PSI Experiment R-89-01 (PIBETA)

A PRECISE MEASUREMENT OF THE $\pi^+ \to \pi^0 e^+ \nu$ DECAY RATE

Progress Report and Beam Request

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11 December 2003

We have completed a set of measurements of the rare pion and muon decays: $\pi^+ \to \pi^0 e^+ \nu$, $\pi^+ \to e^+ \nu$, $\pi^+ \to e^+ \nu \gamma$, and $\mu^+ \to e^+ \nu \bar{\nu} \gamma$. We have determined a new value of the pion beta decay branching ratio $R(\pi^+ \to \pi^0 e^+ \nu) = [1.034 \pm 0.004\,(\mathrm{stat.}) \pm 0.007\,(\mathrm{syst.})] \times 10^{-8}$, a five-fold improvement in accuracy over the previous measurement. We are continuing to make further improvements in our analysis and simulation, in order to reach the stated goal of $\sim 0.5\,\%$ uncertainty. We have analyzed our $\pi^+ \to e^+ \nu \gamma$ decay data and extracted a new value for the pion axial weak form factor $F_A = 0.0115(4)$ assuming the CVC value of $F_V = 0.0259$. This represents a four-fold improvement in precision over the existing world average. However, significant discrepancies in one region of phase space compel us to revisit this decay experimentally. We are therefore requesting additional beam time in 2004.

1. Summary of results to date

The PIBETA experiment is a program of precise measurements of the rare pion and muon decays, chief among them being the pion beta decay, $\pi^+ \to \pi^0 e^+ \nu$. The experiment was approved by the PSI Program Committee in 1992, with the goal to achieve a $\sim 0.5\,\%$ accuracy in the $\pi\beta$ branching ratio in the first stage. We use $\pi^+ \to e^+ \nu$ decay events (π_{e2}) for normalization.

Detector construction was completed in 1998/99, and data acquisition started in the second half of 1999, reaching the design operating conditions before the end of 1999. The experiment continued with two long runs in 2000 and 2001. Since then we have analyzed the acquired data set which comprises 2.2×10^{13} beam pion stops.

The first results of our analysis, already reported at several meetings and conferences, are now prepared for publication, and are available as preprints. We will refer to the following three papers:

I: "Design, Commissioning and Performance of the PIBETA Detector at PSI", E. Frlež et al., hep-ex/0312017, submitted to Nucl. Inst. Meth. A.

II. "Precise Measurement of the $\pi^+ \to \pi^0 e^+ \nu$ Branching Ratio", D. Počanić et al., hep-ex/0312-030, submitted to Phys. Rev. Lett.

III. "Precise Measurement of the Pion Axial Form Factor in the $\pi^+ \to e^+ \nu\gamma$ Decay", E. Frlež et al., hep-ex/0312029, submitted to Phys. Rev. Lett.

Preprint I gives a detailed account of the detector system design and performance, as well as of our experimental method and procedures. Preprints II and III report our physics results for the $\pi\beta$ and $\pi_{e2\gamma}$ channels. Preprint III will be followed shortly by a paper focusing on the departures in our data from the Standard Model predictions, currently in preparation. To avoid duplication of material, papers II and III are appended to this document.

We can summarize the results presented in preprints I–III as follows.

Pion Beta Decay

The experimental signal for pion beta decay events in our data is very clean. The analysis has proceeded smoothly. Our current result for the branching ratio

$$R^{\rm exp}_{\pi\beta} = [1.034 \pm 0.004\,({\rm stat}) \pm 0.007\,({\rm syst})] \times 10^{-8}\,, \tag{1}$$

or, alternatively, for the decay rate,

$$\Gamma^{\rm exp}_{\pi\beta} = [0.3972 \pm 0.0015({\rm stat}) \pm 0.0025({\rm syst})]\,{\rm s}^{-1}\,, \tag{2}$$

represents a five-fold improvement in precision over the most recent previous measurement [1], and is in excellent agreement with the Standard Model prediction using the currently accepted Particle Data Group (PDG) recommended value for V_{ud} [2].

