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A NEW EVALUATION OF THE PION WEAK FORM FACTORS

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We have used the PIBETA large-acceptance detector for a precise measurement of the $\pi^+ \to e^+\nu\gamma$ radiative decay at rest, with a broad phase space coverage. Using the CVC value for the pion vector form factor, $F_V = 0.0259(5)$, we have obtained a new value of the pion axial-vector form factor $\gamma = F_A/F_V = 0.429(14)$. However, significant deviations from the SM predictions are evident in our data. The discrepancy can be accounted for by introducing a pion tensor form factor of $F_T = -0.0016(3)$. The question of the true nature of the observed deviations remains open pending further theoretical and experimental study.

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1. *Motivation*

The PIBETA experiment [1] at the Paul Scherrer Institute (PSI) is a comprehensive set of precision measurements of 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 branching ratio (BR), $\pi^+ \to \pi^0 e^+\nu$ (referred to as π_{e3}, or $\pi\beta$), from the present $\sim 4\%$ to $\sim 0.5\%$.

(b) To measure the branching ratio of the radiative pion decay $\pi \to e\nu\gamma$ ($\pi_{e2\gamma}$, or RPD), allowing a precise evaluation of the pion axial-vector form factor F_A and tensor form factor F_T, predicted to vanish in the Standard Model (SM).

(c) An extensive measurement of the radiative muon decay rate, $\mu \to e\nu\bar{\nu}\gamma$, with a broad phase-space coverage, allowing a search for non-(V−A) admixtures in the weak Lagrangian.

The experiment's second phase calls for a precise measurement of the $\pi \to e\nu$ (known as π_{e2}) decay rate, used for BR normalization in the first phase. The current $\sim 0.35\%$ accuracy would be improved to under 0.2%, in order to provide a precise test of lepton universality, and, hence, of certain extensions to the Standard Model.

In this report we focus on part (b) above. Radiative pion decay offers unparalleled access to information on the pion's structure. Given the unique role of the pion as the quasi-Goldstone boson of the strong interaction, the implications are far reaching.

In the Standard Model description [2] of the radiative pion decay $\pi^+ \to e^+\nu\gamma$, where γ is a real or virtual photon (e^+e^- pair), the decay amplitude $\mathcal{M}$ depends on the vector V and axial vector A weak hadronic currents. Both currents give rise to structure-dependent terms SD_V and SD_A associated with virtual hadronic states, while the axial-vector current alone causes the inner bremsstrahlung process (IB) from the pion and positron.

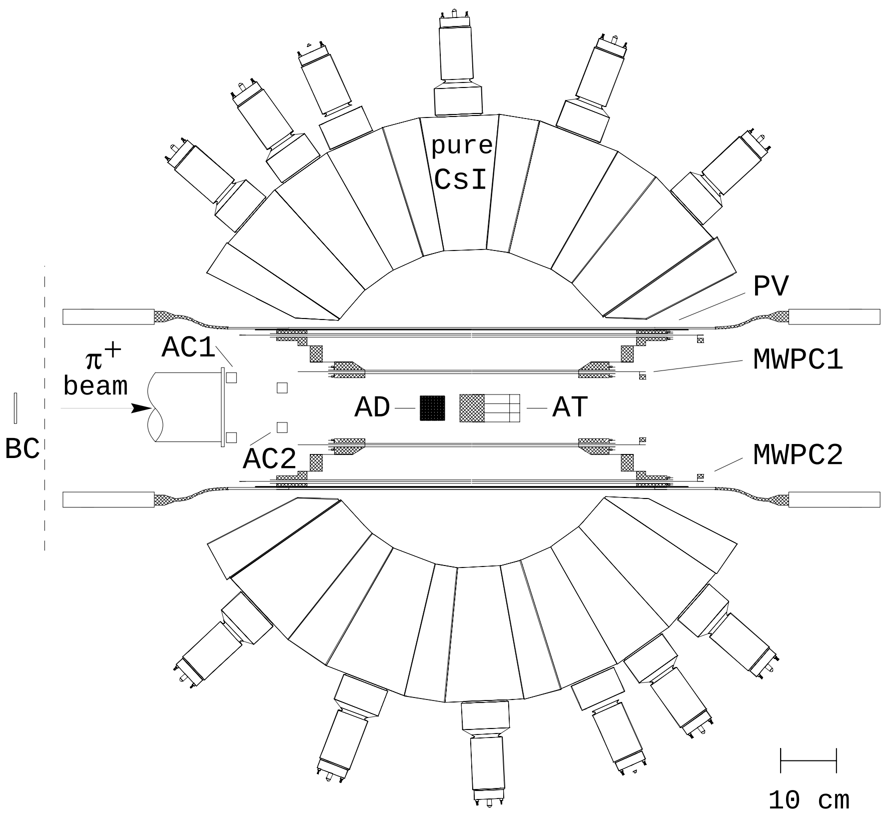
The IB contribution to the decay probability can be calculated in a straightforward manner using QED methods. The structure-dependent amplitude is parameterized by the vector form factor F_V and the axial vector form factor F_A that have to be extracted from experiments.

