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Abstract

27 events of charge-exchange scattering with subsequent decay $\pi^0 \to e^- + e^+ + \gamma$ have been recorded in the hydrogen-filled diffusion cloud chamber placed in the magnetic field and exposed to 128 and 162 MeV negative pion beams. A probability of this decay with respect to the usual decay has been found to be $2\rho_0 = \frac{W(\pi^0 \to e^- + e^+ + \gamma)}{W(\pi^0 \to 2\gamma)} = 0{,}0117 \pm 0{,}0015$. The results of the measurements of momenta and angles of electron-positron pairs are presented. The energy characteristics of pairs and angular distributions experimentally found are in good agreement with the theoretical ones.

Introduction

Neutral pion decay into an electron-positron pair and a γ-ray

$$\pi^0 \to e^- + e^+ + \gamma \qquad (1)$$

was first considered theoretically by Dalitz[1]. This alternative mode of decay may be interpreted as an internal conversion of one of γ-rays in the electromagnetic field of the other one. The coefficient of internal conversion and the energy and angular characteristics of this mode of decay have been calculated by Dalitz, and later on by Kroll and Wada[2] on the basis of the quantum electrodynamics. The results of these calculations depend weakly upon the form of the meson theory. Recently Kerimov et al.[3] calculated the probability of decay (1) with account of the spin states (longitudinal polarizations) of an electron-positron pair and a γ-ray. Experimentally the decay $\pi^0 \to e^- + e^+ + \gamma$ was studied in some investigations[4,5,6,7]. However, the results of these experiments have a comparatively low accuracy. Therefore, in order to make them more accurate a further investigation of decay (1) seemed important.

This paper presents the data concerning 27 decay events $\pi^0 \to e^- + e^+ + \gamma$ found in the diffusion cloud chamber exposed to 128 and 162 MeV negative pion beams. The data of a preliminary analysis of 14 such decays were published earlier[8].

The chamber was filled with hydrogen up to a pressure of 25 atm and placed into the permanent magnetic field of 9000 gauss. The experimental arrangement, the working conditions in the pion beams and the method of analyzing the events are described in more detail in[9,11]. Neutral pions were generated as a result of charge-exchange scattering of π^--mesons. The above-mentioned 27 events of decay (1) were found in double scanning of about 90000 stereophotographs and identified by the ends of negative pion tracks in the gas of the chamber accompanied by the emission of an electron-positron pair. The photos of two such events are given in Fig.1. It is worth while noting that all the pairs found were referred to the pairs of internal conversion since in our experiment due to a small stopping power of a gaseous hydrogen the probability of appearing one pair created by a γ-ray from the decay $\pi^0 \to 2\gamma$ at a distance of less than 1 mm from the point of decay (the external conversion) is 7.10^{-5}.

DETERMINATION OF THE INTERNAL CONVERSION COEFFICIENT

A relative probability of a negative pion decay via the scheme (1), is determined by the expression[1,2]:

$$2\rho_0 = \frac{W(\pi^0 \to e^- + e^+ + \gamma)}{W(\pi^0 \to 2\gamma)} = \frac{2\alpha}{3\pi}\left(\ln \frac{m_{\pi^0}^2}{m_e^2} - \frac{7}{2}\right) = 0{,}0118 \qquad (2)$$

where α is the fine structure constant.

The results of an experimental determination of the coefficient $2\rho_0$ are listed in Table 1.

Table 1.

