INTERNAL CONVERSION PAIRS IN THE DECAY OF NEUTRAL π MESONS*

Yu. A. BUDAGOV, S. WIKTOR, V. P. DZHELEPOV, P. F. ERMOLOV, and V. I. MOSKALEV

Joint Institute for Nuclear Research

Submitted to JETP editor September 18, 1959

J. Exptl. Theoret. Phys. (U.S.S.R.) **38**, 1047-1052 (April, 1960)

Twenty seven charge-exchange scattering events with subsequent decay $\pi^0 \rightarrow e^- + e^+ + \gamma$ were recorded in a hydrogen-filled diffusion cloud chamber located in a magnetic field and operating in 128-Mev and 162-Mev negative pion beams. The probability for this decay relative to that for the usual decay is found to be 0.0117 ± 0.0015. Results of measurements of the momenta and angles of the electron-positron pairs are presented. The experimental energy characteristics of the pairs and angular distributions are in satisfactory agreement with theory.

INTRODUCTION

THE decay of a neutral pion into an electron-positron pair and a photon

$$\pi^0 \rightarrow e^- + e^+ + \gamma \tag{1}$$

was first discussed theoretically by Dalitz.[1] This alternate decay mode may be interpreted as internal conversion of one of the photons in the field of the other. Dalitz, and later Kroll and Wada,[2] used quantum electrodynamics to calculate the internal conversion coefficient and the principal energy and angle characteristics of such decays. The results of these calculations depend only weakly on the form of the meson theory. Kerimov et al.[3] recently calculated the probability for the decay (1) taking into account the spin states (longitudinal polarization) of the electron-positron pair and the photon. Experimentally this decay was studied by a number of authors,[4-7] but with comparatively low accuracy. It was therefore considered important to study the reaction (1) further with the purpose of obtaining more accurate results.

We report here on data based on the study of 27 events representing the $\pi^0 \rightarrow e^- + e^+ + \gamma$ decay, found in a diffusion cloud chamber operating in 128-Mev and 162-Mev negative pion beams. The results of a preliminary analysis of 14 such decays were reported by us previously.[8]

The chamber was filled with hydrogen at a pressure of 25 atmos and placed in a constant magnetic field of 9000 gauss. The experimental setup, the operating conditions in the negative pion beams, and the method of analysis have already been described in more detail previously.[9,10] The neutral pions were obtained by charge-exchange scattering. The indicated 27 cases of the decay (1) were found after scanning twice approximately 90,000 stereo photographs and were identified by π^- meson tracks ending in the gas inside the chamber and accompanied by the emission of an electron-positron pair. Photographs of two such cases are shown in Fig. 1. It should be noted that all the pairs found were assumed to be due to internal conversion, since as a result of the low stopping power of gaseous hydrogen the probability for the appearance of one pair in the present experiment, produced by a photon from the $\pi^0 \rightarrow 2\gamma$ decay, at a distance less than 1 mm from the decay point (external conversion) amounts to 7×10^{-5}.

DETERMINATION OF THE INTERNAL CONVERSION COEFFICIENT

The relative probability for the decay mode (1) for a neutral pion is given by the expression

$$2\rho_0 = \frac{w(\pi_0 \rightarrow e^- + e^+ + \gamma)}{w(\pi^0 \rightarrow 2\gamma)} = \frac{2\alpha}{3\pi}\left[\ln\left(\frac{m_{\pi^0}^2}{m_e^2}\right) - \frac{7}{2}\right] = 0.0118, \tag{2}$$

where α is the fine structure constant. The results of experimental determinations of the coefficient $2\rho_0$ are collected in Table I. The data on $2\rho_0$ of Daniel et al.[4] and Anand[5] were obtained by scanning nuclear emulsions exposed to cosmic rays, where the number of neutral pions produced in a star could not be determined with sufficient accuracy. The value for $2\rho_0$ found by Lindenfeld et al.[6] using counters is also of comparatively low accuracy. Sargent et al.[7] obtained the internal

*Reported at the VI session of the Scientific Council of the Joint Institute for Nuclear Research (May 1959) and at the Kiev Conference on High-Energy Physics (July 1959).

