THE EXPERIMENTAL STUDY OF THE $\pi^- \to e^- \bar{\nu}\gamma$ DECAY IN FLIGHT AND POSSIBLE DEVIATIONS FROM STANDARD MODEL OF WEAK INTERACTION

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The experimental study of the radiative pion decay, $\pi^- \to e^- \bar{\nu}\gamma$ has been performed with a secondary 17 GeV negative pion beam on the IHEP machine with the ISTRA detector of the lnstitute for Nuclear Research. The high energy beam has enabled us to investigate this decay in a wide range of kinematic variables: $E_\gamma >$21 MeV, $E_e >$70–0.8E_γ MeV, which included events with $\Theta_{e\gamma} > 60°$ The vector form factor has been determined in a model independent way: F_V=0.014+0.009. The axial-to-vector form factor ratio has been determined unambiguously: γ=0.41±0.23. The probability of the $\pi \to e\nu\gamma$ decay was found to be B.R. = (1.61+0.23)10^{-7} for the phase space region under consideration. The contributions of the inner bremsstrahlung and of the structure dependent radiation were investigated. Possible deviation from the prediction of Standard Model is discussed.

The amplitude of the radiative

$$\pi^- \to e^- \bar{\nu}\gamma \qquad (1)$$

decay is traditionally described by two terms corresponding to the inner bremsstrahlung (IB) and to the structure-dependent (SD) radiation. The IB contribution can be calculated using the standard QED methods. The SD term is parameterized by two form factors describing the interaction with the vector (F_V) and the axial-vector (F_A) weak hadronic currents [1]. The structure dependent amplitude of decay (1) can be displayed as:

$$M_{SD} = \frac{eG_F V_{ud}}{\sqrt{2}M_\pi}\varepsilon^\mu [F_V e_{\mu\nu\rho\sigma} k^\rho q^\sigma - iF_A(kqg^{\mu\nu} - k_\mu q_\nu)]u(p_e)\gamma^\nu(1+\gamma^5)\nu(\rho_\nu), \qquad (2)$$

where V_{ud} is an element of the Kobayashi–Maskawa mixing matrix; ε^μ is the photon polarization vector; k and q are respectively the pion and photon four-momenta, respectively.

If one assumes CP invariance, the so-defined form factors will be the same as those traditionally used for describing the $\pi^+ \to e^+ \bar{\nu}\gamma$ decay [2]. Both decays have similar energy spectra [3]:

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$$d\Gamma/d_x d_y = \alpha/2\pi\Gamma_{\pi^- e\nu\gamma}\left[IB(x,y) + (m_\pi^2 F_V/m_e f_\pi)^2[(1+\gamma)^2 SD^+ + (1-\gamma)^2 SD^-]\right], \tag{3}$$

where $\gamma = F_A/F_V$, and IB and SD are known functions of the kinematical variables $x=E_\gamma/m_\pi$ and $y=2E_e/m_\pi$ [1,2].

The value of the vector form factor calculated from the measured π^0 lifetime using the CVC is $F_V = 0.0259\pm0.0005$. The theoretical predictions for F_A obtained within different models were in the wide range from $-3F_V$ to $1.4F_V$ [2,5].

All the previous experimental studies of decay (1) were made with stopped pions. Such measurements are sensitive mainly to the SD^+ contribution and, thus, yield two different values for γ [6,7]. The high–statistics measurements at SIN gave the values [8] $\gamma=0.52\pm0.06$ and $\gamma=-2.48\pm0.06$, the positive value being more likely than the negative one. The fact that γ is positive was confirmed by the LAMPF experiment [9], where the unique (3.5 standard deviations) value $\gamma=0.25\pm0.12$ was found. These results have been confirmed additionally by the study of the $\pi^+ \to e^+\bar{\nu}e^+e^-$ decay [10].

Nonetheless, the experimental study of the $\pi \to e\bar{\nu}\gamma$ decay could not be considered completed since (i) there was a discrepancy (approximately 2 st. dev.) between the values of γ obtained at SIN and at LAMPF, (ii) the selection of the sign of ν in the $\pi \to e\nu\gamma$ experiments was not sufficiently reliable, and (iii) the studied kinematical regeon was relatively small.

