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SLAC-TRANS-6

BETA DECAY OF THE PION

by

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With the aid of Cerenkov spectrometers we have detected 43 instances of pion beta-decay. The relative probability of this decay is found to equal $\lambda = (1.1 \pm 0.2) \times 10^{-8}$, which confirms the hypothesis of vector-flux conservation. The values of the constants G and G_β, characterizing pion and nucleon beta-decay, coincide: $G = (1.03 \pm 0.11)\, G_\beta$. The energy spectrum of positrons formed in pion beta-decay agrees with that calculated on the basis of the vector-flux conservation hypothesis.

1 - Introduction

The characteristics of pion beta-decay

$$\pi^+ \rightarrow \pi^0 + e^+ + \nu \qquad (1)$$

are predicted with great accuracy by the weak-interaction theory[ref 1, 2] if the hypothesis of vector-flux conservation is valid.[ref 3, 2] Within the framework of this hypothesis the probability of pion beta-decay can be determined with an error not exceeding several percent:

$$\omega(\pi^+ \rightarrow \pi^0 + e^+ + \nu) = \frac{G^2 \Delta^5}{30\pi^3}\left(1 - \frac{3}{2}\frac{\Delta}{\mu} - 5\frac{m^2}{\Delta^2} + \delta\right) \quad \hbar = c = 1. ^{1)} \tag{2}$$

Here G is the constant of weak vector interaction, Δ the mass difference between a charged and neutral pion,[ref 6, 7] μ the mass of the π^+ meson, m the electron mass, and δ the radiative correction.

Notwithstanding the exceptionally small relative probability $\lambda = \omega(\pi^+ \rightarrow \pi^0 + e^+ + \nu)/\omega(\pi^+ \rightarrow \mu^+ + \nu)$, which according to theory amounts in all to only 1.04×10^{-8}, initial studies carried out in 1961-62[ref 8-11] did show that process (1) is accessible to measurement. The probability λ then arrived at was close to the value predicted on the basis of the vector-flux conservation hypothesis. Reported below are results of further studies of pion beta-decay,[ref 12] undertaken for the purpose

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1) Formula (2) was obtained by Gershteyn.[ref 9]

of measuring the positron spectrum and refining the probability value λ .

2 - Experiment setup

To detect pion beta-decay, we used an apparatus (ref 13) containing four Cerenkov total-absorption spectrometers (Figure 1).

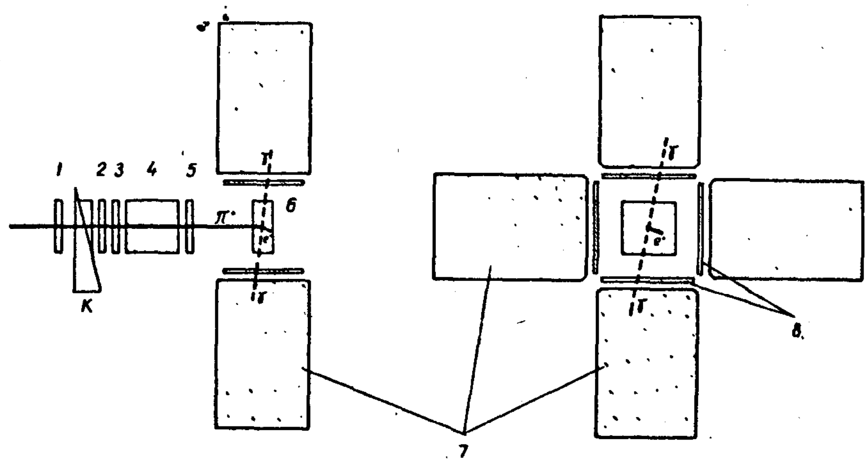

Рис. 1. Постановка опыта. 1-6 - сцинтилляционные счетчики, 7-черенковские спектрометры полного поглощения, 8-сцинтилляционные счетчики антисовпадений, K-тормозящий фильтр. В спектрометрах использованы фотоумножители 58 AVP, в сцинтилляционных счетчиках - 56 AVP

Figure 1: Experiment setup: 1-6 = scintillation counters; 7 = Cerenkov total-absorption spectrometers; 8 = anti-coincidence scintillation-counters, K/-meson/-retarding filter.[TN] In the spectrometers we used /type/ 58 AVP photomultipliers, in the scintillation counters /type/ 56 AVP.

TN = Translator's Note:

Words or phrases enclosed in obliques /in this manner/ have been added by the translator for the purpose of attempting to clarify (for himself) the presumed intended meaning.

The experiments were conducted at the end of 1962 in the synchrocyclotron of the Nuclear Problems Laboratory of the Joint Institute for Nuclear Research. Extracted from the accelerator chamber, a beam of positive pions was shaped by lead diaphragms and magnetic lenses. The pions passed through the series of scintillation counters 1-5, and were stopped in the scintillator of the last counter 6, designed to detect the decay positron. An amplitude analysis of the pulses from these counters enabled us to distinguish clearly occurrences of pion stopping.[ref 14] Gamma quanta from the decay of π^{o} mesons were detected with Cerenkov spectrometers. Between counter 6 and the spectrometers we placed scintillation counters which shielded the spectrometers from charged particles (anticoincidence counters).