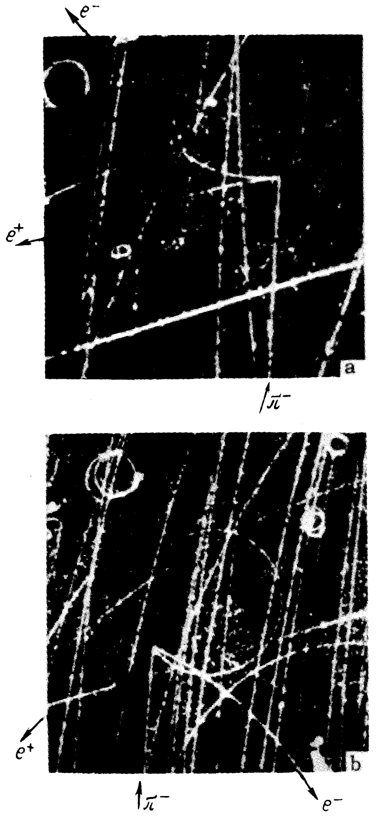

FIG. 1. Photographs of $\pi^- + p \rightarrow \pi^0 + n$ followed by the decay $\pi^0 \rightarrow e^- + e^+ + \gamma$ obtained with a hydrogen diffusion chamber: a – pair No. 3, b – pair No. 6.

TABLE I

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

conversion coefficient by working with slow π^- mesons, which stopped in a hydrogen diffusion chamber. The main difficulty in determining $2\rho_0$ by this method lies in the identification of the pairs due to the π^0 decay and the internal conversion pairs from the reaction $\pi^- + p \rightarrow n + \gamma$. Furthermore, the quantity $2\rho_0$ was found in that work under the assumption that the Panofsky ratio P is 0.94. If one takes for P the value 1.5 – 1.8, as determined more recently,[11] then the value of the coefficient $2\rho_0$, calculated from the data of Sargent et al., will be in disagreement with its theoretical value and other experimental data.

The method for determining the internal conversion coefficient adopted in this work makes use of fast negative pions, when the number of pairs due to internal conversion of photons from the reaction $\pi^- + p \rightarrow n + \gamma$ amounts to only 1% of the number of $\pi^0 \rightarrow e^- + e^+ + \gamma$ decays. Therefore the contribution from such pairs may be neglected in the computation of the coefficient $2\rho_0$.

In addition the number of π^0 mesons decaying in the usual way (into two photons) can be accurately determined from the number of elastic scattering events and the known ratio of elastic and charge-exchange scattering cross sections. The direct determination of the number of charge-exchange events is extremely difficult in a diffusion chamber due to local insensitive regions and edge effects.

The coefficient $2\rho_0$ is determined from the formula

$$2\rho_0 = \frac{N_{\text{pair}}}{N_{\text{el}}} \frac{\sigma_{\text{el}}}{\sigma_{\text{total}} - \sigma_{\text{el}}} \frac{\eta_{\text{el}}}{\eta_{\text{pair}}}, \tag{3}$$

where N_{pair} and N_{el} are the number of decay and elastic scattering events respectively; σ_{total} is the total cross section for the $\pi^- p$ interaction; σ_{el} is the total elastic $\pi^- p$ scattering cross section; η_{pair} and η_{el} are the efficiencies for the observation of events corresponding to the decay (1) and to elastic scattering.

The same selection criteria were applied to the pairs from π^0 decays as were used for elastic $\pi^- p$ scattering.[10] These criteria were satisfied by 26 pairs and 1285 elastic scattering events. A correction was made in the number of elastic scattering events connected with Coulomb scattering and the interference between Coulomb and nuclear scattering. For σ_{total} and σ_{el} entering into Eq. (3) we took the average values of total $\pi^- p$-interaction cross sections[12] and total elastic cross sections,[10] weighted by the number of elastic scattering events at 128 Mev and 162 Mev.