The statistics and overall accuracy of the present experimental data on the radiative pion decay [3–8] cannot rule out contributions from other allowed terms in the interaction Lagrangian, namely the scalar S, pseudoscalar P, and tensor T admixtures [9]. Nonzero values of any of these amplitudes would imply new physics outside the Standard Model. In particular, reports from the ISTRA collaboration [10, 11] have indicated a nonzero tensor term, $F_T = -0.0056\,(17)$. A tensor term of that size could only be explained by coupling to particles outside the Standard Model. A careful analysis by Herczeg could not rule out this possibility on the basis of all other beta decay constraints [12].

Moreover, the ratio of F_A/F_V in $\pi \to e\nu\gamma$ decay directly determines the chiral perturbation theory parameter sum $(l_9 + l_{10})$, or, equivalently, α_E, the pion polarizability [13–15]. These quantities are of longstanding interest since they are among the few unambiguous predictions of chiral symmetry and QCD at low energies. The current status of these measurements is not satisfactory, as there is considerable scatter among the various experimental determinations of F_A/F_V, and the accepted PDG average value has a 14% uncertainty.

2. Experimental method

The PIBETA apparatus is a large solid angle non-magnetic detector optimized for the detection of photons and electrons in the energy range of 5 – 150 MeV with high efficiency, energy resolution and solid angle. The main sensitive components of the apparatus, shown and labeled in Fig. 1, are:



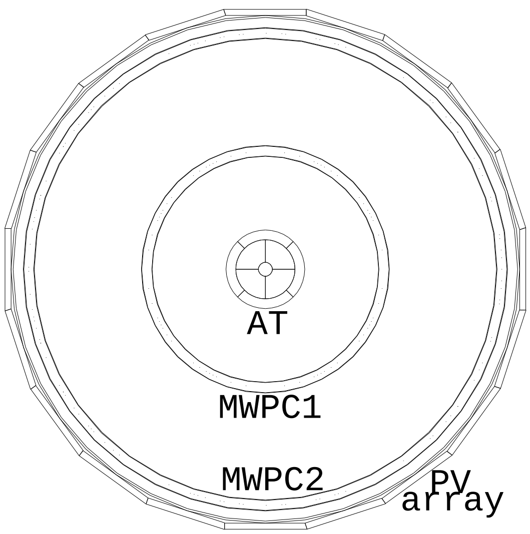


Fig. 1. (a) (above) Schematic cross section of the PIBETA apparatus showing the main components: beam entry counters (BC, AC1, AC2), active degrader (AD), active target (AT), wire chambers (MWPCs) and support, plastic veto (PV) detectors and PMTs, pure CsI calorimeter and PMTs. (b) (right) Axial (beam) view of the central detector region showing the 9-element active target and the charged particle tracking detectors.

(a) beam defininining plastic scintillator detectors: BC, a thin forward beam counter, AC_1 and AC_2, cylindrical active collimators, AD, an active degrader, AT, a 9-element segmented active target;

(b) charged particle tracking and identification: $MWPC_1$ and $MWPC_2$, cylindrical chambers, and PV, a 20-bar segmented thin plastic scintillator hodoscope;

(c) a 240-element segmented spherical pure-CsI shower calorimeter, subtending a solid angle of $\sim 80\%$ of 4π.

The building and testing of the detector components were completed in 1998, followed by the assembly and commissioning of the full detector apparatus. Data acquisition with the PIBETA detector started in the second half of 1999, initially at a reduced pion stopping rate, as planned. The experiment ran subsequently during 2000 and 2001 at $\sim 1\,\mathrm{MHz}$ π^+ stopping rate.

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.

3. *Results and analysis*

We have used both one- and two-arm triggers to collect a clean set of $> 43\,\mathrm{k}$ $\pi^+ \to \mathrm{e}^+\nu\gamma$ decays. The PIBETA experiment has good sensitivity in three distinct regions in the RPD phase space

A: with e^+ and γ emitted into opposite hemispheres, each with energy exceeding that of the Michel edge ($E_\mathrm{M} \simeq 52$ MeV), recorded in a two-arm trigger,

B: with an energetic photon ($E_\gamma > E_\mathrm{M}$), and $E_{e+} \geq 20$ MeV, recorded in the one-arm trigger,

C: with an energetic positron ($E_{e+} > E_\mathrm{M}$), and $E_\gamma \geq 20$ MeV, recorded in the one-arm trigger.