The scintillation counters and Cerenkov spectrometers were placed in multilayered magnetic shields to eliminate the influence of the accelerator's stray magnetic field. All the counters and spectrometers were furnished with sources of light pulses, of nanosecond duration, with the aid of which we were able to simulate the pion stop and the decay /process/ (1). This made it possible rapidly to calibrate the entire apparatus as the measurements proceeded.

The Cerenkov spectrometers and counter 5 were connected into a coincidence circuit(ref 15) with a delayed "gate," of 8×10^{-8} sec duration, which triggered the sweep of a five-beam high-speed oscilloscope.(ref 16) The pulse-buildup time on the oscilloscope screen was 4×10^{-9} sec, the beams having a vertical-deflection sensitivity of 60 mv/cm. The pulses from all the counters and spectrometers of the apparatus were mixed together(ref 16) and fed into the oscilloscope inputs. In the process, the pulses of counters 3, 4, 6, and 8 were shaped with respect to length. Particular attention was given to the shaping of the pulse in counter 6. For this counter we selected feed conditions that cut to a minimum overshoots and afterpulses. Counter 6 was tested with the aid of two sources of light pulses that simulated the pulse from a stopped pion and that from the decay positron occurring shortly thereafter. Varying the delay time and amplitudes of these pulses showed that the positron in decay (1) can be reliably detected if the time delay t between the instant of its formation and the stopping of the pion exceeds 6×10^{-9} sec. The same result was obtained from our analysis of the occurrences of $\pi^+ - \mu^+$ decay detected in the calibration experiments (see Figures 2 and 10).

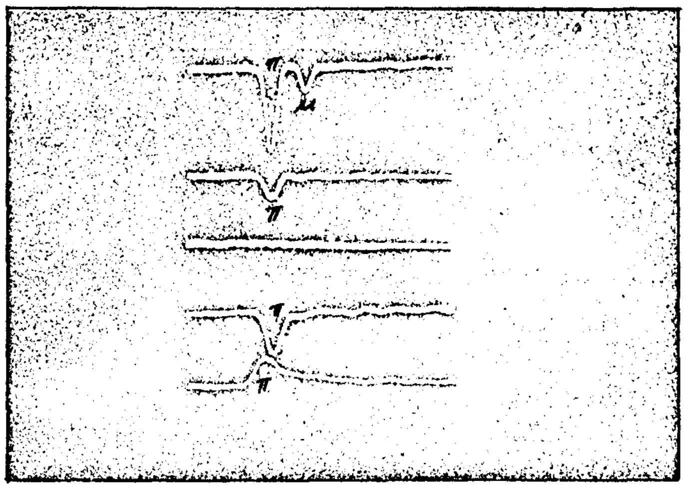

Рис. 2. Фотография случая $\pi^+ - \mu^+$ -распада. π -импульсы, возникающие в счетчиках 5, 4, 3, 6 при торможении и остановке π^+ -мезона, μ -импульс в счетчике 6 от μ^+-мезона.

Figure 2: Photograph of an instance of $\pi^+ - \mu^+$ decay. The π pulses occurring in counters 5, 4, 3, and 6 due to retardation and stopping of a π^+ meson; the μ pulse in counter 6 produced by a μ^+ meson.

To photograph the pulses, we used a Zeiss lens (German Democratic Republic) having a speed of 1:0.75 and focal length of 100 mm. The photographing was done with an RFK motion-picture

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Translator's Note: The RFK may stand for "Russian Photographic Camera," but the translator is not sure.

camera on highly sensitive "Isopanchrome 13" film.

The tuning and calibration of the apparatus were done in experiments in which we recorded the charge exchange of π^- mesons stopped in a target placed between /the/ Cerenkov spectrometers.

Translator's Note:

In the translator's opinion the presence (or absence) of "the" here makes a difference, i.e., affects the meaning. There being no word for "the" in Russian, however, the reader will have to draw his own conclusions.

We used as target liquid hydrogen and lithium hydride. Final calibration of the apparatus was done on the basis of a time/amplitude analysis of photographs taken during detection of the low-intensity charge-exchange process

$$\pi^- + p \rightarrow \pi^0 + n \qquad \text{(ref 17)}$$

in the scintillator of counter 6 (see Figure 3). This analysis showed that the selected detection method assures a resolving time of 2×10^{-10} sec for the scintillation counters, 7×10^{-10} sec for the spectrometers.