The detection efficiency for elastic $\pi^- p$ scattering events was determined from missed events, whose tracks lie in a plane close to the vertical, and was found to be 90%; the pair detection efficiency was assumed to be the same. The relative probability for the decay (1), as calculated from Eq. (3) with the above remarks taken into account, was found to be $2\rho_0 = 0.0117 \pm 0.0015$, and the internal conversion coefficient for photons from the π^0 decay was found to be $\rho_0 = 0.0058 \pm 0.0008$, where the indicated errors are statistical probable errors. This value for $2\rho_0$ is in good agreement with the theoretical value (2).

ANGLE AND ENERGY CHARACTERISTICS OF THE PAIRS

Table II shows the results of the analysis of the 27 electron-positron pairs found in this work. The total energy of the electron, the positron, and the pair are listed in the first three columns of the table. In the following columns are listed the cor-

TABLE II

Pair No.	E^-, Mev	E^+, Mev	$E=E^-+E^+$, Mev	α, degrees (l.s.)	θ, degrees (l.s.)	θ^*, degrees (c.m.s.)
1	—	—	—	2.5	118	128
2	>192	46	>238	16	50	60
3	19	41	60	36	95	107
4	148	>74	>222	7	91	103
5	20	111	131	8	145	151
6	27	6	33	22	117	127
7	89	67	156	6	50	60
8	>14	>96	>110	5	100	111.5
9	—	—	—	2	110	121
10	75	105	180	53	140	147
11	39	>152	>191	3	99	111
12	10	24	34	38	86	98
13	166	20	186	28	65	75
14	22	27	49	46	118.5	128.5
15	33	40	73	25	76	88
16	25	>51	>76	20	101	112.5
17	7.3	52	59.3	5	119	129
18	23	>122	>145	2	89	101
19	79	27	106	29	44	53
20	42	14	56	17.5	97	108
21	—	32	>32	25	90	102
22	16	187	203	13	92	104
23	45	47	92	32.5	62	73
24	>67	79	>146	5	91	103
25	21	65	86	74	93	105
26	39	29	68	10.5	54	64
27	63	41	104	8	141	148

relation angles α (i.e., the angle between the positron and the electron) in the laboratory frame, and also the angle θ between the direction of the total momentum of the pair and the direction of motion of the π^- meson in the laboratory system (l.s.) and the corresponding angle θ^* in the center-of-mass system (c.m.s.). Momenta (energies) were measured with an accuracy of $\sim 10\%$, whereas angles were measured with an accuracy of 1°. In the case of very short tracks only lower limits for the corresponding energies are listed in the table. Events 1 and 9 were found in emulsions exposed without the magnetic field.

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

1. The experimental distribution of pairs $n(\alpha)$ in correlation angles α is shown in Fig. 2. The solid line in Fig. 2 represents the theoretical form for this distribution as obtained by Dalitz (private communication) in the rest system of the π^0. For angles $\alpha > 2°$ this distribution is of the form $n(\alpha)d\alpha \sim d\alpha/\alpha$. If the velocity of the π^0 meson is taken into account the distribution is shifted only insignificantly in the direction of smaller angles and it therefore follows from Fig. 2 that the experimental distribution is not in contradiction with theory.

In the rest frame of the neutral pion, half of the pairs should be emitted with a correlation angle less than $\alpha_{1/2} = 18.1°$ (according to Dalitz). In this work we found for $\alpha_{1/2}$ the value 16°.

