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New Results from the PIBETA Experiment

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We report interim results of the PIBETA experiment analysis for the pion beta decay and pion radiative decay. The former is in excellent agreement with the SM predictions at the 1 % accuracy level.

1 Experiment Goals and Motivation

The PIBETA experiment[1] at the Paul Scherrer Institute (PSI) is a comprehensive set of precision measurements of the rare decays of the pion and muon. The goals of the experiment's first phase are:

(a) To improve the experimental precision of the pion beta decay rate, $\pi^+ \to \pi^0 e^+ \nu$ (known as π_{e3}, or $\pi\beta$), from the present $\sim 4\,\%$ to $\sim 0.5\,\%$. The improved experimental precision will begin to approach the theoretical accuracy in this process, and thus for the first time enable a meaningful extraction of the CKM parameter V_{ud} from a non-baryonic process.

(b) To measure the branching ratio (BR) of the radiative decay $\pi \to e\nu\gamma$ ($\pi_{e2}R$, or RPD), enabling a precise determination of the pion form factor ratio F_A/F_V, and, hence, of the pion polarizability. Due to expanded phase space coverage of the new measurement, we also aim to resolve the longstanding open question of a nonzero tensor pion form factor.

(c) A necessary part of the above program is an extensive measurement of the radiative muon decay rate, $\mu \to e\nu\bar{\nu}\gamma$, with broad phase space coverage. This new high-statistics data sample is conducive to a precision search for non-$(V-A)$ admixtures in the weak Lagrangian.

(d) Both the $\pi\beta$ and the $\pi_{e2}R$ decays are normalized to the $\pi \to e\nu$ (known as π_{e2}) decay rate. The first phase of the experiment has, thus, produced a large sample of π_{e2} decay events. The second phase of the PIBETA program will seek to improve the π_{e2} decay branching ratio precision from the current $\sim 0.35\,\%$ to under $0.2\,\%$, in order to provide a precise test of lepton universality, and thus of certain possible extensions to the Standard Model (SM).

Recent theoretical work[2,3] has demonstrated low theoretical uncertainties in extracting V_{ud} from the pion beta decay rate, i.e., a relative uncertainty of 5×10^{-4} or less, providing further impetus for continued efforts in improving the experimental accuracy of this process.

2 Experimental Method

The πE1 beam line at PSI was tuned to deliver $\sim 10^6\ \pi^+$/s with $p_\pi \simeq 113$ MeV/c, that stop in a segmented plastic scintillator target (AT). The major detector systems are shown in a schematic drawing in Fig. 1. Energetic charged decay products are tracked in a pair of thin concentric MWPC's and a thin 20-segment plastic scintillator barrel detector (PV). Both neutral and charged particles deposit most (or all) of their energy in a spherical electromagnetic shower calorimeter consisting of 240 elements made of pure CsI. The CsI radial thickness, 22 cm, corresponds to $12\,X_0$, and the calorimeter subtends a solid angle of about 80 % of 4π sr.