The high energy of the decaying particles allow one to overcome the principal difficulties one encounters in experiments with stopped pions. Owing to the high detection efficiency; the wide range of measured angles and energies of secondary particles; and the substantial suppression of the background from the

$$\begin{tikzcd} \pi \arrow[r] & \mu\nu \arrow[d] & \\ & {} \arrow[r] & e\nu\nu\gamma \end{tikzcd} \quad \text{and} \quad \begin{tikzcd} \pi \arrow[r] & \mu\nu\gamma \arrow[d] & \\ & {} \arrow[r] & e\nu\nu \end{tikzcd}$$

decays, one is able to distinguish decay (1) in a wide range of kinematical variables with only a small admixture of the background.

Our experiment was performed at the ISTRA detector of INR (the modern variant of the set up ISTRA–M is shown on fig.1) The results discussing here were obtained on first version, which hasn't the magnetic spectrometer, hadron calorimeter and guard system) with a 17 GeV pion beam produced by the IHEP U-70 accelerator. The admixture of K^- and μ^- in the beam was respectively 3% and 2%. Special attention was paid to the purity of pion isolation. Pions decayed in an 18 m long decay volume. Pion and electron tracks were measured respectively by the scintillation hodoscopes (HM) [11] and by the proportional chambers (PC) with an induced charge readout [12]. The electrons and photons from the decays were detected in an 20×24 array of the lead glass spectrometer (SP) [13].

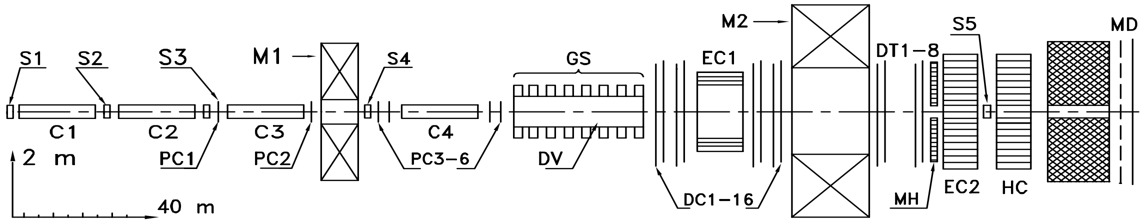

Fig.1. The layout of ISTRA–M setup: S1–S5–scintillation counters; C1–4–Cherenkov gas counters; M1,M2–beam and spectrometer magnets; PC1–6– proportional chambers; DV– decay volume; GS– guard system; DC1–16– drift chambers; EC1 and EC2– lead glass Cherenkov calorimeters; DT1–8– drift tubes; MH– matrix hodoscope; HC– hadron calorimeter; MD– muon detector.

The experimental setup is described in detail in our previous papers on the kaon decays [14] and in the complete review of ISTRA detector [15]. Main results of the study of radiative pion decay were published in ref [16]. About 3.7×10^{11} pions passed through the setup, yielding 14.5×10^{6} triggers. The main requirements for recording an event on the tape were (i) that one observed a single charged particle (an electron) coming out of the decay volume, and (ii) that the energy absorption in SP be more than 1 GeV.

Most of the events recorded on the tape were inelastic interactions in matter outside the decay volume and complementary decays of μ^-, π^- and K$^-$. These events and the events from kaon decays recorded in a special run were used for monitoring the apparatus and for describing and normalizing the background. The parameters for Monte Carlo simulations were accurately tested by analyzing the detected $\mu\to e\nu\nu$, $\pi\to e\nu$ and K$\to e\nu\pi^0$ decays.