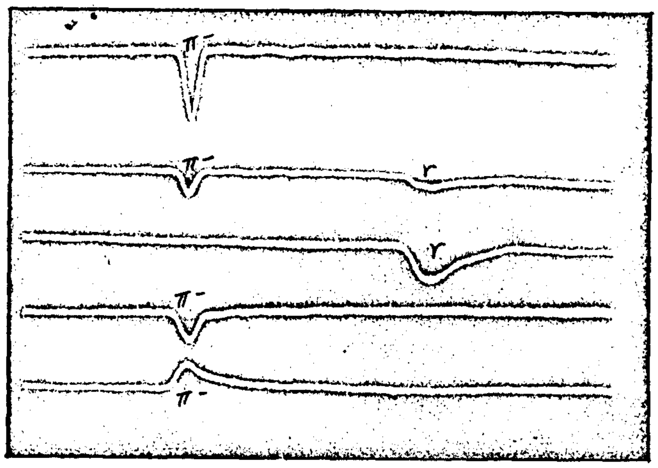


Рис. 3. Фотография случая перезарядки π^--мезона в сцинтилляторе счетчика 6. π – те же импульсы, что на рис. 2, γ – импульсы от двух противоположных спектрометров.

Figure 3: Photograph of an instance of the charge exchange of a π^- meson in the scintillator of counter 6. The π pulses are the same ones as in Figure 2; the γ pulses are from two opposite spectrometers.

3 - The measuring

The basic measuring lasted some 500 hours. During this time 4×10^{10} pions were passed through the apparatus. In the course of the measurements the entire unit was test-calibrated every two hours by means of light-pulse sources (Figure 4). The stability and linearity of the oscilloscope's sweep were checked also---by photographing standard sine waves, having

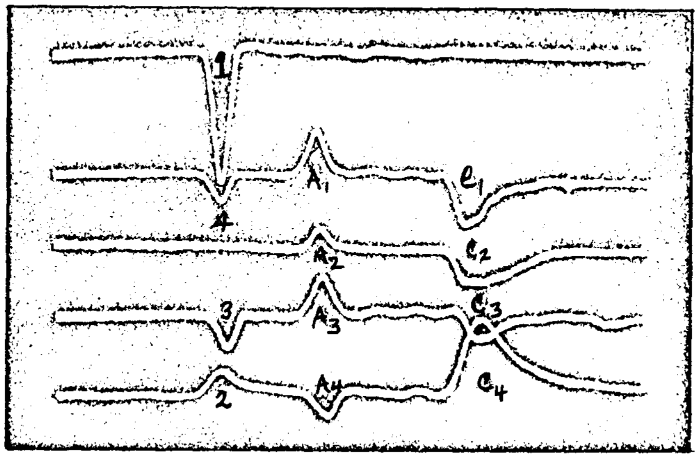


Рис. 4. Одновременное срабатывание импульсных источников света во всех счетчиках и спектрометрах установки (калибровка). 2, 3, 4, 1 – импульсы от счетчиков 5, 4, 3, 6. $A_1 - A_4$ – импульсы от счетчиков антисовпадений, $C_1 - C_4$ – импульсы от черенковских спектрометров.

Figure 4: Simultaneous operation of the light-pulse sources in all the counters and spectrometers of the apparatus (calibration). 2, 3, 4, and 1 are pulses from counters 5, 4, 3, and 6. A_1 to A_4 are pulses from the anticoincidence counters, C_1 to C_4 pulses from the Cerenkov spectrometers.

a frequency of 100 mc, from a stabilized quartz-crystal oscillator. In addition, repeated periodically were test experiments in which we recorded the charge exchange of negative pions in the scintillator of counter 6 and in the lithium-hydride target.

The photographs obtained were examined first via slide projector. We singled out those instances in which the photograph showed a pion stop accompanied by a delayed pulse and an absence of pulses from the anti-coincidence counters (see Figure 5a, b, c). The photographs on which anti-coincidence-counter pulses appeared (Figure 6) were analyzed separately, and served as a source of information on the pion's radiative decay

$\pi^+ \rightarrow \gamma + e^+ + \nu$.