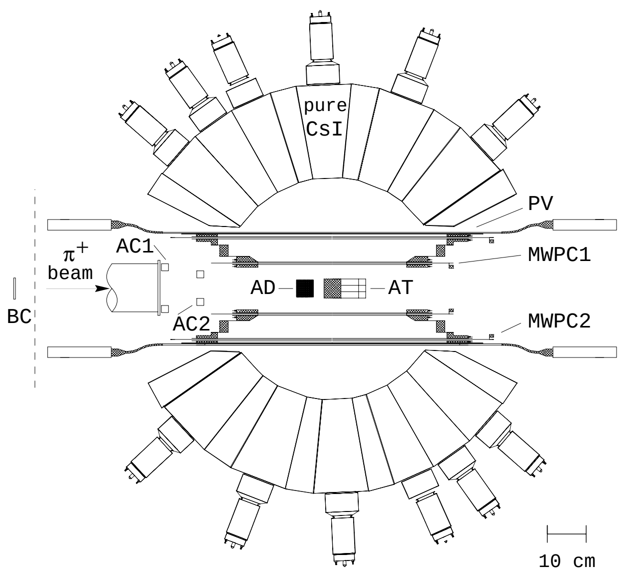

Figure 1. A schematic cross section of the PIBETA detector system. Symbols denote: BC–thin upstream beam counter, AC1,2–active beam collimators, AD–active degrader, AT–active target, MWPC1,2–thin cylindrical wire chambers, PV–thin 20-segment plastic scintillator barrel. BC, AC1, AC2, AD and AT detectors are also made of plastic scintillator.

The basic principle of the measurement is to record all non-prompt large-energy (above the $\mu \to e\nu\bar{\nu}$ endpoint) electromagnetic shower pairs occurring in opposite detector hemispheres (non-prompt two-arm events). In addition, we record a large prescaled sample of non-prompt single shower (one-arm) events. Using these minimum-bias sets, we extract $\pi\beta$ and π_{e2} event sets, using the latter for branching ratio normalization. In a stopped pion experiment these two channels have nearly the same detector acceptance, and have much of the systematics in common.

A full complement of twelve fast analog triggers comprising all relevant logic combinations of one- or two-arm, low- or high calorimeter threshold , prompt and delayed (with respect to π^+ stop time), as well as a random and a three-arm trigger, were implemented in order to obtain maximally comprehensive and unbiased data samples.

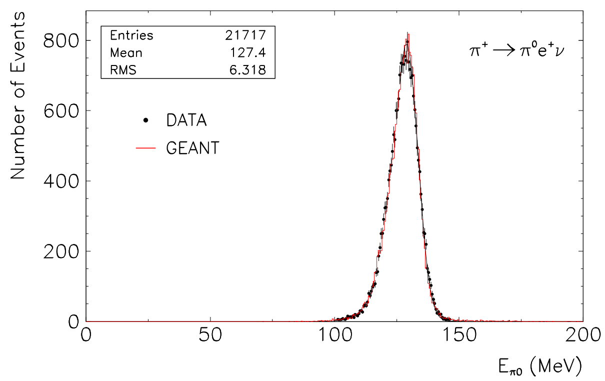

Figure 2. π^0 energy spectrum for a subset of the measured $\pi^+ \to \pi^0 e^+ \nu$ decay data; solid curve: GEANT simulation.

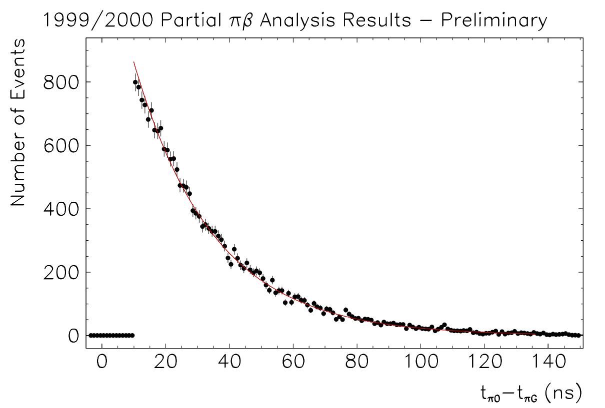

Figure 3. Histogram of time differences between the beam pion stop and the $\pi\beta$ decay events (dots); curve: pion lifetime exponential curve. A software cut at 10 ns was applied.