We are continuing to refine the analysis and simulation, and foresee no obstacles in reaching the stated goal of $\sim 0.5\,\%$ accuracy. We note that our statistical uncertainty is somewhat larger than originally planned, due to excessive down time in 2001, our last year of running. In our next analysis pass we will include $\pi\beta$ decay events occurring closer in time to the beam π^+ stop than the current 10 ns cut, yielding several thousand more events. The proposed 2004 measurements would add $\gtrsim 5000$ $\pi\beta$ events. All told, our $\pi\beta$ statistical uncertainty should end up below 0.4 %.

The π_{e2} decay

This is the process we have used to normalize our $\pi\beta$ and $\pi e2\gamma$ results. We have also performed independent normalizations to the number of stopped beam pions and have found the results consistent with the π_{e2} normalization. We have, furthermore, investigated evaluating $\Gamma(\pi_{e2})/\Gamma(\text{total})$ on the same basis, using two different approaches. Both methods agree with the PDG recommended value [2] (as well as with the SM prediction [3]) at the sub-1 % level. One has to keep in mind that the 1999–2001 run was optimized for $\pi\beta$ decay measurement, and therefore is not indicative of the ultimate accuracy of π_{e2} detection with the PIBETA detector. We therefore see our π_{e2} analysis as encouraging in terms of a dedicated precise measurement of the π_{e2} branching ratio.

Given the great interest in an accurate experimental test of lepton universality, we intend to use the proposed 2004 beam time to perform several tests of π_{e2} detection systematics. A dedicated π_{e2} measurement will, however, require a new experimental proposal, and is outside the scope of this report.

The $\pi_{e2\gamma}$ decay

As we have reported previously, the radiative pion decay $\pi^+ \to e^+\nu\gamma$ (RPD), has turned out to be the great surprise of our experiment. Our measurements of the branching ratio for this decay are presented in detail in Preprint III. To summarize, we have evaluated the $R(\pi_{e2\gamma})$ for three kinematic regions, which we have labeled as A, B, and C. Data in regions A and C are mutually compatible within the framework of the Standard Model (including the CVC-mandated value of $F_V = 0.0259(5)$, the pion vector form factor, [2]). Data from region B are in disagreement; their inclusion into the SM fit lowers the extracted value of F_A, the pion axial-vector form factor, such that

$$F_A/F_V \equiv \gamma = 0.443(15) \text{ for all three regions, but} \quad (3)$$

$$\gamma = 0.480(16) \text{ for regions } A \text{ and } C \text{ only.} \quad (4)$$

Naturally, we cannot ignore data in region B. We have spent a great deal of time and effort to track down any possible sources of detection and/or analysis inefficiency which would manifest itself only in the low-E_{e+}/high-E_γ kinematics of region B. We can report that our analysis yields differential and integral branching ratios in agreement with the SM predictions for all measured rare decays at the 1 % level or better. Most importantly this is true for the $\mu \to e\nu\bar{\nu}\gamma$ decay, which features its own version of "region B". An inefficiency amounting to $\sim$ 20 % would show up in these analyses, yet it has not [4].

Turning to theory, we have investigated the possibility of unusually large radiative corrections affecting primarily the kinematic region B. Dubna theorists Kuraev and Bystritsky have recently revisited [5] the radiative corrections to the $\pi_{e2\gamma}$ decay originally calculated by Nikitin [6]. E. Velicheva has taken the expressions obtained by Kuraev and Bystritsky, and calculated the corrections that apply to our kinematic regions. The corrections range from 0.6 % to 1.7 %, depending on the region, and were included in our analysis presented in paper III, leaving us with the 19 % shortfall in region B discussed above.