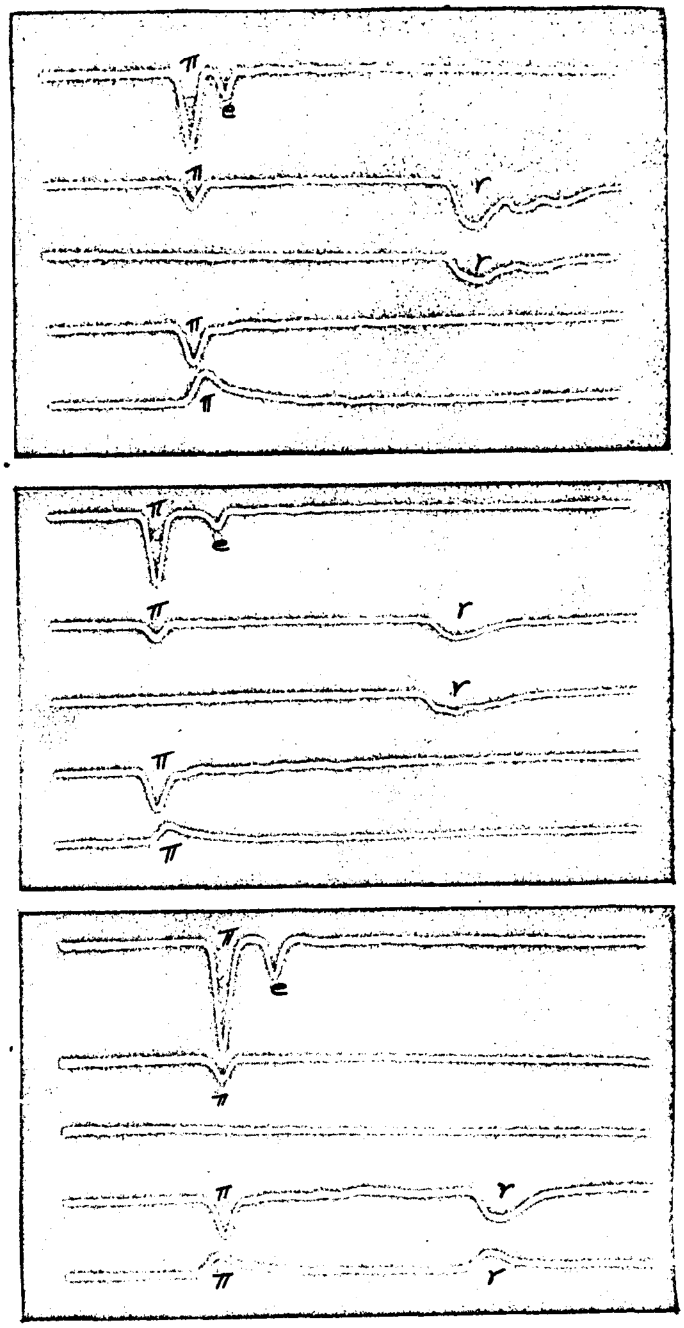


Рис. 5 а, б, в. Типичные фотографии бета-распада пионов. π и γ – те же импульсы, что и на рис.3. е – импульсы от позитронов распада. t =17, 31и 25 10^{-9} сек, соответственно.

Figure 5a, b, c: Typical photographs of pion beta-decay. The π and γ pulses are the same as in Figure 3. The e pulses are from decay positrons. t = 17, 31, and 25 /x/ 10^{-9} (?) sec, respectively.

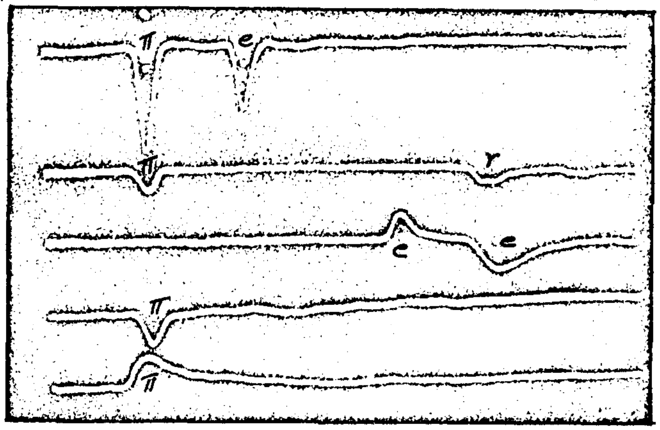


Рис. 6. Фотография радиационного распада $\pi^+ \to \gamma + e^+ + \nu$. π и γ – те же импульсы, что на рис. 3. e – импульсы от позитрона в счетчиках 6 и 8 и в спектрометре.

Figure 6: Photograph of the radiative decay $\pi^+ \to \gamma + e^+ + \nu$. The π and γ pulses are the same as in Figure 3. The e pulses are from positron/s/ in counters 6 and 8 and in /the/ spectrometer.

The 330 photographs left after we had taken out the first group were subjected to a time analysis. It was found that 61 events satisfying the necessary time criteria (pulses from γ quanta and positrons coincide in the time-resolution range) were in the decay (1) category. A final sorting of the events was made on the basis of an amplitude analysis of the pulses from the Cerenkov spectrometers. This analysis showed that, as the energy threshold E_{th} of the detected gamma quanta rises, the background-noise level abruptly drops,(ref 12) and at