The calibration decay $\pi\to e^-\bar{\nu}$ was recorded simultaneously with the data from the leading process. The off–line treatment of both decays was performed in a similar way. In order to select $\pi\to e^-\bar{\nu}\gamma$ the following cuts were used: (i) two showers in SP; (ii) one of the showers must have a corresponding track in PC; (iii) for the l-C fit, at the point where the π and e tracks intersect each other $\chi^2 < 9$, (iv) the angle between these tracks is $5< \Theta_{\pi e} <25$ mrad; (v) the decay vertex is inside the decay volume; (vi) the electron energy (in the lab system) is $E_e > 1$ GeV; (vii) the photon energy (lab system) is $E\gamma >2$ GeV; and (viii) the distance between the showers in SP is $D_{e\gamma} >10$ cm. The events with a single shower in SP followed by cuts (ii)$\div$(vi) were selected for $\pi\to e\nu$ detections. About $4\times10^4 \pi\to e^-\bar{\nu}$ decays have been selected.

We were able to use the absolute normalization of the $\pi\to e^-\bar{\nu}\gamma$ by using the well-known branching ratio decay of $\pi\to e^-\bar{\nu}(1.228\pm0.022)\times10^4$ since both processes were detected and processed in a similar manner.

The normalization was corrected by a factor R=0.91±0.06 which was found by analyzing the experimental data. This correction takes into account possible systematic errors and additional nonefficiency of $\pi\to e^-\bar{\nu}\gamma$ detection caused by detection of a photon. Fig. 2a shows the distribution of events versus the decay mass $M=E_e+E_\gamma+|p_e+p_\gamma|$.

The peak in the interval 100<M<180 MeV corresponds to decay (1). Decay (1) was analyzed together with the background events. The following sources of background were considered : (a) the kaon decays; (b) inelastic interactions inside and outside the decay volume; (c) the decays with only one electron ($\pi\to e\nu$, $\mu\to e\nu\nu$ e.t.c.) followed by an accidental shower in SP; (d) the $\mu\to \epsilon\nu\nu\gamma$ decay and cascade decays, and

$$\begin{tikzcd} \pi \arrow[r] & \mu\nu \arrow[d] & \\ & {} \arrow[r] & e\nu\nu\gamma \end{tikzcd} \qquad \begin{tikzcd} \pi \arrow[r] & \mu\nu\gamma \arrow[d] & \\ & {} \arrow[r] & e\nu\nu \end{tikzcd}$$

The background processes (a)÷(c) contribute mainly to the region M>200 MeV (Fig. 2a).

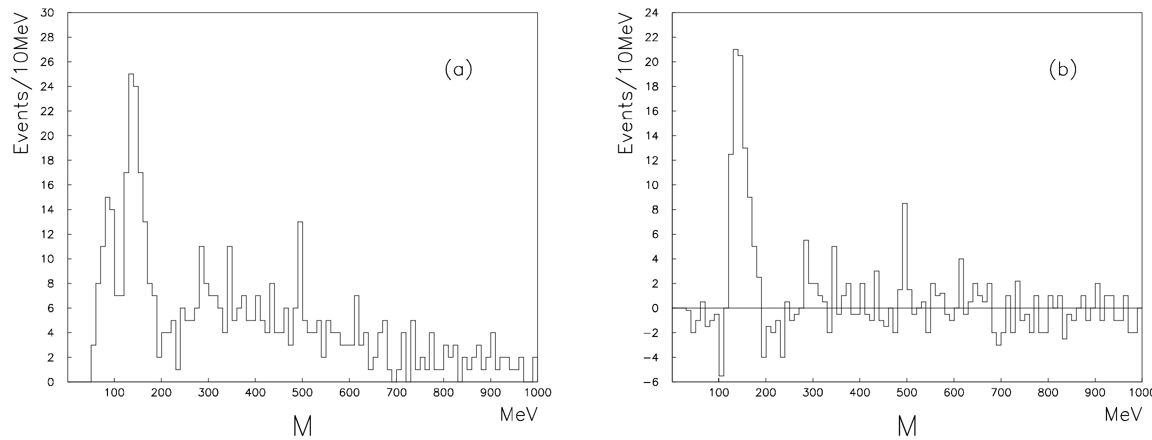

Fig.2. Events distribution for M=E_e+Eγ+$|p_e + p_\gamma|$ of all events and (b) after normalized distribution of background processes have been subtracted.