Another possible theoretical explanation for the anomaly involves the destructive interference of the QED internal bremsstrahlung amplitude (IB) with a small tensor amplitude, normally assumed absent in the Standard Model. As unlikely as this may seem, the subject has been seriously considered over the past fifteen years. A deficit similar to the one we found, was noted in the $\pi_{e2\gamma}$ measurement of the ISTRA experiment [7, 8]. Using these data Poblaguev extracted a pion tensor form factor of $F_T = -0.0056\,(17)$ [9, 10]. In a subsequent careful analysis, Herczeg could not rule out this possibility on the basis of all the known constraints from beta decay [11]. On the other hand, Chizhov has proposed a new intermediate chiral boson with an anomalous interaction with matter, in order to account for the apparent non-(V−A) behavior in RPD [12]. Poblaguev has recently revisited the problem, suggesting the possibility of an even bigger tensor form factor, $F_T = -0.0115\,(33)$ [13]. There have been other papers during the 1990's addressing the same question, e.g., Refs. [14, 15].

The possibility that F_V may actually differ from the CVC value is normally not considered. Scadron and coworkers, however, point out that F_V is experimentally poorly determined [the PDG world average is $F_V = 0.017\,(8)$]. They use the experimental value to support the linear sigma model prediction of $\gamma = 2/3$ [16]. A lower value of F_V would tend to improve the fits in region B, although the overall agreement would still not be satisfactory. We have not given serious consideration to this possibility.

Our purpose here is not to speculate about the possible theoretical explanation for the anomaly we have observed. We instead wish to produce the most precise set of experimental data to serve as s solid basis for critical comparisons of theoretical predictions. With that in mind, we note that our data are least precise in region B, the one kinematic region where the putative tensor interaction makes the greatest difference (adding $F_T \neq 0$ in our fits produces a negligible change in the differential yields in regions A and C). In particular, we note that the accidental background in region B is highest, with S/B of 3.8, compared with 7.6 and > 300 for regions C and A, respectively. This is understandable since the data were acquired with a one-arm trigger at a high pion stopping rate in the target, in the presence of an intense Michel background.

We illustrate this point quantitatively in Fig. 1 where we show our data and two of our recent fits for region B. In order to compare with previous work, we use the standard decay amplitude parametrization including F_T, and plot the differential decay rate against the kinematic variable λ, which can be calculated in two ways. First, we evaluate λ on the basis of the measured positron energy E_{e+} and opening angle $\theta_{e\gamma}$, i.e., $\lambda_1 = (2E_e/m_\pi)\sin^2(\theta_{e\gamma}/2)$, shown in the top panel of the figure. Second, we evaluate λ based on the measured photon and positron energies, $x = 2E_\gamma/m_\pi$ and $y = E_{e+}/m_\pi$, such that $\lambda_2 = (x+y-1)/x$. The two plots are evaluated completely independently, and demonstrate the consistency of our method. However, the event sets in both plots are identical. For this reason we do not average λ_1 and λ_2, but instead show them separately.

The effect of the destructive interference of the tensor term with the IB amplitude is clearly visible in both plots. The present error bars on our data points, as well as their scatter in the central region where the Michel background subtraction was maximal, compromise the quality of the data, and impede a decisive and unambiguous discrimination between theoretical predictions. We will present a more detailed account of the observed effect in our forthcoming preprint. Data analysis and simulation of the $\pi_{e2\gamma}$ and $\mu \to e\nu\bar{\nu}\gamma$ decays is continuing.

2. Measurements proposed for 2004

Given the unique sensitivity of the region B to the putative tensor interaction, the longstanding interest in this open question, and the less than optimal quality of our data in region B, we propose to revisit the $\pi_{e2\gamma}$ decay with a dedicated run optimized for regions B and C.

The first phase of the PIBETA experiment was run with $\sim 8-9\times 10^5$ pion stops/s in the target. The optimal stopping rate for one-arm trigger acquisition of RPD data with our detector is somewhere between 100 and 200 kHz, depending on the reduction of data acquisition (DAQ) dead time. One of the unknown parameters is the amount of improvement of DAQ live time fraction following the planned replacement of the front-end DAQ computer with a new faster model. In the absence of empirical information, we have used the conservative lower number for event rate estimates. Turning off the DSC digitizer for all but the beam detectors restores $\sim 10\,\%$ to the live time fraction. This is justified given the lower event rates in the other detectors.