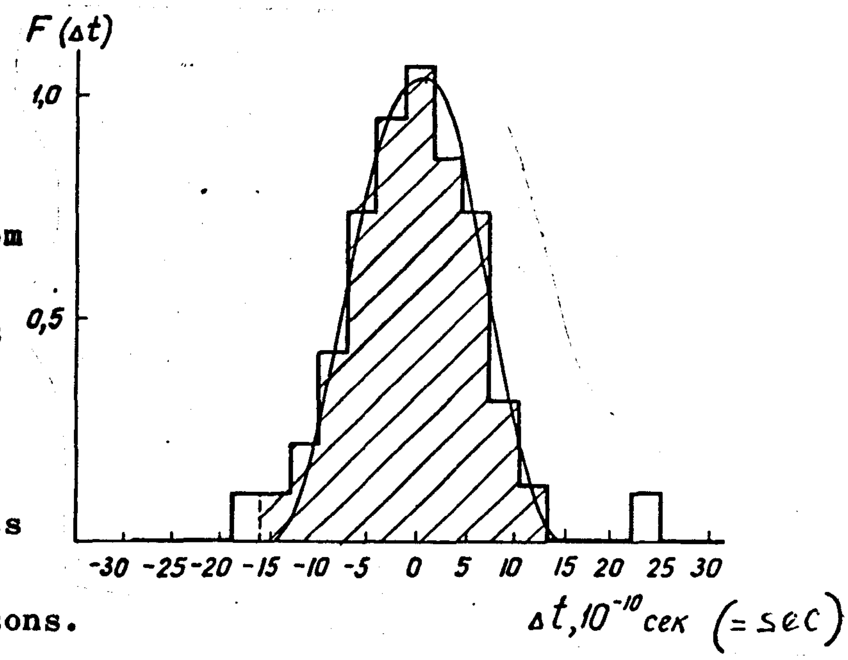
E_{th} = 30 mev pion beta-decay events are reliably distinguishable.

Translator's Note:

The subscript in the Russian, notwithstanding its resemblance to the Greek pi, is believed to be a Russian p standing for <u>porog</u> = "threshold" = th.

After introduction of the threshold E_{th} = 30 mev .

52 events satisfied the time and amplitude criteria. The random-coincidence background-noise level we determined in terms of the time distributions of the pulses from the Cerenkov spectrometers and in counter 6. One of these distributions is shown in Figure 7.



Time distribution of detected events. Δt is the delay of the pulse from counter 6 (positron) in comparison with the pulses from the spectrometers. The curve is the same distribution obtained in the calibration experiments with detection of the charge exchange of π^- (?) mesons.

Figure 7

Рис.7. Временное распределение зарегистрированных событий. Δt – задержка импульса от счетчика 6 (позитрон) относительно импульсов от спектрометров. Кривая – то же распределение, полученное в калибровочных опытах при регистрации перезарядки π^- -мезонов.

Translator's Note: (?) = illegibility on translator's copy of original Russian.

The number of random $\gamma\gamma - e^+$ and $\gamma e^+ - \gamma$ coincidences was found to be six. The background associated with the simulated $\mu^+ - e^+$ decay process (with emission of a γ quantum) was determined on the basis of photographs (Figure 8), on which we observed, between the pulses from the stopped pion and the positron, a pulse from a μ^+ meson (1 event). Finally, we had to expect

Figure 8:

Photograph of one of the instances wherein, between the pulses from the pion and positron, we observed a pulse from a μ^+ meson.

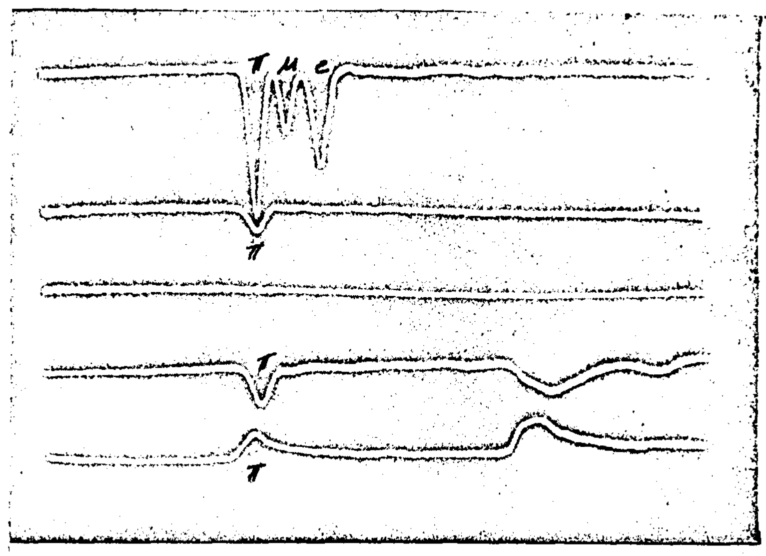


Рис. 8. Фотография одного из случаев, где между импульсами от пиона и позитрона виден импульс от μ^+-мезона.

two more background events on the basis of the two detected instances wherein the amplitude of the pulse from the positron was too large. The total number of background events was found, therefore, to be nine. The number N of detected instances of pion beta-decay comes to: N = 43 ± 7 .

4 - M e a s u r e m e n t   r e s u l t s

In the described experiments we recorded coincidences of pairs of γ quanta traveling both in opposite directions (Figure 3) and at an angle /to each other/ of 90° (Figure 9).

