energy reduced in the wedged active degrader (wAD), and stop in the target. Combining the signals from the four wedges (a horizontal pair and a vertical pair) of the wAD provides information on the *x*-*y* position of the beam pion as it reaches the AT. Signals from the beam detectors (BC, wAD, and AT) are digitized in a 2 GS/s waveform digitizer. Figure 1 shows the layout of the main detector components.

The primary method of evaluating the π_{e2} branching ratio, as outlined in the experiment proposal [7], is to normalize the observed yield of $\pi\to e\nu$ decays in a high-threshold calorimeter energy trigger (HT) to the number of sequential decays $\pi\to\mu\to e$ in an all-inclusive pre-scaled trigger (PT). To be accepted in either trigger, an event must contain the positron signal within a 250 ns gate which starts about 40 ns before the pion stop time. The π_{e2} events are isolated and counted within the HT data sample via their 26 ns exponential decay time distribution with respect to the pion-stop time reference. On the other hand, the PT provides the corresponding number of sequential $\pi\to\mu\to e$ decays, again via their well defined time distribution with respect to the π stop time. Finally, by analyzing the beam counter waveform digitizer data we separate π_{e2} events (two pulses in the target waveform: pion stop and decay positron), from the sequential decay events (three pulses in the target waveform, produced by the pion, muon and positron, respectively). Thus identified π_{e2} events serve to map out the energy response

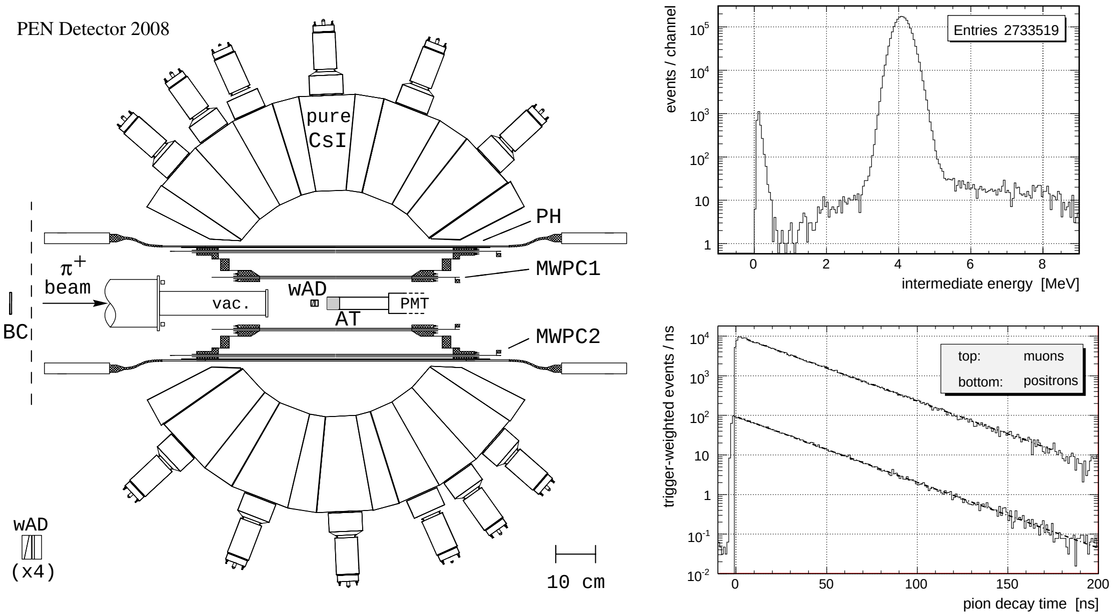

FIGURE 1. Left: Cross section drawing of the PEN detector system. A small schematic representation of the wedged Active Degrader (wAD) is included in the lower left corner. Right: Energy distribution of the intermediate muon in the $\pi\to\mu\to e$ decay chain, extracted from AT waveform data (top). Time dependence of the $\pi\to\mu$ and $\pi\to e$ decays, from the AT waveform data.

function of the calorimeter, enabling us to evaluate the low energy "tail," not accessible in the HT data. A measure of the performance of the beam detectors, and of the current state of the art of the waveform analysis is given in Fig. 1 (right), showing excellent identification of the $\pi\to\mu\to e$ and $\pi\to e\nu$ decays. The underlying waveform analysis is illustrated in Fig. 2. Figure 3 shows the positron energy spectra for π_{e2} decays and $\mu\to e$