The real events were extracted from the tapes to analyze their contributions. The normalization of each background was checked in different ways which gave similar results. The backgrounds (d) associated with muon decays corresponds to the peak at 80 MeV (Fig. 2a). It was simulated by Monte–Carlo calculations and was normalized by extracting the

and

$$\mu \longrightarrow e\nu\nu \qquad \begin{tikzcd} \pi \arrow[r] & \mu\nu \arrow[d] & \\ & {} \arrow[r] & e\nu\nu \end{tikzcd}$$

decays when the $\pi \to e^- \bar{\nu}$ decay was analysis. Fig. 2b shows the M distribution after the normalized distributions of background processes have been subtracted. In the spectrum obtained there are no indications of the presence of some background that has not been taken into account within the whole range of M variation.

The value of γ was calculated from the maximum likelihood analysis of the three–dimensional distribution (versus E_e, E_g, M) for the events selected with the additional cut M«200 MeV (Fig. 2a). Histogram bins were chosen in such a way so that one could efficiently distinguish between the IB and SD contributions and the backgrounds.

The logarithm of the likelihood function was defined as a sum over the histogram bins:

$$I_0 = 2 \ln L = 2 \sum_k (n_k \ln N_k/n_k - n_k + N_k), \tag{4}$$

where n_k is the number of events in the k-th bin; $N_k=\sum_a N_k^a(\gamma R, P_a)$ is the corresponding expected number of events; N_k^a is the number of events associated with the a-th process (terms of decay (1) and backgrounds); and P_k is the normalization of the backgrounds.

In order to take into account the errors in P_a and R, these parameters were considered to be free, and the likelihood function was extended by

$$I = I_0 - (P_a - \mathbf{P_a})G_{ab}^{-1}(P_b - \mathbf{P_b}) - (R - \mathbf{R})^2/\sigma^2 \tag{5}$$

where $\mathbf{P_a}$ and $\mathbf{R}$ are mean values of these parameters, G_{ab} is the error matrix for P_a, and σ is the error in R. Fig. 3 shows the likelihood function

$$l_\gamma = \sup_{R,P} l(\gamma, R, P_a) \tag{6}$$

versus γ. From the analysis of l_γ one gets: γ=0.41±0.23. The value $\gamma=-2.4$ is suppressed by a factor of $W=5\times10^9$, which corresponds to 6.7 standard deviations. The broken line shows the behavior of the likelihood function without normalization to the total number of events. In this case γ=0.50±0.26 and $W=5\times10^4$ (4.6 standard deviations).

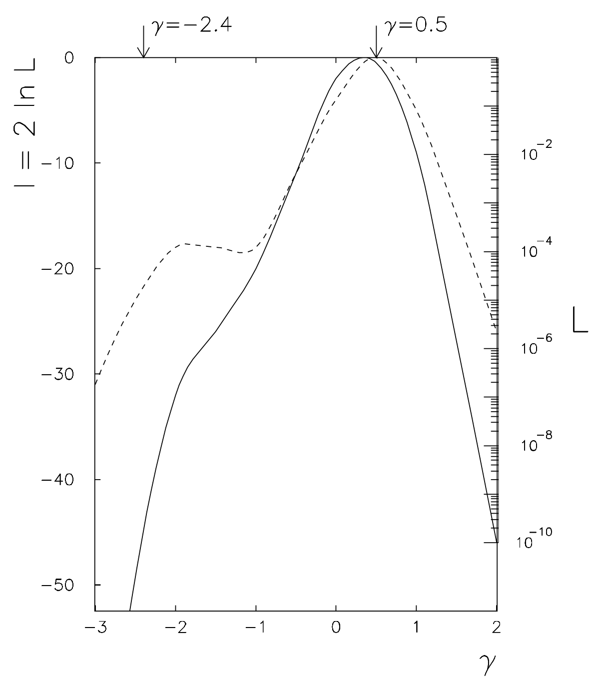

Fig.3. Likelihood function versus γ (solid line: with normalization to the total number of events; dashed line: without normalization.)