The high quality of the PIBETA data is clearly demonstrated in the histograms of the calorimeter energy and event timing (following the π^+ stop time), as well as of

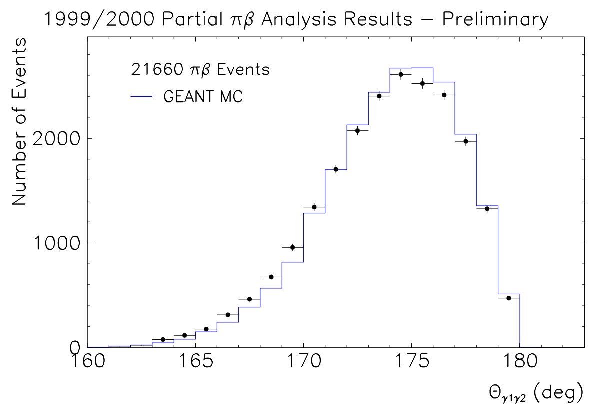

Figure 4. Histogram of the measured γ-γ opening angle in pion beta decay events ($\pi^+ \to \pi^0 e^+ \nu$) for a subset of acquired data; solid curve: GEANT simulation.

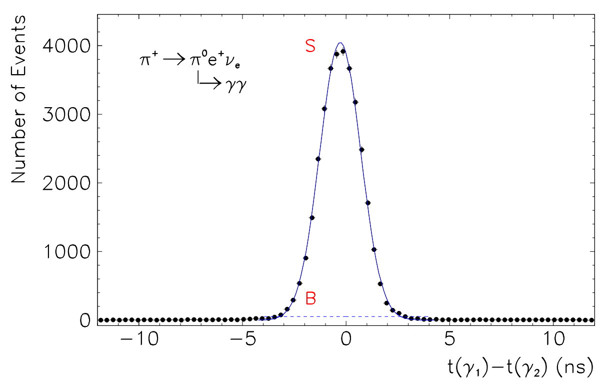

Figure 5. Histogram of γ-γ time differences for the same set of $\pi\beta$ data events (dots); curve: fit. Signal to background ratio exceeds 250.

the $\gamma - \gamma$ opening angle and time difference for a subset of the recorded pion beta decay events, shown in Figs. 2–5.

In particular, the low level of accidental background is evident in the $\gamma - \gamma$ relative timing histogram in Fig. 5; the peak to background ratio exceeds 250. The histogram of recorded $\gamma - \gamma$ opening angles for pion beta events, shown in Fig. 4, provides possibly the most sensitive test of the Monte Carlo simulation of the apparatus, and of the systematics related to the geometry of the beam pion stopping distribution. The latter is the single largest contributor to the overall uncertainty in the acceptance, and, hence, in the branching ratio.

3 First Results: Pion Beta Decay

The first phase of measurements took place in 1999, 2000 and 2001, resulting in some 60,000 recorded pion beta events. The figures of Section 2 are based on a data subset acquired in 1999 and 2000. Our current ***preliminary***

working result for the pion beta decay branching ratio, extracted from the above analysis, is

$$BR \simeq 1.044 \pm 0.007(\text{stat.}) \pm 0.009(\text{syst.}) \times 10^{-8}\ . \qquad (1)$$

Our result is to be compared with the previous most accurate measurement of McFarlane et al.[4]:

$$BR = 1.026 \pm 0.039 \times 10^{-8}\ ,$$

as well as with the SM Prediction (Particle Data Group, 2002[5]):

$$\begin{aligned} BR = 1.038 - 1.041 \times 10^{-8} \quad & (90\%\text{C.L.}) \\ (1.005 - 1.008 \times 10^{-8} \quad & \text{excl. rad. corr.}) \end{aligned}$$

We see that even our working result strongly confirms the validity of the CVC hypothesis and SM radiative corrections[6,2,3]. Another interesting comparison is with the prediction based on the most accurate evaluation of the CKM matrix element V_{ud} using the CVC hypothesis and the results of measurements of superallowed Fermi nuclear decays (Particle Data Group 2002[5]):

$$BR = 1.037 \pm 0.002 \times 10^{-8}\ .$$

Thus, our current preliminary working result is in very good agreement with the predictions of the Standard Model and the CVC hypothesis. The quoted systematic uncertainties are being reduced as our analysis progresses. To put this result into broader perspective, we can compare the central value of V_{ud} extracted from our data with that listed in PDG 2002[5]:

$$\begin{aligned} \text{PDG 2002:} \quad & V_{ud} = 0.9734(8), \\ \text{PIBETA prelim:} \quad & V_{ud} = 0.9771(56). \end{aligned}$$