The quality of our $\pi^+ \to \mathrm{e}^+\nu\gamma$ data is illustrated in Fig. 2. The left panel of the figure shows the timing difference between the detected e^+'s and γ's for the three kinematic regions of the decay, as noted. Plotted in the right panel of Fig. 2 is the kinematic variable $E_{\mathrm{e}^+} + E_\gamma + |\boldsymbol{p}_\mathrm{e} + \boldsymbol{p}_\gamma|$ ("invariant pion mass"), with the out-of-time events subtracted; it is in excellent agreement with Monte Carlo simulations, demonstrating that our RPD signal is clean in all three regions.

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. Details of the full

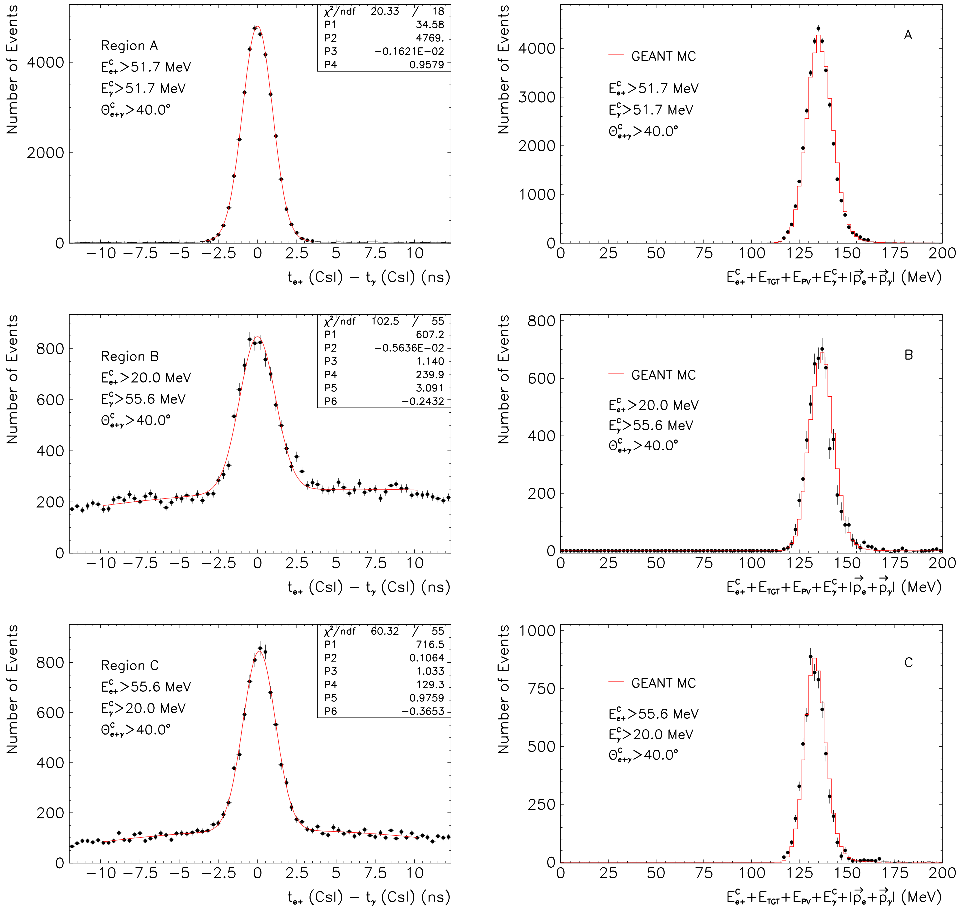


Fig. 2. e-γ timing difference for $\pi \to e\nu\gamma$ decay events in regions A, B, and C (left panels, top to bottom, respectively). The right panels plot the reconstructed invariant π^+ mass variable, for our radiative pion decay event data (dots) in regions A, B, and C, and simulation (histogram).

data analysis require a longer presentation than is possible here, so we only give a brief discussion.

Simultaneous as well as separate fits to our data in regions A, B and C confirm the theoretically expected ratio of $F_\mathrm{A}/F_\mathrm{V} \simeq 0.5$. In particular, we find in a Standard Model fit with F_A set free, and $F_\mathrm{V} = 0.0259(5)$ fixed by the CVC hypothesis

$$\gamma = \frac{F_\mathrm{A}}{F_\mathrm{V}} = 0.429 \pm 0.014 \qquad \text{or} \qquad F_\mathrm{A} = 0.01111(36)\,, \tag{1}$$

which represents a fourfold improvement in accuracy over the current world average. This result provides the most accurate experimental determination to date of the pion polarizability, α_{E}, and of the χPT parameter sum $(l_9 + l_{10})$.