The main modification of the detector consists of substituting a simpler one-piece active target in place of the nine-piece target detector used in the main PIBETA run.

The breakdown of the counting statistics in the first-phase RPD data set is $N_A : (N_B + N_C) =$ 31 k : 12 k. Running for three months with a reduced pion stopping rate and suitably modified trigger, we can collect up to 20 k clean events with S/B $> 40:1$ in regions B and C. The expected error limits for the planned new data in region B are shown in Fig. 1 on the line of data points at the bottom of each plot. The measurement will also add some $\gtrsim 3000$ region A events, leading to

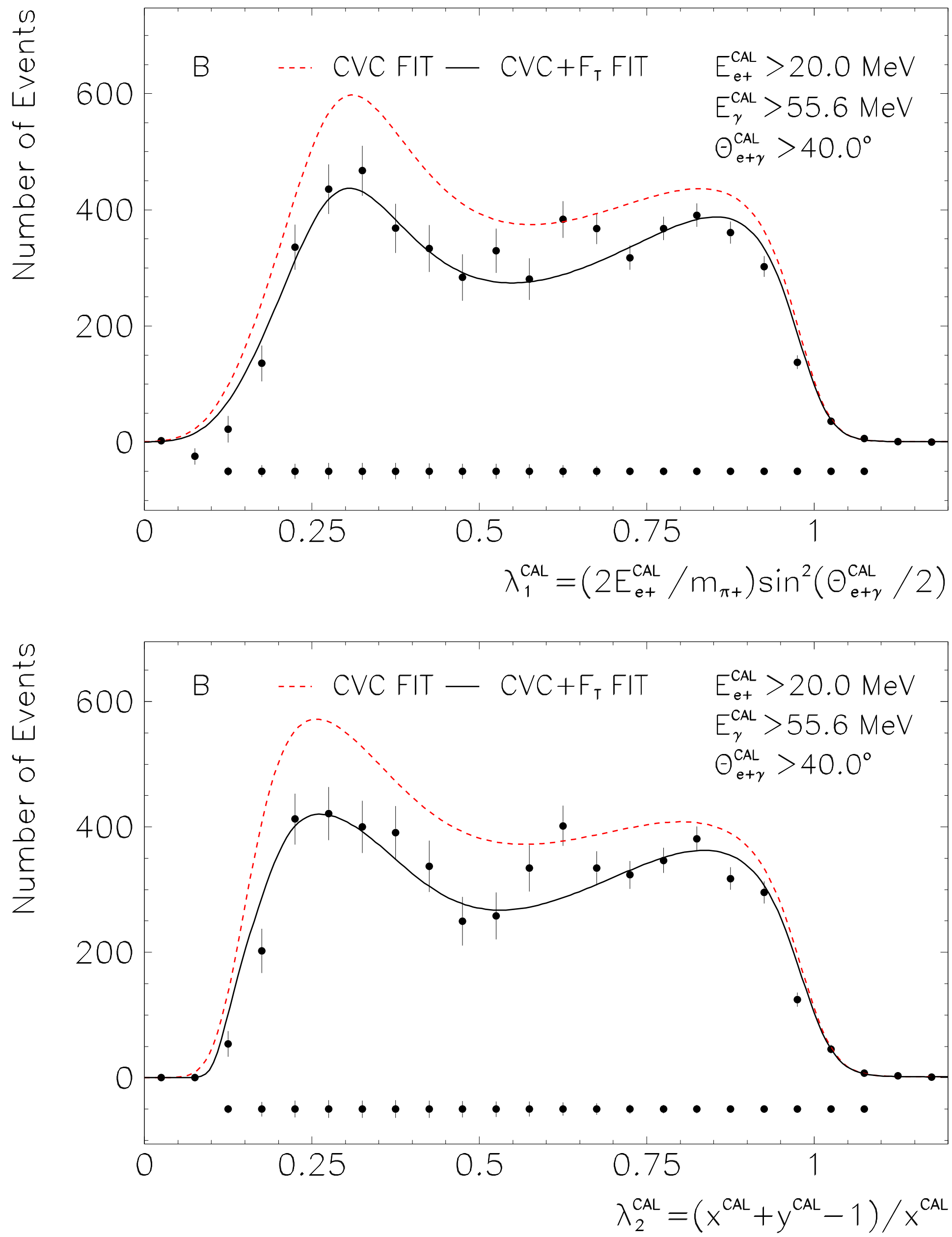

Figure 1: Top panel: measured spectrum of $\lambda_1 = (2E_e/m_\pi)\sin^2(\theta_{e\gamma}/2)$ in RPD for the kinematic region B, with limits noted in the figure. Dashed curve: three-region global best fit with the pion form factor $F_V = 0.0259$ fixed by the CVC hypothesis, $F_T = 0$, and F_A free. Solid curve: $F_V = 0.0259$ and $F_A = 0.0115$ from the first fit, this time with F_T released to vary freely, resulting in $F_T = -0.0018\,(3)$. Error bars on the points at bottom of graph reflect the expected uncertainties in the proposed dedicated measurement of the RPD. Bottom panel: same as above, but plotting the variable λ evaluated purely on the basis of photon and positron energies: $\lambda_2 = (x + y - 1)/x$, where $x = 2E_\gamma/m_\pi$, and $y = 2E_\gamma/m_\pi$. The agreement between the two methods is very good; the slight differences are due to the detector response functions for the measured observables.

a further improvement in the precision of the F_A/F_V ratio determination.

Just as important as the proposed RPD measurement will be the new data on the radiative muon decay, $\mu \to e\nu\bar{\nu}\gamma$. We project adding some 300k new radiative muon decay events to our data set by appropriately adjusting the prescaling factor on the low-threshold two-arm trigger. This will approximately double the number of events in this channel recorded so far. However, the new data set will be much cleaner