Table 1 summarizes the main sources of uncertainties and gives their values both in the current analysis, and those that are expected to be reached in a full analysis of the entire dataset acquired to date. We have temporarily enlarged the systematic uncertainty quoted in Eq. 1 pending a resolution of the discrepancy found in the RPD channel and discussed in the following section.

Table 1. Summary of the main sources of uncertainty in the extraction of the pion beta decay branching ratio. The column labeled "current" corresponds to the present analysis based on a portion of the data taken.

Summary of uncertainties (%)	Dataset analyzed: partial*	full
external:		
pion lifetime	0.019	0.019
$BR(\pi \to e\nu)$	0.33	$\sim 0.1^\dagger$
$BR(\pi^0 \to \gamma\gamma)$	0.032	0.032
internal:		
$A(\pi\beta)/A(e\nu)$	0.5	< 0.3
$\Delta t(\gamma - e)$	0.03	0.03
E threshold	< 0.1	< 0.1
statistical:	0.7	~ 0.4
total:	~ 0.9	$\lesssim 0.5$

* Subset of the 1999 and 2000 data.
† Requires a new measurement.

4 First Results: Radiative Pion Decay

As was already pointed out, we have recorded a large data set of radiative decays: $\pi^+ \to e^+\nu\gamma$ and $\mu^+ \to e^+\nu\bar{\nu}\gamma$. To date we have analyzed both pion and muon radiative decays, though with more attention devoted to the former, as it is an important physics background to other decays under study. The pion radiative decay analysis has given us the most surprising result to date, and has commanded significant effort on our part to resolve the issue.

The different event triggers used in our experiment are sensitive to three distinct regions in the RPD phase space:

- region A with e^+ and γ emitted into opposite hemispheres, each with energy exceeding that of the Michel edge ($E_M \simeq 52$ MeV), recorded in the main two-arm trigger,
- region B with an energetic photon ($E_\gamma > E_M$), and $E_{e+} \geqslant 20$ MeV, recorded in the one-arm trigger, and
- region C with an energetic positron ($E_{e+} > E_M$), and $E_\gamma \geqslant 20$ MeV, also recorded in the one-arm trigger.

The RPD data are of a similar quality to our $\pi\beta$ event set; due to limited space we omit the details here, and direct the interested reader to Ref. [1] instead.

Together, the three regions overconstrain the Standard Model parameters describing the decay, and thus allow us to examine possible new information about the pion's hadronic structure, or non-(V−A) interactions. Appropriate analysis of these data is involved and nuanced, requiring a longer presentation than is possible here. We therefore only summarize the salient results of our work in progress on this pion decay channel.

Our analysis indicates a measurable departure from SM predictions. Standard Model with the V−A electroweak sector requires only two form factors, F_A and F_V to describe the so-called structure-dependent amplitude in RPD. The remainder of the decay amplitude is accounted for by QED in the inner-bremsstrahlung (IB) term. The pion vector form factor is strongly constrained by the CVC hypothesis, while existing data on the radiative pion decay (PDG

2002[5]) suggest that $F_A \simeq 0.5\, F_V$, yielding

$$F_V = 0.0259 \pm 0.0005\ , \qquad \text{and} \qquad F_A \simeq 0.012\ .$$

Simultaneous as well as separate fits of our data in regions A, B and C confirm the above ratio of $F_A/F_V \simeq 0.5$. However, they show a statistically significant deficit in RPD yield in one region of phase space, for high E_γ and lower E_e (mostly in region B), compared to predictions based on the above values of the pion form factors.