2. The distribution of the pairs in the parameter

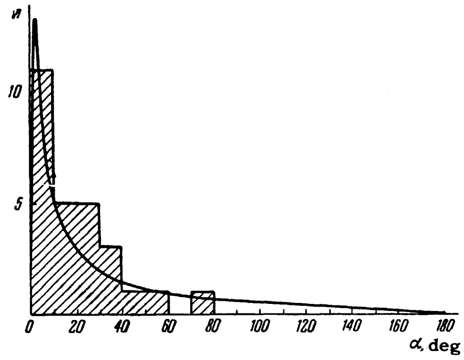

FIG. 2. The distribution of pairs from the decay $\pi^0 \to e^- + e^+ + \gamma$ in correlation angle α (l.s.). The solid curve refers to the theoretical distribution in the π^0 rest frame as obtained by Dalitz (private communication)

$$y = |p_{e^-} - p_{e^+}| / |\mathbf{p}_{e^-} + \mathbf{p}_{e^+}|, \quad (4)$$

where $\mathbf{p}_{e^-}$ and $\mathbf{p}_{e^+}$ are the momenta of the electron and positron in the laboratory frame, is shown in Fig. 3 in the form of a histogram. This parameter characterizes the division of energy between the particles of a pair. The smooth curve represents the theoretical distribution in the parameter y in the rest frame of the neutral pion, as obtained by Kroll and Wada. The parameter y depends only weakly on the velocity of the π^0 meson. It is seen from the figure that the distribution of pairs in the parameter y is in agreement with theory and there is no tendency for the particles in a pair to share the energy equally, as suggested by the results of Sargent et al.[7] and particularly strongly by the results of Anand.[5]

3. An important theoretical characteristic of

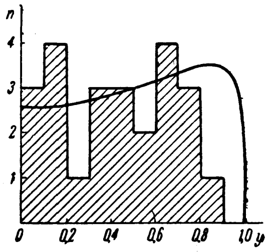

FIG. 3. The distribution of pairs in the parameter y. The solid curve refers to the theoretical distribution.[2]

the pairs from the decay (1) is their distribution in the parameter

$$x = (E^- + E^+)^2 - (\mathbf{p}_{e^-} + \mathbf{p}_{e^+})^2, \qquad (5)$$

where E^-, E^+, $\mathbf{p}_{e^-}$, and $\mathbf{p}_{e^+}$ are the total energies and momenta of the electrons and positrons. The parameter x is an invariant and can be interpreted as the degree to which the intermediate photon, which converts into the pair, is virtual, or as the square of the "rest mass" of the virtual photon. On the assumption that the linear dimensions of the currents responsible for the electromagnetic radiation in the decay of the π^0 are small compared to $2\hbar/m_\pi c$, the following distribution was obtained by Dalitz:[1]

$$f(x) = \frac{x + 2m_e^2}{x^2}\left(\frac{x - 4m_e^2}{x}\right)^{1/2}(m_\pi^2 - x)^3. \qquad (6)$$

This distribution is shown in Fig. 4 by the solid curve; the histogram shows the pair distribution in the parameter x based on the results of this work.

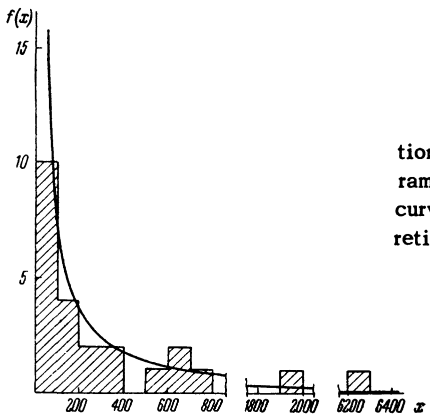

FIG. 4. The distribution of pairs in the parameter x. The solid curve refers to the theoretical distribution.[1,2]

It can be seen that the majority of pairs has small values of x. This means that the intermediate photon is virtual to a small degree only, i.e., the characteristics of the internal conversion pairs from the decay (1) should not be very different from the characteristics of pairs produced by real photons (external conversion). Consequently the angular distribution of the pairs should practically coincide with the angular distribution of photons from the decay $\pi^0 \to 2\gamma$. In Fig. 5 we show in the form of a histogram the angular distribution of pairs in the angle θ^* in the π^--p center-of-mass frame