$2\rho_0$	The author
0.020 ± 0.006	Daniel et al.[4]
0.013 ± 0.004	Anand[5]
$0.0145^{+0.0080}_{-0.0045}$	Lindenfeld et al.[6]
0.0106 ± 0.0017	Sargent et al.[7]
0.0117 ± 0.0015	This paper

The data on $2\rho_0$ were obtained by Daniel et al.[4], and Anand[5] as a result of scanning the nuclear emulsions exposed to the cosmic rays, when the number of neutral pions generated in stars could not be determined with a sufficient accuracy. The magnitude of $2\rho_0$ found by Lindenfeld et al[6] using the scintillation counters has a comparatively low accuracy. Sargent et al.[7] have obtained the internal conversion coefficient in the experiment with slow negative pions which stopped in hydrogen filled diffusion cloud chamber. The main difficulty in determining the magnitude of $2\rho_0$ was to identify the pairs from the decay of a neutral pion and the pairs of the internal conversion from the reaction $\pi^- + p \to \gamma + n$. Besides, the magnitude of $2\rho_0$ has been obtained on condition that Panofsky's ratio P is equal to 0.94. If it is accepted that $P = 1.5 - 1.8$ found in more recent papers[10] the value of the coefficient $2\rho_0$ calculated by the data of Sargent's et al. paper will not agree with the theoretical value for this coefficient and with other experimental data.

A method for determining the internal conversion coefficient applied in the present paper is based upon the use of high energy negative pions when the number of pairs from the internal conversion of γ-rays in the reaction $\pi^- + p \to \gamma + n$ is only 1% of the number of the decays $\pi^0 \to e^- e^+ \gamma$

Therefore, in calculating the coefficient $2\rho_0$ it is possible to neglect the contribution from these pairs. Besides, the number of neutral pions decaying in a usual way (into two γ -rays) may be accurately determined by the number of elastic scattering events and by the well-known ratio of the cross sections for elastic and charge-exchange scattering. A direct counting of the number of charge-exchange events in the diffusion chamber is extremely difficult due to the local non-sensitive regions and edge effects.

The coefficient $2\rho_0$ was determined by the formula

$$2\rho_0 = \frac{N_p}{N_{el}} \cdot \frac{\sigma_{el}}{\sigma_t - \sigma_{el}} \cdot \frac{\eta_{el}}{\eta_p} \qquad (3)$$

where N_p and N_{el} are the number of decay $\pi^0 \to e^- + e^+ + \gamma$ and elastic scattering events respectively; σ_t is the total cross section for $(\pi^- p)$ -interaction; σ_{el} is the total cross section for elastic ($\pi^- p$)-scattering; η_p and η_{el} are the efficiencies of observing the decay events $\pi^0 \to e^- + e^+ + \gamma$ and the elastic scattering events.

The same selection criteria as in paper/11/ for the events of elastic ($\pi^- p$) - scattering were applied to the pairs from neutral pion decay. 26 pairs and 1285 elastic scattering events satisfy these selection criteria. A correction due to Coulomb scattering and to the interference of the Coulomb and nuclear scattering was introduced into the number of elastic scattering events. As σ_t and σ_{el} entering into expression (3) we used the mean values of the total cross sections for $\pi^- p$ -interaction/12/ and the total cross sections for elastic scattering/11/ weighted by the number of elastic scattering events at 128 and 162 MeV.

The efficiency of observing the elastic $\pi^- p$-scattering events is determined by the missed ones the tracks of which are situated in the plane close to vertical and is equal to 90%, the efficiency for observing the pairs is assumed to be the same. With account of the remarks mentioned above a relative probability of the decay $\pi^0 \to e^- + e^+ + \gamma$ calculated by formula (3) is equal to $2\rho_0 = 0.0117 \pm 0.0015$, whereas the photon internal conversion coefficient in the decay of neutral pion is found to be $\rho_0 = 0.0059 \pm 0.0008$. The errors indicated are the statistical probable errors. The value $2\rho_0$ obtained here is in a good agreement with a theoretical one (2).

