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 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, \( \pi^+ \rightarrow \pi^0 e^+ \nu \) (known as \( \pi e_3 \), 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 \( \pi \rightarrow e\nu\gamma \) (\( \pi e_2R \), 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, \( \mu \rightarrow e\nu\gamma \), 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 \( \pi e_2 R \) decays are normalized to the \( \pi \rightarrow e\nu \) (known as \( \pi e_2 \)) decay rate. The first phase of the experiment has, thus, produced a large sample of \( \pi e_2 \) decay events. The second phase of the PIBETA program will seek to improve the \( \pi e_2 \) 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] has demonstrated low theoretical uncertainties in extracting \( V_{ud} \) from the pion beta decay rate, i.e., a relative uncertainty of \( 5 \times 10^{-4} \) or less, providing further impetus for continued efforts in improving the experimental accuracy of this process.

2 Experimental Method

The \( \pi E1 \) beam line at PSI was tuned to deliver \( \sim 10^6 \pi^+/s \) with \( p_{\pi} \approx 113 \text{ MeV}/c \), 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 4\( \pi \) sr.

![Figure 1](image-url)
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 $\pi\nu$ 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 $\pi^+$ stop time), as well as a random and a three-arm trigger, were implemented in order to obtain maximally comprehensive and unbiased data samples.

In the histograms of the calorimeter energy and event timing (following the $\pi^+$ stop time), as well as of the $\gamma-\gamma$ opening angle and time difference for a subset of recorded pion beta decay events, shown in Figs. 4-5, 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 results show that...
working result for the pion beta decay branching ratio, extracted from the above analysis, is

$$BR \approx 1.044 \pm 0.007\text{(stat.}) \pm 0.009\text{(syst.)} \times 10^{-8}.$$  \quad (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]):

$$BR = 1.038 - 1.041 \times 10^{-8} \quad (90\%\text{C.L.)})$$

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]:

PDG 2002: $V_{ud} = 0.9734(8)$,

PIBETA prelim: $V_{ud} = 0.9771(56)$.

Table 1 summarizes 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: |
|------------------------------|------------------|
| external:                   |                  |
| pion lifetime               | 0.019            |
| $BR(\pi \rightarrow e\nu)$  | 0.33             |
| $BR(\pi^0 \rightarrow \gamma\gamma)$ | 0.032 |
| internal:                   |                  |
| $A(\pi\beta)/A(\pi\nu)$    | 0.5              |
| $\Delta t(\gamma - e)$      | 0.03             |
| $E$ threshold               | < 0.1            |
| statistical:                | 0.7              |
| total:                      | ~ 0.9            |

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

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. \[11] 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\cite{5} suggest that $F_A \approx 0.5 F_V$, yielding

$$F_V = 0.0259 \pm 0.0005,$$

and

$$F_A \approx 0.012.$$  

Simultaneous as well as separate fits of our data in regions A, B and C confirm the above ratio of $F_A/F_V \approx 0.5$. However, they show a statistically significant deficit in RPD yield in one region of phase space, for high $E_e$ and lower $E_\gamma$ (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\cite{7,8}. This first observation was interpreted by Poblaguev\cite{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\cite{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 $\lambda = (2E_e/m_\mu) \sin^2(\theta/2)$ in $\pi^+ \rightarrow e^+\nu\gamma$ 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.](image)

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 $\pi \rightarrow e\nu\gamma$ decay confirms that $F_A/F_V \approx 0.5$, in agreement with the world average. However, events with a hard $\gamma$ 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.

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.

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