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Abstract

An event of charge-exchange scattering $\pi^- + p \to \pi^0 + n$ with subsequent decay $\pi^0 \to e^- + e^+ + e^- + e^+$ has been observed in scanning the photographs obtained in the hydrogen-filled diffusion cloud chamber placed into magnetic field and exposed to the 160 Mev π^--meson beam. One decay of this mode was detected in per 2500 events of π^0-meson decays via the usual scheme $\pi^0 \to 2\gamma$. The estimation of the π^0-meson mass gives the value 141 ± 8 Mev. In the rest system of π^0-meson the opening angles of pairs are equal to 7^0 and 12^0, and the angle between the pair planes does not exceed 37^0. The other possible interpretations of the event observed have a very small probability.

Introduction

As is known, besides the usual decay

$$\pi^0 \to 2\gamma \tag{1}$$

on the average about one π^0-meson in 80 decays via the scheme suggested by Dalitz[1]:

$$\pi^0 \to e^- + e^+ + \gamma \tag{2}$$

This mode of decay may be interpreted to be an internal conversion of one of γ-rays in the field of another γ-ray. The process of a double internal oonversion is also possible; it leads to π^0-meson decay into two electron-positron pairs:

$$\pi^0 \to e^- + e^+ + e^- + e^+ \tag{3}$$

According to the theoretical calculations[2] the probability of the decay (3) with respect to the usual deoay (I) is equal to 3.47×10^{-5} (if the π^0-meson spin is zero). All the particles produced by the decay of π^0-mesons via decay scheme (3) are charged and so, they are easily detected in the cloud or bubble chamber. Therefore, the observation of such decays in the chamber can give an important information on π^0-meson properties. Thus, measuring the momenta of all four eleotrons from the curvature radii in the magnetic field one oan determine the mass of π^0-meson and the investigation of the angular oorrelation between the pair planes makes it possible to find directly a spin and a parity of π^0-meson [2,3]. However, due to the extremely small probability the systematic experimental investigation of the process (3) is rather difficult. We know only one case of such a decay which was described in the literature. Investigating the production of heavy unstable particles in cosmic rays with a controlled cloud chamber Hodson, Ballam, Arnold et al.[4] have found an event whioh kinematics is consistent with that of the decay $K^+ \to \pi^+(\mu^+) + \pi^0 + Q$, $\pi^0 \to e^- + e^+ + e^- + e^+$. Sinoe in this investigation only 60 $V^{\pm}$-decays were registered and not in all of them π^0-mesons were produced, the probability of the decay (3) detection was very small. As the authors themselves note the deteotion of the decay (3) under the oonditions of their experiment in whioh not a single event of more probable decay (2) was registered, is unusual statistical fluctuation. The opening angles between an electron and a positron in the case[4] turned out to be so small (0.5° and 1.7° in the lab.system) that it was not possible to determine the angle between pair planes.

The present paper deals with the event of charge-exchange scattering $\pi^- + p \to \pi^0 + n$ with the subsequent decay $\pi^0 \to e^- + e^+ + e^- + e^+$ registered in the diffusion cloud chamber (Fig I.).

EXPERIMENTAL DETAILS

The photograph of the decay described here was taken in the course of investigation of the π^--meson scattering by protons in the diffusion cloud chamber filled with hydrogen up to 25 atmospheres. The inside diameter of the chamber was 380 mm, the sensitive volume heigth at 7 deg/cm temperature gradient was equal to 6-7 cm. The cloud chamber was placed into the constant magnetic field of 9000 gauss (at the center of the sensitive volume). The magnetic field variation in the sensitive volume of the chamber does not exceed with height 3,5% and with radius 2,5%. The topography of the magnetic field was taken with the help of a magnetometer operating on the principle of the Hall effect and callibrated by the proton resonance method*). The photographs were taken by a stereophotocamera with two objectives " Гелиос-37" (f=62mm) on Панхром-X 35 mm film of sensitivity equal to 1000 units ГОСТ. The objectives "Гелиос-37" were corrected for the distortion arising in photographing through the upper glass windows of the chamber 25 mm thick and had the resolution 50 lines/mm in the center of the field of vision. The base of the stereophotocamera is equal to 120 mm, the object distance is about I meter.

The diffusion cloud chamber was exposed to the beam of π^--mesons of 160 Mev mean energy from the Joint Institute for Nuclear Researoh synchrooyolotron. The beam intensity was kept so that in the average 30-40 tracks of π^--mesons were registered in each photograph. The operation cycle of the chamber was equal to 8 sec. In the set of expositions about 90000 stereophotographs were taken; in scanning them besides 1400 events of the elastic $\pi^- p$-scattering, 26 events of charge-exchange scattering with the following decay $\pi^0 \to e^- + e^+ + \gamma$, the event $\pi^- + p \to \pi^0 + n$, $\pi^0 \to e^- + e^+ + e^- + e^+$ discussed here was found. The results of treatment of 14 decays $\pi^0 \to e^- + e^+ + \gamma$ were published by us earlier |6|.

MEASUREMENT PROCEDURE AND RESULTS

As is seen from Fig. I. which gives the stereophotograph of the event analyzed the track of one of π^--mesons |I| passing through the chamber cuts off inside the sensitive layer, and from the cut-off point four particles of the ionization close to jinimum are emitted: two of them being positive |3 and 5| and two- negative |2 and 4|.

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*) We wish to thank D.P. Vasilevskaja and Yu.N. Denisov for their permission to use this devioe.

The event was measured by the reprojection method. The device and the main characteristics of the reprojector are analogous to those described in the paper [7]. The following measurements were made directly by the reprojection method:

1) the curvature radii of all five tracks;

2) angles α between an insident π^--meson and each decay particle;

3) azimuthal angles β of each decay particle;

4) depth angles γ, that is, angles between the direction of a particle and the horisontal plane. Angles α, β and γ for one decay particle are schematically shown in Fig. 2.