The wide range of the kinematical variables measured in our experiment has enabled us to determine the value of F_V without using the CVC hypothesis. Considering the value of F_V to be a free parameter in the fit, one gets $|F_V|$=0.014±0.009. The result obtained agrees both with the CVC prediction and with the SINDRUM value $|F_V|=0.023^{+0.015}_{-0.013}$ [10]. We also performed the data processing in a more general way. One can present the decay rate density as

$$N_{\pi\to e\nu\gamma}(x,y) = \mathrm{a}_{IB}N_{IB}(x,y) + \mathrm{a}_{SD+}N_{SD+}(\mathrm{x},\mathrm{y}) + \mathrm{a}_{SD-}N_{SD-}(x,y), \tag{7}$$

where a_{IB}, a_{SD} are free parameters proportional to the probabilities of the corresponding processes. By substituting distribution (7) into the likelihood function (5) one can determine the values of these probabilities. The results recalculated for the branching ratios for the kinematical region x>0.3, y>1-0.8x, in which decay (1) was detected effectively are presented in table 1.

Table 1. The probabilities of $\pi\to e^-\bar{\nu}\gamma$ decay in the kinematical region E_γ >21 MeV, E_e >70-0.8E_γ. The results of the fit with constraint a_{SD-} >0 are shown in parenthesis.

Process	Probability ($\times 10^7$)	Expected calculated value ($\times 10^7$)	Ways to obtain expected results
IB	1.62±0.20(1.30±0.17)	1.70	QED calculation
SD^+	0.56±0.21(1.40)±0.20	0.67±0.07	experimental data [7÷9]
SD^-	-0.58±0.20(<0.3, 95%CL)	0.04	experimental data
			for SD^+, CVC,γ >0
total	1.61±0.23(1.70±0.22)	2.41±0.007	

For the experimental values, the results of the fit with the constraint a_{SD-} >0 are shown in the parenthesis. For comparison, we give the expected values: the QED calculation for IB radiation and the SD contributions evaluated using the results of experiments with stopped pions [1]. There is a good agreement for the IB and SD^+ contributions. The discrepancy for the total branching ratio (more than 3 standard deviations) is related to the negative (unphysical) value of the SD contribution. We cannot explain this result by a systematic error due to the specific features of event detection and/or their processing.

The discrepancy is observed when we process events with harder cuts, as well as without the background normalization or without normalization to the $\pi\to e^-\bar{\nu}\gamma$ decay [16]. In the latter case the decay probability was actually calibrated using the number of events at the muon peak ≈80 MeV (Fig. 2a).

The absolute normalization is checked additionally by the agreement between the measured and the calculated probabilities for the IB and SD^+ contributions.

So, we found some discrepancy for the total decay probability, and the kinematical distributions for missing events are similar to the of the SD^- radiation [16]. It should be noted [17] that decay (1) may be sensitive to search for deviations from the Standard Model since a $\pi\to e^-\bar{\nu}\gamma$ decay is strongly suppressed.

In particular, the negative value for a_{SD} may be simulated by adding tensor radiation term to the structure–dependent amplitude:

$$M_T = \mathrm{i}(eG_F V_{ud}/V2)\epsilon^\mu q^\nu F_T \mathbf{u}(\mathrm{p}_e)\sigma_{\mu\nu}(1+\gamma^5)\nu(\mathrm{p}_\nu). \tag{8}$$

The decay rate densities for the SD^- radiation and the interference term between the inner bremsstrahlung and the tensor radiation are similar, so a destructive interference may reproduce the results of our fit, giving F_T=-(5.6±1.7)×10^{-3}. This value does not contradict listed constraints on a tensor coupling from nuclear beta decay as well as from muon decay (if universality is supposed) [17]. This result also does not contradict to the previous experiments carried out with stopped pions [18].

A number of work [19] were devoted to possible deviation from *SM* in radiative pion decay. In one of them the inserting of antisymmetric tensor fields into the standard electroweak theory may explain results of this work as well as [20].

It is evident that additional experimental and theoretical investigation of this problem should be carried out. At the present understanding of the problem we prefer to interpret the above result as an upper limit $| F_T | < 10^2$.

It also should be pointed out that if there are additional terms in the structure dependent amplitude (not of the V–A type), the results obtained for γ and F_V should be corrected.

The works in the study of the $\pi \to e^- \bar{\nu}\gamma$ decay will be continued on the new ISTRA–M setup shown on the Fig. 1.

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