ANGULAR AND ENERGY CHARACTERISTICS OF PAIRS

The results of the analysis of 27 electron-positron pairs found in our experiment are given the Table 2. In the first three Colomns of the Table are presented the total energies of an electron and a positron and the total energy of a pair. In the next Colomns are listed the correlation angles α_{lab} (i.e., the angles between a positron and an electron), as well as the angles between the direction of the total pair momentum and the direction of pion motion θ_{lab} and θ^* (c.m.s.). The accuracy of measuring the momenta (energy) was $\sim 10\%$ the accuracy of measuring the angles was 1^o. In case of very short tracks the Table presents only lower limits for the corresponding energies.

TABLE II.

N pairs	E^- (MeV)	E^+ (MeV)	$E=E^-+E^+$ (MeV)	α (deg.) /l.s./	θ (deg.) /l.s./	θ^* (deg.) /s.c.m. /
I	-	-	-	2,5	II8	I28
2	>I92	46	>238	I6	50	60
3	I9	4I	60	36	95	I07
4	I48	> 74	>222	7	9I	I03
5	20	III	I3I	8	I45	I5I
6	27	6	33	I22	II7	I27
7	89	67	I56	6	50	60
8	>I4	>96	>II0	5	I00	III,5
9	-	-	-	2	II0	I2I
I0	75	I05	I80	53	I40	I47
II	39	>I52	>I9I	3	99	III
I2	I0	24	34	38	86	98
I3	I66	20	I86	28	65	75
I4	22	27	49	46	II8,5	I28,5
I5	33	40	73	25	76	88
I6	25	>5I	>76	20	I0I	II2,5
I7	7,3	52	59,3	5	II9	I29
I8,	23	>I22	>I45	2	89	I0I
I9	79	27	I06	29	44	53
20	42	I4	56	I7,5	97	I08
2I	-	32	>32	25	90	I02
22	I6	I87	203	I3	92	I04
23	45	47	92	32,5	62	73
24	>67	79	>I46	5	9I	I03
25	2I	65	86	74	93	I05
26	39	29	68	I0,5	54	64
27	63	4I	I04	8	I4I	I48

Events N 1 and N 9 are found on the films exposed without a magnetic field.

It is interesting to compare the experimental data obtained with the results of the calculations made by Dalitz and Kroll and Wada.

1. Experimental distribution of pairs $n(\alpha)$ by the correlation angles is plotted in Fig.2. On the same picture is given a theoretical form of this distribution obtained by Dalitz/13/ in the rest system of a neutral pion (solid curve). For the angles $\alpha > 2^{\circ}$ this distribution is of the form $n(\alpha)\, d\alpha \sim \frac{d\alpha}{\alpha}$. Since the account of a neutral pion velocity would have only led to an insignificant displacement of this distribution to smaller angles, then from Fig.2 one can see that the experimental distribution obtained does not contradict to a theoretical one.

In the rest system of a neutral pion a half of pairs must emit within the correlation angle $\alpha_{1/2} = 18.1^{\circ}$/13/, in the present esperiment for $\alpha_{1/2}$ the value 16° was obtained.

2. In Fig.3 the distribution of pairs is plotted against the parameter $y = \frac{|P_{e^-} - P_{e^+}|}{|\vec{P}_{e^-} + \vec{P}_{e^+}|}$ where $\vec{p}_{e^-}$ and $\vec{p}_{e^+}$ are the momenta of an electron and a positron in the lab.system. This parameter characterizes the energy division between the particles of a pair. A smooth curve is a theoretical distribution of pairs by the parameter y in the rest system of a neutral pion obtained in Kroll and Wada's paper/2/. The magnitude of y depend weakly upon the velocity of a neutral pion. The distribution of pairs by the parameter y, as is seen from Fig.3, is consistent with a theoretical one and there is no tendency to the energy division between the particles of a pair in equal parts which revealed itself in Sargent's et al. experiment/7/ and, especially, in Anand's experiment/5/.