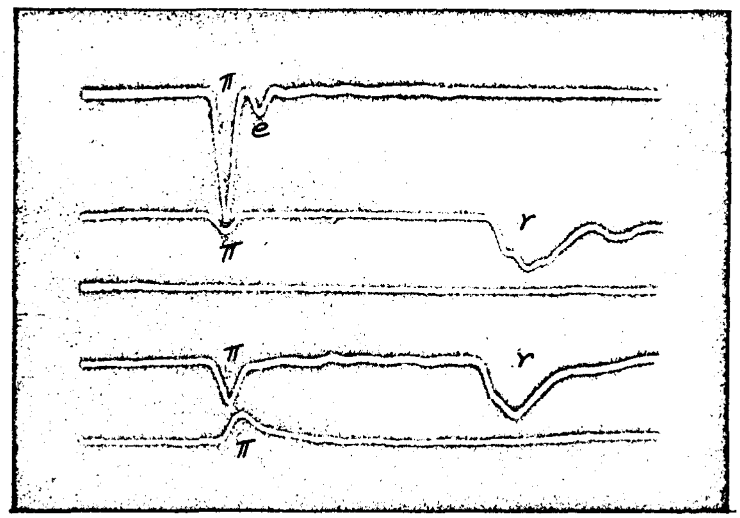
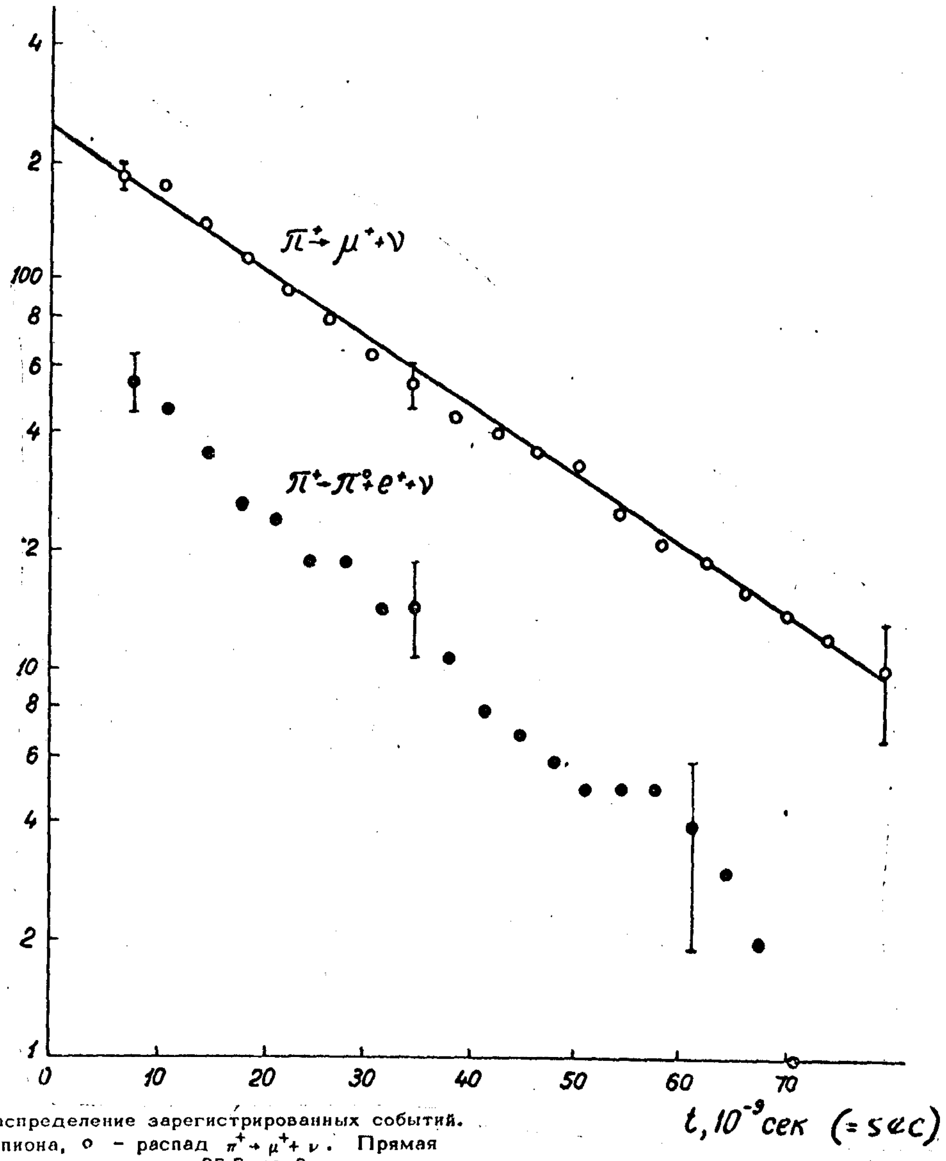


Рис. 9. То же, что и на рис. 5, но γ -кванты зарегистрированы двумя соседними спектрометрами. $t = 15 \cdot 10^{-9}$ сек.