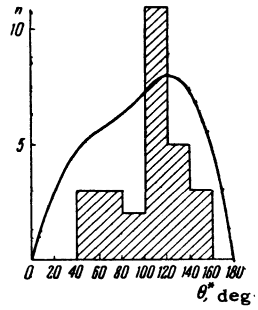

FIG. 5. Angular distribution of the pairs relative to the direction of of the π^- mesons in the π^--p center-of-mass system. The solid curve refers to the angular distribution $\sin\theta^*\, d\sigma/d\Omega$ (in an arbitrary scale) of photons from the decay of neutral pions produced in the reaction $\pi^- + p \to \pi^0 + n$ by 150-Mev π^- mesons.[13]

obtained in this work. It is seen that this distribution is not in contradiction with the solid curve which represents $(d\sigma/d\Omega)\sin\theta^*$ (arbitrary scale) and corresponds to the photon angular distribution from the decay of π^0 mesons obtained from the reaction $\pi^- + p \to \pi^0 + n$ with 150 Mev π^- mesons.[13]

The total energies of the pairs $E = E^- + E^+$ are, as was to be expected, contained in the interval 17 — 270 Mev, corresponding to the limits of the calculated energy spectrum of photons from the decay of neutral pions produced by the charge-exchange process.

In conclusion, it should be noted that in the scanning of the photographs one event was found corresponding to the decay of a π^0 according to the mode $\pi^0 \to e^- + e^+ + e^- + e^+$.[9] Not one of the 27 pairs has kinematics in agreement with the decay mode $\pi^0 \to e^- + e^+$, the relative probability of which is of order 10^{-7} according to estimates by Drell.[14]

The authors are grateful to Prof. R. Dalitz for communicating some unpublished theoretical calculations.

[1] R. H. Dalitz, Proc. Phys. Soc. **A64**, 667 (1951).

[2] N. M. Kroll and W. Wada, Phys. Rev. **98**, 1355 (1955).

[3] Kerimov, Mukhtarov, and Gadzhiev, JETP **37**, 575 (1959), Soviet Phys. JETP **10**, 407 (1960).

[4] Daniel, Davies, Mulvey, and Perkins, Phil. Mag. **43**, 753 (1952).

[5] B. M. Anand, Proc. Roy. Soc. **A220**, 183 (1953).

[6] Lindenfeld, Sachs, and Steinberger, Phys. Rev. **89**, 531 (1953).

[7] Sargent, Cornelius, Rinehart, Lederman, and Rogers, Phys. Rev. **98**, 1349 (1955).

[8] Budagov, Viktor, Dzhelepov, Ermolov, and Moskalev, JETP **35**, 1575 (1958), Soviet Phys. JETP **8**, 1101 (1959).

[9] Budagov, Viktor, Dzhelepov, Ermolov, and Moskalev, JETP **36**, 1080 (1959), Soviet Phys. JETP **9**, 767 (1959).

[10] Budagov, Viktor, Dzhelepov, Ermolov, and Moskalev, Reported by Pontecorvo at the Confer-

ence on High Energy Physics, Kiev, July 1959; JETP **38**, 734 (1960), Soviet Phys. JETP **11**, 531 (1960).

[11] Fischer, March, and Marshall, Phys. Rev. **109**, 533 (1958); E. L. Koller and A. M. Sachs, Bull. Am. Phys. Soc. **4**, 24 (1959).

[12] Klepikov, Meshcheryakov, and Sokolov, Conference on High Energy Physics, Kiev, July 1959.

[13] Ashkin, Blaser, Feiner, and Stern, Phys. Rev. **101**, 1149 (1956).

[14] S. D. Drell, Nuovo cimento **11**, 693 (1959).

Translated by A. M. Bincer
211