3. An important energy characteristic of pairs from the decay $\pi^{\circ} \to e^- + e^+ + \gamma$ is their distribution by the parameter: $X = (E^- + E^+)^2 - (\vec{p}_{e^-} + \vec{p}_{e^+})^2$ where E^-, E^+, $\vec{p}_{e^-}$ and $\vec{p}_{e^+}$ are the total energies and momenta of electrons and positrons. The parameter X is an invariant and may be interpreted as a degree of virtuality of an intermediate photon turning into the pair or as a square of the 'rest mass' of a virtual photon.

The distribution

$$f(X) = \frac{X + 2m_e^2}{X^2} \left(\frac{X - 4m_e^2}{X} \right)^{1/2} \left(m_{\pi}^2 - X \right)^3 \qquad (3)$$

was obtained by Dalitz (1) under the assumption that a linear dimension of the currents producing the electromagnetic fields in π°-meson decay is small if compared with the magnitude of $2 \cdot \hbar / m_{\pi} c$.

This distribution is presented in Fig.4 by a solid curve, On the same Figure in the form of a histogramm is given the distribution of pairs by the parameter X, obtained by the results of the present paper. It can be seen that most of the pairs has small values of X. This points to a low degree of the virtuality of an intermediate photon, i.e., the characteristics of internal conversion pairs by the decay $\pi^{\circ} \to e^- + e^+ + \gamma$ must be close to those generated by real photons (an external conversion). Due to this the angular distribution of pairs must practically coincide with the angular distribution of γ-rays from the decay $\pi^\circ \to 2\gamma$. In Fig. 5 in the form of a histogramm is presented the obtained angular distribution of pairs by the angles θ^* in the center-of-mass system $\pi^- p$. It does not contradict the angular distribution of γ-rays from the decay of neutral pions generated in the reaction $\pi^- + p \to \pi^\circ + n$ at an energy of negative pions 150 MeV /14/. This distribution is shown in the same Figure as a curve $\frac{d\sigma}{d\Omega} \cdot \sin\theta^*$ (in an arbitrary scale).

As for the total energies of the pairs $E = E^- + E^+$ they are, as it should be expected, within the interval 17-270 MeV corresponding to the limits of the calculated energy spectrum of γ-rays from a neutral pion decay generated in the charge-exchange process.

It should be noted in conclusion that in scanning the photos one event of a neutral pion decay via the scheme $\pi^\circ \to e^- + e^+ + e^- + e^+$ /9/ was observed.

The kinematics of none of 27 pairs satisfy the decay $\pi^\circ \to e^- + e^+$ the relative probability of which is of the order of 10^{-7} according to Drell's estimates. /15/