Figure 9: Same as Figure 5, but the γ quanta are recorded by two adjacent spectrometers. $t = 15 \times 10^{-9}$ sec.

The γ quanta forming in the decay (1) fly apart at an angle close to 180°.. Under the conditions of our experiments the result of this should have been that (allowance made for the angular resolution of the apparatus) the expected number $N_{||}$ of pion beta-decay occurrences recorded by the opposed spectrometers will exceed by /one/ order of magnitude the number $N_{\perp}$ recorded by the two adjacent spectrometers: $N_{\perp}/N_{\parallel} = 0.12$. In the case of the selected events the indicated angular correlation indeed does occur: $N_{\perp}/N_{\parallel} = 0.16 \pm 0.11$. With $E_{th} = 36$ mev we get $N_{\perp}/N_{\parallel} = 0.05 \pm 0.13$.

The time distribution of the recorded instances, shown in Figure 10, also confirms the correctness of our identification of the observed decay.



Integral time distribution of the recorded events. • = instances of pion beta-decay; o = the decay $\pi^+ \to \mu^+ + \nu$. The straight line corresponds to a mean lifetime of $\tau = 25.5 \times 10^{-9}$ sec.

Figure 10

Рис. 10. Интегральное временное распределение зарегистрированных событий. • – случаи бета-распада пиона, ○ – распад $\pi^+ \to \mu^+ + \nu$. Прямая соответствует среднему времени жизни $\tau = 25{,}5 \cdot 10^{-9}$ сек.

As seen from that Figure---where, for comparison, we give the distribution for an ordinary $\pi^+ - \mu^+$ decay---the mean lifetime of the observed decay coincides with the mean lifetime of the π^+ meson. The amplitude distribution of the pulses in the Cerenkov spectrometers (energy spectrum of γ quanta) is also close to that expected for pion beta-decay (Figure 11).

Integral distribution F(A) of the recorded events in terms of the amplitudes A of the pulses in the Cerenkov spectrometers. The curve is the same distribution obtained in the calibration tests with recordings of the charge exchange of π^- mesons.

Figure 11

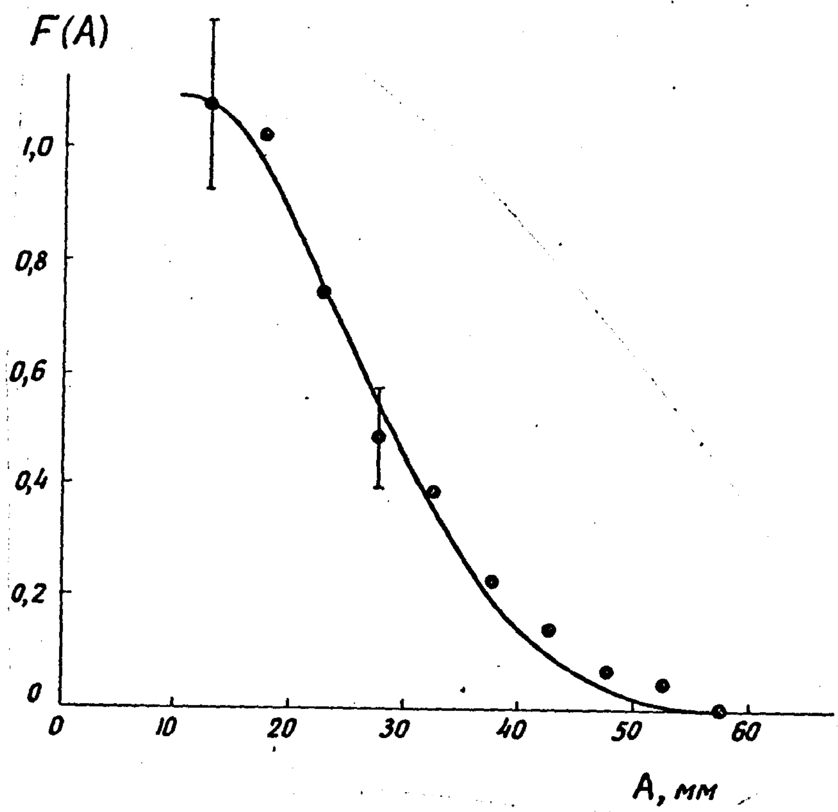


Рис. 11. Интегральное распределение $F(A)$ зарегистрированных событий по амплитудам A импульсов в черенковских спектрометрах. Кривая - то же распределение, полученное в калибровочных опытах при регистрации перезарядки π^--мезонов.

The energy spectrum of the positrons that form in a pion beta-decay is shown in Figure 12. It coincides with the spectrum calculated on the basis of vector-flux conservation and corrected to allow for the resolution of counter 6.

