The Radiative Pion Decay Anomaly Revisited

W. Bertl for the PIBETA collaboration

Paul Scherrer Institute, CH-5232 Villigen, Switzerland

Abstract. The radiative pion decay $\pi^+ \to e^+\nu_e\gamma$ allows one to study the weak form factors of the pion in great detail. However, recent experiments found discrepancies between experimental data and theory in some selected phase space regions. Those discrepancies led to speculations about a tensor current contribution pointing to exotic interactions. The PIBETA collaboration addressed this question in a dedicated precision experiment performed at the Paul Scherrer Institute in Switzerland. We present first preliminary results of this work here. Those new data are in good agreement with Standard Model assumptions without the need to introduce exotic currents.

Keywords: pion decay, weak form factors, weak tensor current
PACS: 11.30.Rd, 11.40.-q, 13.20.Cz, 14.40.Aq

The radiative decay of charged pions $\pi^+ \to e^+\nu_e\gamma$ (RPD) is described by two main processes: a) radiation from propagating charged particles precisely calculable by QED, and b) radiation off weak hadronic currents directly from the vertex. The latter process (also named the structure dependent part) is represented by phenomenological form factors. According to the Standard Model only vector and axial-vector currents should contribute to the structure dependent terms (for a comprehensive overview see [1]). Using the conserved-vector-current hypothesis (CVC) the vector form factor F_V is connected with the lifetime of neutral pions [2]. The axial-vector form factor F_A is calculable in strong interaction theories allowing to test the validity of the underlying models.

Early experiments suffered from low event rates and high background and limited acceptance to energetic photons and positrons. In two recent experiments [3, 4] the analyzed kinematic regions were extended to lower energies and, surprisingly, both found a smaller branching ratio than theoretically predicted. It was shown that the observed deficit, in the absence of an experimental explanation, could in principle be caused by an anomalous non-(V-A) interaction [5, 6, 7, 8]. Results from [4] were obtained with the PIBETA detector in the course of a precision measurement of the $\pi^+ \to \pi^0 e^+\nu_e$ $(\pi\beta)$ branching ratio [9]. Due to the small branching ratio of this process ($\approx 10^{-8}$) the pion stop rate used was on average $6.8 \cdot 10^5 \pi^+/s$ not optimal for the radiative decay measurement. In 2004 the PIBETA collaboration remeasured RPD at stop rates around $10^5\pi^+/s$ with a slightly simplified PIBETA spectrometer. As in the previous experiment [4] 3 broad kinematic regions were covered:

- Region A: E_γ and E_{e^+} > 51.7 MeV, $\Theta_{e\gamma} > 40^o$
- Region B: E_γ > 55.6 MeV, E_{e^+} > 15 MeV, $\Theta_{e\gamma} > 50^o$
- Region C: E_γ > 15 MeV, E_{e^+} > 55.6 MeV, $\Theta_{e\gamma} > 40^o$

Note that due to more favourable rate conditions it was possible to lower analysis thresholds from previous 20 to 15 MeV.

Accidental background was corrected for by subtracting non-coincident photon-positron distributions from coincident ones. Events originating from radiative muon decay (RMD) were distinguished from pion decays by their kinematics and longer lifetime. Those events free of strong interaction effects were independently analyzed as a cross check for exotic interactions and resulted in a new limit on the $\overline{\eta}$ Michel parameter [10]. In addition, $\pi\beta$-events contaminated the RPD sample. Corrections for them were determined from GEANT simulations and our own $\pi\beta$-measurements. Normalization of the RPD rate was achieved by simultaneously recording $\pi^+ \to e^+\nu_e$ decays whose branching ratio is known to 0.4 % [11, 12]. A direct determination of this branching ratio based on our data showed excellent agreement with those two dedicated experiment with only about twice the error margin.