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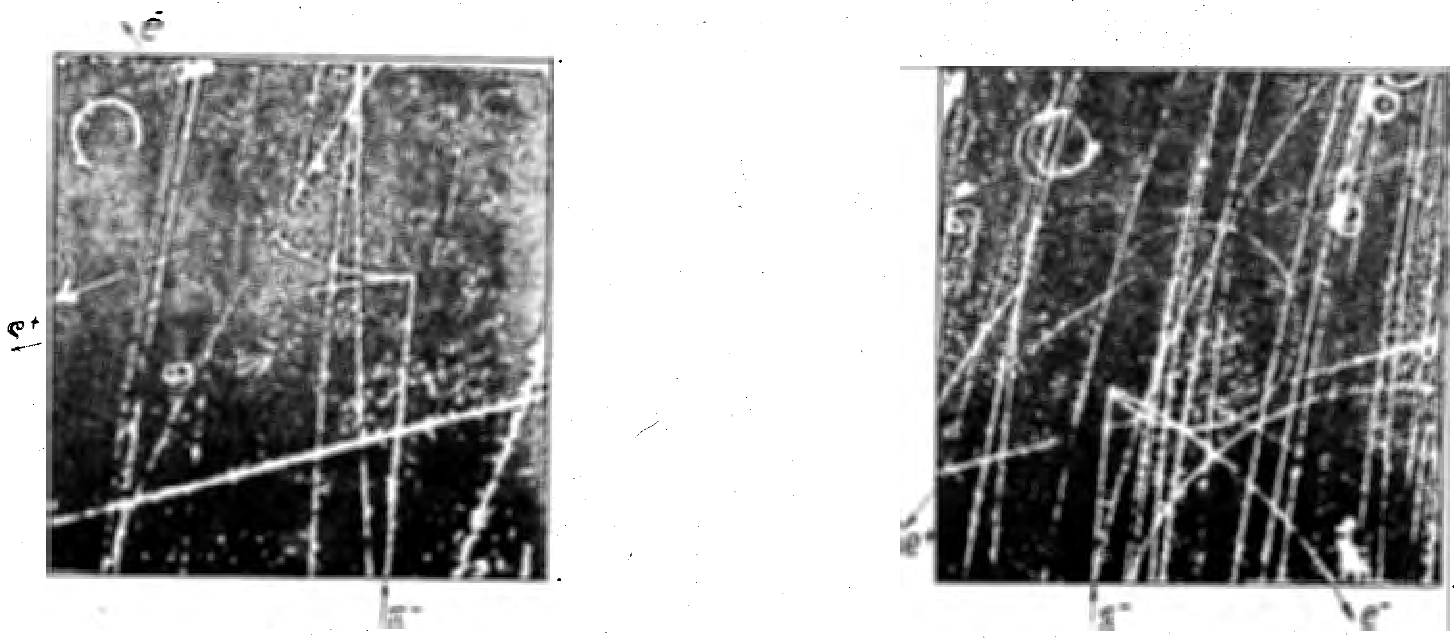

Fig. 1. Photos of the events $\pi^- + p \to \pi^0 + n$ with subsequent decay $\pi^0 \to e^- + e^+ + \gamma$ obtained in hydrogen-filled diffusion cloud chamber: a-pair N 3, b- pair N 6.