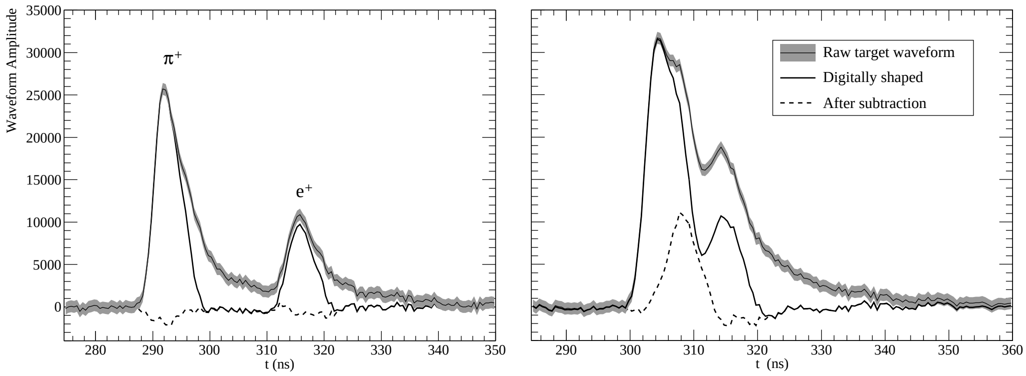

FIGURE 2. Target detector waveforms: raw (solid with shaded uncertainty band), and digitally shaped (solid curve) to suppress the pulse tails. Left: an event in which no residual pulse (dashed curve) was found after subtracting the stopped π^+ and emitted e^+ pulses. Right: an event in which a closely spaced intermediate muon pulse (dashed curve) was found after subtracting the π^+ and e^+ pulses. Uncertainty bands for the shaped and subtracted waveforms (not shown) are of similar size to the raw ones.

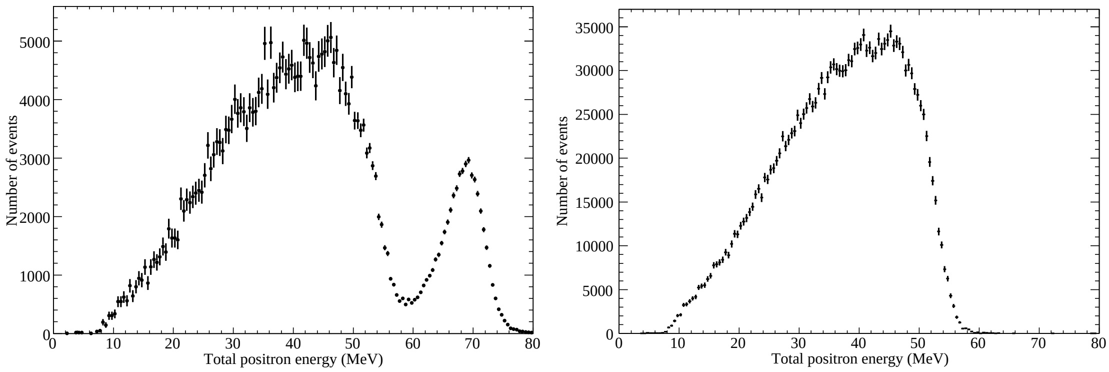

FIGURE 3. Measured e^+ energy spectrum for early (0 to 50 ns; left), and late decay times (200 to 250 ns; right). Early decays show a distinct $\pi \to e\nu$ peak above the $\pi \to \mu \to e$ continuum (additionally suppressed by a target energy cut). The $\pi \to e\nu$ peak is essentially gone by 200 ns.

decays recorded in our detector.

Two engineering runs were completed, in 2007 and 2008, respectively. All detector systems are performing to specifications, and $\sim 5 \times 10^6$ π_{e2} events were collected. The experiment will continue with a major run in 2009, which is intended to double the existing data sample. Prior to the run, the wedged degrader will be replaced by a single thin degrader, and a mini time projection chamber (mini-TPC). The position resolution, ~1–2 mm, achieved using the wAD, is limited by pion multiple scattering in the wedges. The new system will improve the beam position resolution by about an order of magnitude, with the mini-TPC adding excellent directional resolution, as well. Both are needed to achieve improved systematics and better control of decays in flight.

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