than the old, with $S/B \geq 15$, i.e., comparable to the new RPD data. This is significant as a possibly more stringent test of a small tensor term in the weak Lagrangian. In other words, while hadronic structure effects may well be responsible for the anomalies we have observed in RPD, such effects are absent in muon decay. Thus, a clean high-statistics set of radiative muon decay data should provide a basis for tests of non-(V–A) interaction terms. Before this can be fully accomplished, though, more theoretical work is needed. One of the tasks will be to update the calculation of radiative corrections for $\mu \to e\nu\bar{\nu}\gamma$ decay. There are indications that a theory group at Dubna may soon take up this tasks. Furthermore, M. Chizhov has undertaken to investigate the possible signature of a tensor term in the radiative muon decay observables. We therefore expect that our radiative muon decay data will be valuable in clearing up the current controversy.

Finally, the measurement will add $\gtrsim 5000$ $\pi\beta$ decay events to our data set.

3. Resources and beam request

We request three months of data acquisition beam time plus three weeks for set-up and calibration in the πE1 beam area, i.e., a total of 15 weeks. Given the detector and personnel readiness requirements, we request that this period begin in mid-May and run through August 2004.

There are no major costs associated with the requested run. The main expenditures are the material costs of operating the detector (MWPC gas, supplies). The cost of replacing the front-end computer is modest, on the order of 1–2 kCHF. We estimate the overall material and supply costs of the proposed run to be about 20 kCHF.

While several current collaboration members will not be available for the proposed run (Crawford, Daum, Ritt), new members are set to join: T. Sachelashvili (PSI), M. Korolija, plus a possible student (IRB, Zagreb). On the theoretical side we are joined by E. Velicheva (Dubna) and M. Chizhov (Univ. of Sofia and CERN). The collaboration is open to other new collaborators.

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