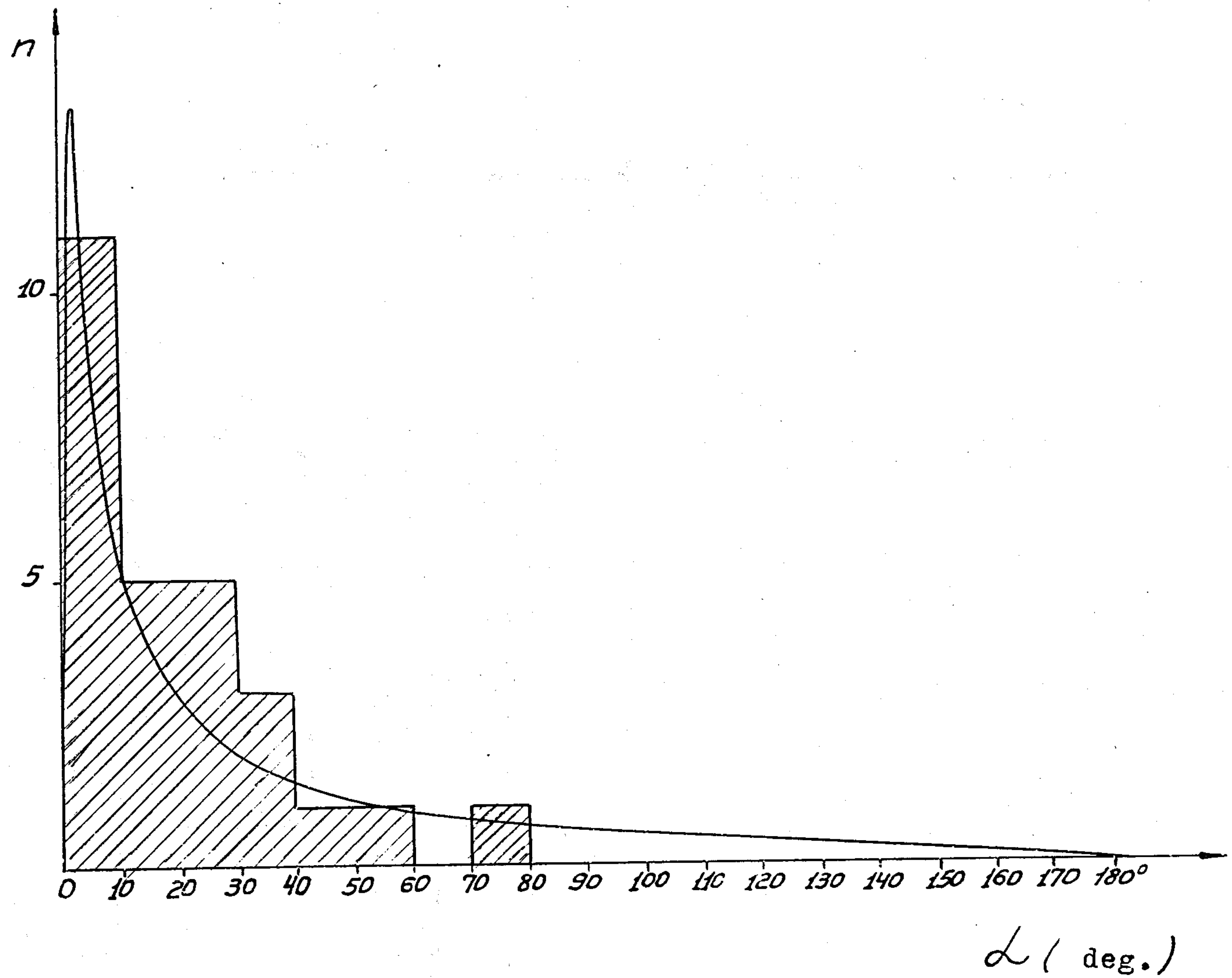

Fig. 2. Distribution of pairs from the decay $\pi^0 \to e^- + e^+ + \gamma$ by the correlation angles α_{lab}. The solid curve shows the theoretical distribution in the rest system of a neutral pion obtained by Dalitz/13/.