A larger deficit in RPD yield, though less statistically significant than our result due to far fewer events, was first reported by the ISTRA collaboration[7,8]. This first observation was interpreted by Poblaguev[9,10] as indicative of the presence of a tensor weak interaction in the pion, giving rise to a nonzero tensor pion form factor $F_T \sim -6 \times 10^{-3}$. Subsequently, Peter Herczeg[11] found that the existing experimental evidence on beta decays could not rule out a small nonzero value of F_T of this order of magnitude. Tensor interaction of this magnitude could only be explained by the existence of leptoquarks.

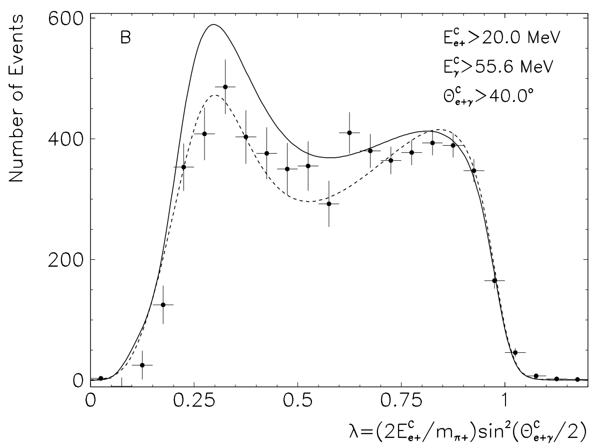

Figure 6. Measured spectrum of the kinematic variable $\lambda = (2E_{e+}/m_{\pi+})\sin^2(\theta_{e\gamma}/2)$ in $\pi^+ \to e^+\nu\gamma$ decay for the kinematic region B, with limits noted in the figure. Solid curve: fit with the pion form factor F_V fixed by the CVC hypothesis, $F_T = 0$, and F_A free. Dashed curve: as above, but with F_T also released to vary freely, resulting in $F_T = -0.0016\,(3)$. Work in progress.

We illustrate our working results in Fig. 6 which shows a projected one-dimensional distribution of λ, a convenient kinematic variable based on E_e that ranges from 0 to 1 regardless of E_γ. It is clear that for lower values of λ (and therefore of E_e), an SM fit with only $F_V, F_A \neq 0$ overestimates the experimental yield. Adding a nonzero tensor form factor of $F_T \sim -0.0016$ produces statistically significantly better agreement with the data. The fits are two-dimesional and encompass all three kinematic regions, A, B, and C. This work is in progress, and the reuslts are subject to change—we are currently refining the analysis as well as the fit strategies.

Taken at face value, this working result should not be interpreted as an indication of the existence of a tensor weak interaction, i.e., of leptoquarks. Instead, if it holds up in our final analysis, it would first suggest that the standard treatment of the RPD may not at this time correctly incorporate all known SM physics. Radiative corrections seem to be a particularly good candidate for reexamination.

5 Conclusions

We have extracted an experimental branching ratio for the pion beta decay at the 1 % uncertainty level, and expect to reduce the uncertainty by another factor of about two in the near future. Our result agrees with the CVC hypothesis and radiative corrections for this process, and it opens the way for the first meaningful extraction of the CKM parameter V_{ud} from a non-baryonic process.

Our analysis of the $\pi \to e\nu\gamma$ decay confirms that $F_A/F_V \simeq 0.5$, in agreement with the world average. However, events with a hard γ and soft e^+ are not well described by standard theory, requiring "$F_T \neq 0$". A new theoretical look at this decay is needed. We can, though, rule out a large "F_T", as reported in analyses of the ISTRA data.

The high statistics and broad coverage of our RPD data in principle guarantee extraction of pion weak form factor values with exceptionally low uncertainties. However, it appears that there may be significant theoretical uncertainties in the process of the form factor extraction. We hope that any remaining theoretical questions will be resolved in the near future, eventually enabling the field to make use of the full potential of the PIBETA data.

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