However, our simultaneous fits demonstrate a statistically significant deficit of RPD yield in the region B, compared to V$-$A calculations with the above values of F_{V} and F_{A}. In order to account for this deficit, we need to introduce a tensor term destructively interfering with the IB amplitude, which has led to the result

$$F_{\mathrm{T}} = -0.0016\,(3)\,. \tag{2}$$

The effect of the tensor term is best illustrated in Fig. 3 showing the measured distribution of λ, a relevant kinematic variable based on E_{e} and $\theta_{\mathrm{e}\gamma}$, in the region B. The solid curve, including a negative tensor form factor, is clearly preferred by the data, which is reflected in a much reduced value of χ^2.

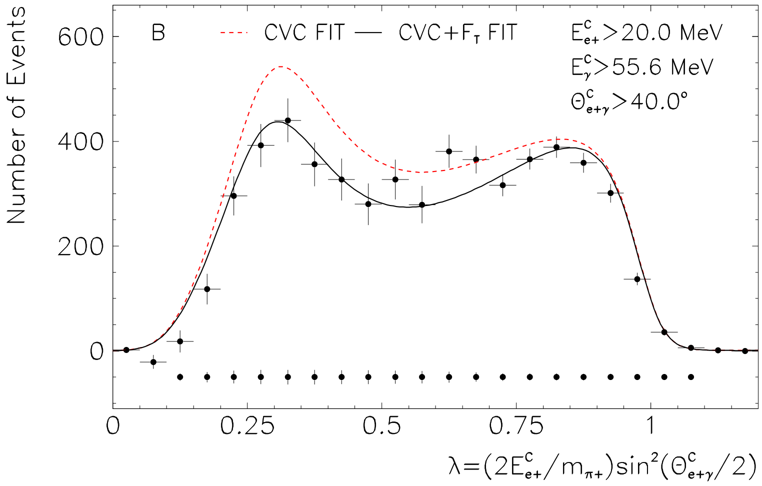


Fig. 3. Measured spectrum of $\lambda = (2E_e/m_\pi)\sin^2(\theta_{e\gamma}/2)$ in RPD for the kinematic region B, with limits noted in the figure. Dashed curve: fit with the pion form factor $F_V = 0.0259$ fixed by the CVC hypothesis, $F_T = 0$, and F_A free. Solid curve: F_V and $F_A = 0.01111$ from the first fit, this time with F_T released to vary freely, resulting in $F_T = -0.0016\,(3)$. Error bars on the points at bottom of graph reflect the expected uncertainties in the proposed dedicated measurement of the RPD.

Unfortunately, region B is characterized by the lowest signal/accidental background (S/B) ratio of the three regions, cf. Fig. 2, and, consequently the data in the region B are of lower quality than in the region C, and especially the region A. This is a consequence of the priority having been given to the $\pi\beta$ data in PIBETA's first phase which favored running at higher pion stop rate. Even with this compromise, our data unambiguously deviate from the SM (V$-$A) behavior by over 5σ. At the same time, though, they rule out the large ISTRA value of $(-F_{\mathrm{T}}) \simeq 0.006 - 0.012$ [10, 11].

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 the region B, we plan to revisit RPD with a dedicated run optimized for the regions B and C. The breakdown of the counting statistics in the first-phase RPD data set is $N_{\rm A} : (N_{\rm B} + N_{\rm C}) = 31\,{\rm k} : 12\,{\rm k}$. 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 $> 20 : 1$ in regions B and C. The expected error limits for these planned data in the region B are shown in Fig. 3 on the line of data points at the bottom of the plot. In the process, we will also improve our precision on the $F_{\rm A}/F_{\rm V}$ ratio.

4. Conclusion

We note in closing that the discrepancy from the SM behavior observed in our RPD data must also be reexamined from the theoretical side. It is imperative to ascertain that all known SM processes are correctly included in the published theoretical amplitudes [2, 16] used in our analysis.

Acknowledgements

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NOVO ODREĐIVANJE PIONSKIH FAKTORA OBLIKA

Primijenili smo detektor PIBETA, koji pokriva velik prostorni kut, za točno mjerenje radioaktivnog raspada $\pi^+ \to e^+\nu\gamma$ mirnih π^+, uz veliko zahvaćanje faznog prostora. Uzevši CVC vrijednost pionskog vektorskog faktora oblika, $F_V = 0.0259(5)$, dobili smo novu vrijednost pionskog aksijalno-vektorskog faktora oblika $\gamma = F_A/F_V = 0.429(14)$. Naši podaci ukazuju na velika odstupanja od predviđanja standardnog modela. Ta se odstupanja mogu objasniti uvođenjem tenzorskog faktora oblika $F_T = -0.0016(3)$. Daljnja teorijska i eksperimentalna istraživanja su nužna da bi se utvrdila stvarna priroda opaženih odstupanja.