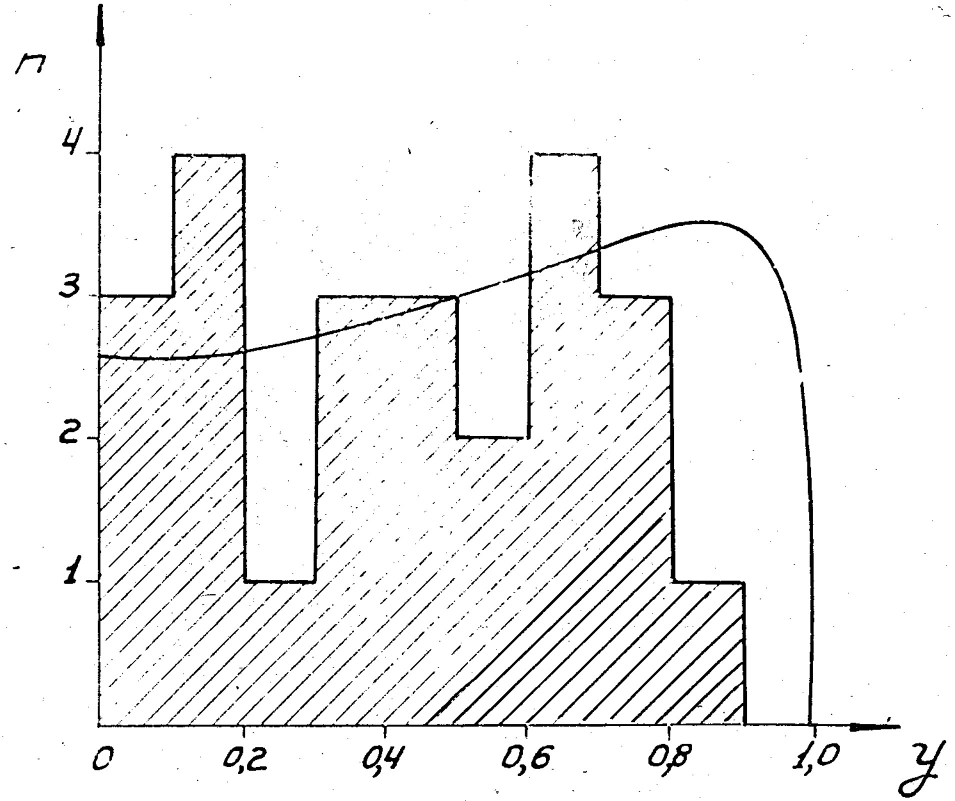

Fig. 3. Distribution of pairs by the parameter $y = \frac{|P_{e^-} - P_{e^+}|}{|\vec{P}_{e^-} + \vec{P}_{e^+}|}$. Solid curve - theoretical distribution/2/.