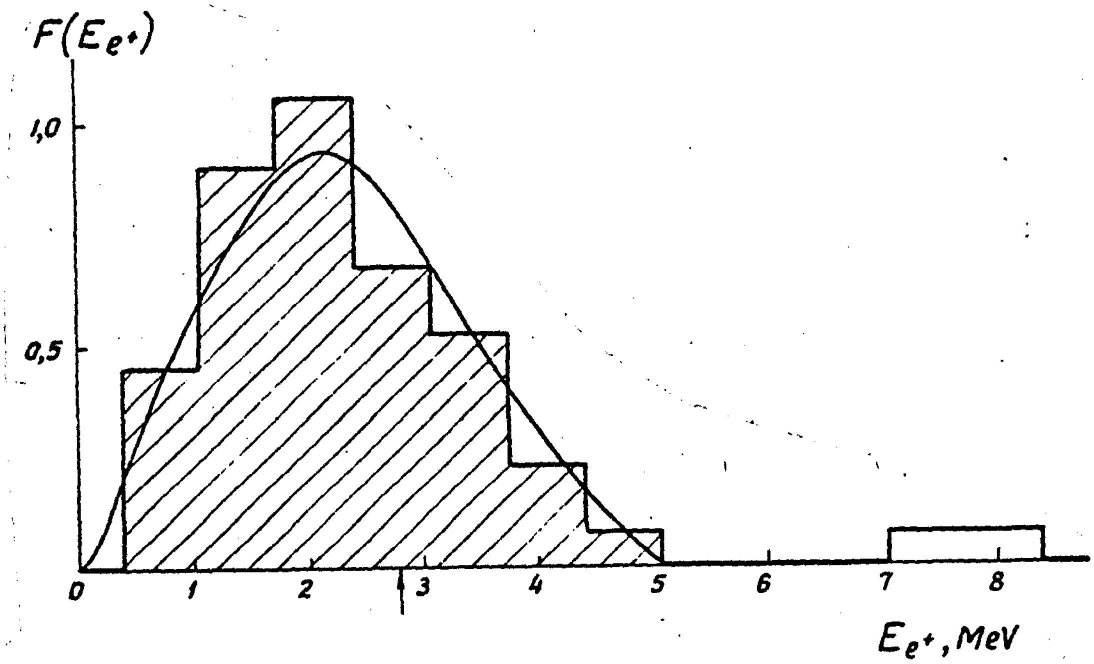


Рис. 12. Энергетический спектр позитронов, образующихся при бета-распаде пионов. Кривая вычислена с учетом разрешения аппаратуры. Стрелкой на шкале энергий позитронов E_{e^+} указано положение максимума распределения импульсов от μ^+-мезонов в распаде $\pi^+ \to \mu^+ + \nu$

Figure 12: Energy spectrum of the positrons that form in a pion beta-decay. The curve is plotted with allowance made for the resolution of the apparatus. The arrow on the positron energy-scale E_e+ points to the position of peak distribution of pulses from μ^+ mesons in the decay $\pi^+ \to \mu^+ + \nu$.

We determined the probability of pion beta-decay in terms of the number N of detected decay occurrences, allowance being made for the experimentally determined efficiency of our equipment.

To determine the efficiency, the spectrometers were irradiated with γ quanta from the charge exchange of π^- mesons in hydrogen. The place and angle at which the γ quanta entered the spectrometer were varied. The obtained velocity of /the/ light was compared with the velocity of light from γ -quanta scintillation detectors of known efficiency. In determining the efficiency of the apparatus we took into account the shift and finite length of the "gate" ($10 < t < 85 \times 10^{-9}$ sec), the energy thresholds for γ quanta ($E_{th} = 30$ mev) and the positron (0.6 mev), the absorption of γ quanta in counters 6 and 7, and the scanning efficiency. For the efficiency of pion beta-decay detection we got $(10.5 \pm 1.4)\%$.

The relative probability of pion beta-decay was found to be $\lambda = (1.1 \pm 0.2)\ 10^{-8}$ ---which agrees with the value theoretically expected. The constant G characterizing the beta decay of a pion [see (2)] coincides with the vector constant G_β characterizing the beta decay of nuclei: $G = (1.03 \pm 0.11)G_\beta$.

Averaging the findings in this paper with the results obtained at CERN,(ref 18) we get: $G = (1.04 \pm 0.07)G_\beta$.

In conclusion we take this opportunity to thank G.P. Zorin, V.I. Orekhov, A.V. Revenko, N.N. Khovanskiy, V.A. Chernyye, L.N. Andianova and her staff, N.B. Yedovina, N.M. Kovaleva, and K.A. Baycher and his staff, for their help in building the apparatus and with the work. We are indebted to Kim Ge Fa, E.V. Nyag, Z.F. Prokoshkina, and M. Sgonova for scanning and analyzing the photographs.

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