Results for the weak form factors of our first analysis[1] [13] were obtained with a global fit procedure simultaneously minimizing the error-weighted difference between experimental and theoretical branching ratios for all kinematic regions as a function of parameters $\gamma \equiv F_A/F_V$ and a. Parameter a represents the form factors q-dependence assuming a general form like $F(q) = F(0)(1 + a \cdot q^2)$. The large number of observed RPD events (of order 28000) makes it possible to subdivide the 3 regions into 8 smaller bins and consequently using more parameters (F_A, F_V, a) in a global fit of all 8 regions. The results of all global fits using different sets of parameters and kinematic regions, respectively, were all in agreement within their uncertainties. Averaging the fit results from the 8 region analysis and those of the 3 regions we conclude for

$$\gamma \equiv F_A/F_V = 0.450 \pm 0.082 \quad \text{and} \quad F_V = 0.0262 \pm 0.0015. \tag{1}$$

From which follows that

$$F_A = 0.0118 \pm 0.0003. \tag{2}$$

The final result for the q-dependence parameter a was obtained averaging the fit results received from all independent methods

$$a = 0.241 \pm 0.093 \tag{3}$$

Using the best-fit results from the 8 region analysis the branching ratios for the original 3 regions were determined and are now in very good agreement with theoretical predictions based on standard (V-A) assumptions (see table 1), in contrast with the results from our previous experiment [4].

TABLE 1. Theoretical and experimental branching ratios for best values of γ obtained from the 8 regions analysis

Region	Theoretical BR($\times 10^8$)	Experimental BR($\times 10^8$)
A	2.6410 ± 0.0005	2.655 ± 0.058
B	14.490 ± 0.005	14.59 ± 0.26
C	37.900 ± 0.028	37.95 ± 0.60

[1] A second independent analysis is in progress

SUMMARY OF RESULTS (PRELIMINARY)

The value for F_A represents the currently most accurate measurement of the weak vector form factor of the pion and is in good agreement with our previous result published in [4] where it was derived using data from region A only. The accuracy of our measurement of F_V has improved sixfold compared to the last published experimentally determined value [3] and agrees very well with $| F_V(0) | = 0.0262 \pm 0.0009$ calculated using CVC [14] and the most recent value for the π^0 lifetime [15]. The q-dependence parameter a has been determined for the first time.

Analysis of the radiative muon decay $\mu^+ \to e^+ \nu_e \overline{\nu}_\mu \gamma$ [10] consistently showed no sign of an exotic current contribution. For the Michel parameter $\overline{\eta}$ which vanishes in the standard model we obtained

$$\overline{\eta} = -0.084 \pm 0.050(stat) \pm 0.034(syst) \tag{4}$$

leading to an upper limit $\overline{\eta} < 0.033(@68\%\, C.L.)$. Because the previous published values had rather large uncertainties the new, 3-fold improved, world average comes down to

$$\overline{\eta} < 0.028(@68\%\, C.L.). \tag{5}$$

In order to understand the deficit of the RPD branching ratio in region B in our previous experiment [4] we have already started to reanalyze those data. The higher beam rate caused a significant increase of the background which renders the analysis much more difficult. However, once the problem with those data is corrected, they will significantly add to the 2004 data set statistics, as region A received much more data in the first run than in the 2004 run. Combining the data of both experiments will lead to almost equally populated regions with a total of more than 60000 events, which will further improve our weak form factor uncertainties.

This experiment has been supported by the U.S. National Science Foundation, the U.S. Department of Energy, the Paul Scherrer Institute, the University of Zurich and the Russian Foundation for Basic Research.

REFERENCES

1. D. A. Bryman, P. Depommier and C. Leroy, Phys. Rep. **88**, 151 (1982).
2. R. P. Feynman and M. Gell-Mann, Phys. Rev. **109**, 193 (1958).
3. V. N. Bolotov et al., Phys. Lett. **B243**, 308 (1990).
4. E. Frlež et al., Phys. Rev. Lett. **93**, 181804 (2004).
5. V. N. Bolotov et al., Phys. Lett. B **243**, 308 (1990).
6. P. Herczeg, Phys. Rev. D **49**, 247 (1994).
7. A. V. Chernyshev et al., Mod. Phys. Lett. A **12**, 1669 (1997).
8. M. V. Chizhov, Mod. Phys. Lett. A **8**, 2753 (1993).
9. D. Počanić et al., Phys. Rev. Lett. **93** 181803 (2004).
10. B. Vandevender, Ph.D. thesis, University of Virginia, Charlottesville, Virginia, 2005.
11. D. I. Britton et al., Phys. Rev. Lett. **68**, 3000 (1992).
12. G. Czapek et al., Phys. Rev. Lett. **70**, 17 (1993).
13. M. Bychkov, Ph.D. thesis, University of Virginia, Charlottesville, Virginia, 2005.
14. V. G. Vaks and B. L. Ioffe, Nuovo Cimento **10**, 342 (1958).
15. S. Eidelman et al., Phys. Lett. B**592**, 1 (2004).