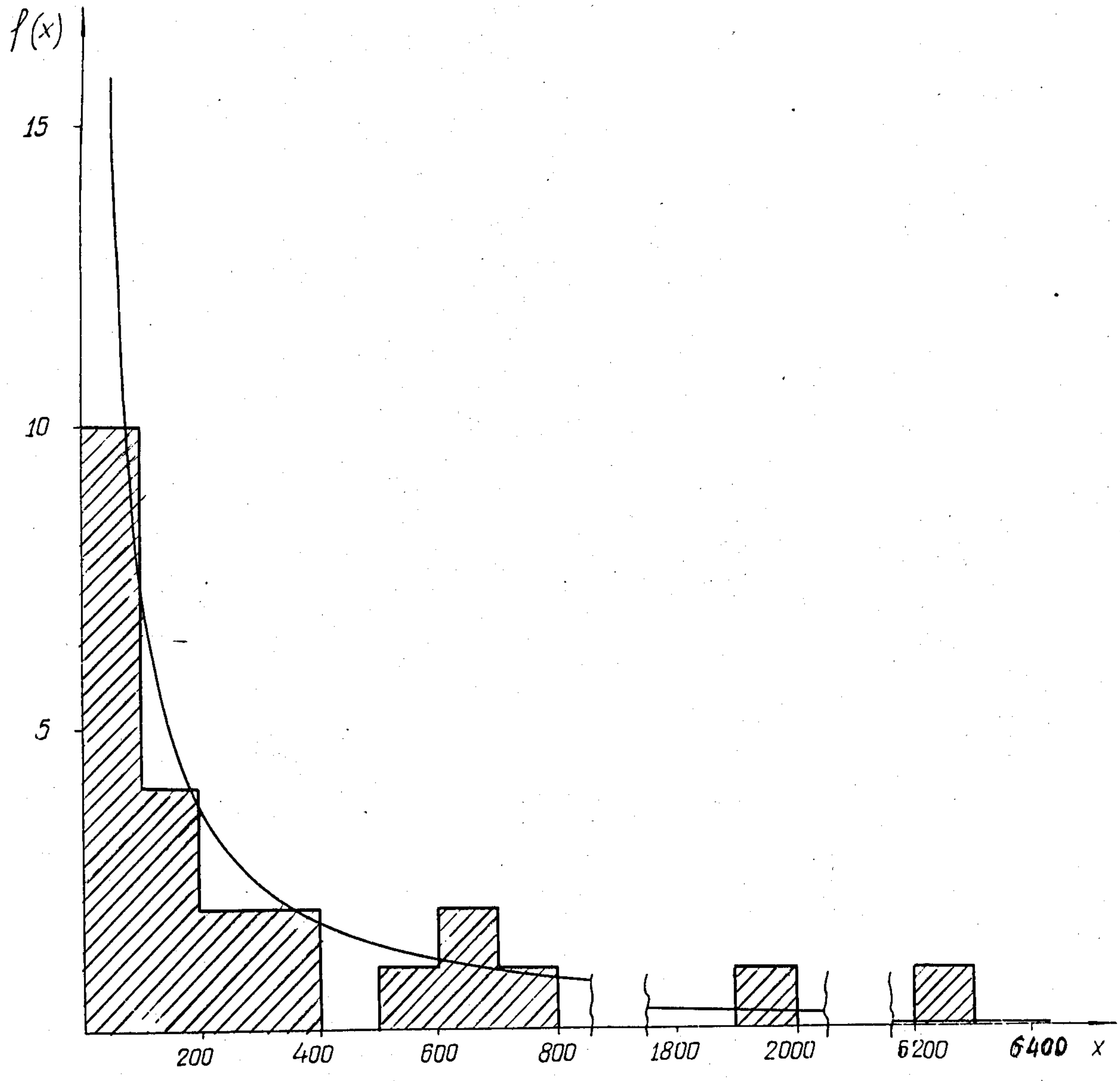

Fig. 4. Distribution of pairs by the parameter $X = (E^- + E^+)^2 - (\vec{P}_{e^-} + \vec{P}_{e^+})^2$.
Solid curve - theoretical distribution /1,2/.

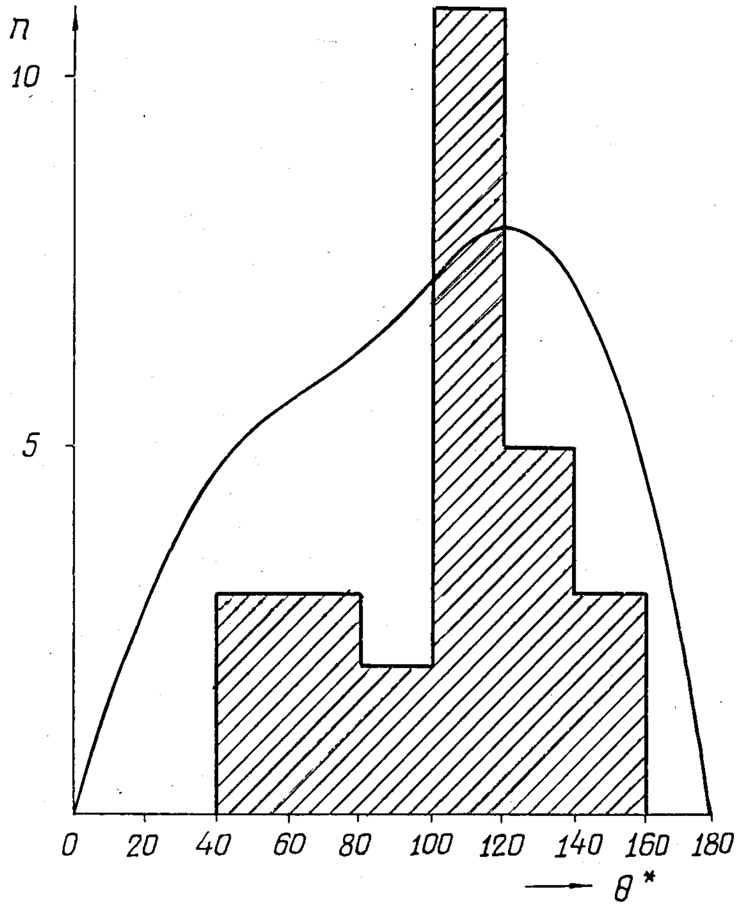

Fig. 5. Angular distribution of pairs with respect to the direction of negative pions in the center-of-mass system $\pi^- p$. Solid curve - angular distribution $d\sigma/d\Omega \cdot \sin\theta^*$ (in an arbitrary scale) of γ - rays from the decay of neutral pions produced in the reaction $\pi^- + p \rightarrow \pi^0 + n$ at an energy of negative pions of 150 MeV /14/.