Curvature radii of the tracks were measured with the help of pattern as well as by the coordinate method using the microscope УИМ-22. Both methods of measurement have given equal results within the experimental errors. The measurement accuracy of the curvature radius of each track depends upon the value of curvature, the length and the direction of the track in space. Corrections for inhomogeneity of the magnetic field (~2%) and for the film shrincage (~1%) were introduçed into the values of particle momenta which were obtained from the measured radii and depth angles γ. Corrections due to distortion of the optical system and to the fact that the track image on the film is the conical projection of the real track, were not taken into account in the coordinate method measurements because they were very small. The estimates showed that the multiple scattering of particles in the gas of a chamber as well as bremsstrahlung radiation had no importance here.

Table I presents the values of the curvature radii obtained as the average measurement data on the two photos of a stereopair by the reprojection and coordinate methods as well as the corresponding particle momenta. Errors indicated for radii are the maximum measurement errors. For momenta the total errors are given taking into account the inaccuracy of measurements of the curvature radii and depth angles, and the inambiguity connected with introducing corrections.

Table I

Nubmer of tracks	Particle	Curvature radius (cm)	Momentum (Mev/c)
I	π^-	105 ± 5	272 ± 16
2	e^-	20 ± 4	72 ± 18
3	e^+	3.75 ± 0.15	13.9 ± 0.7
4	e^-	4.2 ± 0.1	15.8 ± 0.5
5	e^+	29 ± 3	100 ± 13

Ionization density caused by particles in the chamber was estimated visually, and for all the particles did not exceed more than 1.5 times the minimum one. The comparison of the obtained particle momenta with their ionization shows that all the decay particles are electrons.

The measured angles α, β and γ are listed in Table II. The accuracy of the angle measurement is equal to $\pm 1^\circ$. Corrections for angles due to the film shrincage are negligibly small.

Table II

Track number	Particle	α	β	γ
2.	e^-	138°	84°	42°
3	e^+	138°	94°	42°
4	e^-	127°	-56°	-41°
5	e^+	128°	-48°	-36°

The direction and the value of the total momentum of all four electrons is easily obtained from the measured electron momenta and angles α and β : $P_t = (147 \pm 26)$ Mev/c; $\alpha_t = 153 \pm 2^\circ$, the total energy of all the electrons being 202 ± 32 Mev. It follows from the kinematics of the process $\pi^- + p \to \pi^\circ + n$ at the kinetic π^--meson energy 166 ± 14 Mev (this corresponds to the measured π^--meson momentum 272 ± 16 Mev/c) that π°-meson emitted at the angle $153^\circ \pm 2^\circ$ must have the momentum 163 ± 7 Mev/c and the total energy 212 ± 6 Mev. Thus, four electrons are kinematically equivalent to π°-meson emitted in the reaction $\pi^- + p \to \pi^\circ + n$ at the angle $153^\circ \pm 2^\circ$.

Relatively large errors in the value of the total energy and the total momentum of the four electrons make it possible to estimate only roughly π°-meson mass. However, taking into account some kinematic relations connecting π°-meson mass with the measured values of momenta and angles we can make the π°-meson mass more definite. This value which is found to be 141 ± 8 Mev agrees within the experimental errors with usually accepted mass of 135 Mev.

Table III gives the angles between particles and pair planes calculated in the laboratory system and the rest system of π°-meson as well as electron momenta in the rest system of π°-meson. To calculate these values such limits of the variation of particle momenta within the experimental errors indicated in Table I were taken which kinematically corresponds to π°-meson mass 135 Mev.

Table III

Track number	Particle	Lab. system		Rest system of π°-meson		
		Angle between particles	Angle between planes	Momentum (Mev/c)	Angle between particles	Angle between planes
2	e^-	$\theta_{23}^{lab} = 6.5 \pm 1^\circ$	$\varphi^{lab} = 75^\circ \pm 10^\circ$	56.1	$\theta_{23} = 7 \pm 2^\circ$	$\varphi < 37^\circ$
3	e^+			11.9		
4	e^-	$\theta_{45}^{lab} = 6.5 \pm 1.5^\circ$		9.0	$\theta_{45} = 12 \pm 4^\circ$	
5	e^+			58.7		

In the rest system of π^o-meson the decay particles produce two electron-positron pairs with small angles between an electron and a positron (Table III) and with equal and oppositively directed momenta; the sum of momentum projections on the coordinate axis being balanced with great accuracy. (In principle one can consider the event observed to be π^o-meson decay into two electron-positron pairs with an opening angle close to 180^o. However, according to [1] the emission of such two wideangle pairs as a result of the internal conversion is about 400 times less probable than that of a pair with angles $\sim 10^o$).

As the opening angles θ between pair particles are comparatively small, the angle between pair planes can be determined only with great error . The calculations show that in the rest system of π^o-meson its value does not exceed 37^o although the angles close to 90^o are more probable for a pseudoscalar meson.

POSSIBLE EXAMPLES OF THE OTHER INTERPRETATIONS

We shall consider a number of possible explanations of the event observed.

a) Let π^o-meson resulting from charge-exchange scattering decays via the scheme(I) into two γ-rays which are converted then into electron-positron pairs at such a close distance from the decay point of π^o-meson that it cannot be resolved in the photograph. The probability of both γ-rays conversion into hydrogen of the chamber within I mm (the track width is~0.5 mm) is equal to 2.2×10^{-12}. As on all the films 1400 events of the elastic $\pi^- p$-scattering were detected, and the ratio of cross sections for charge-exchange and elastic π^--p scattering for these energies is 1.8 [6], the total number of π^o-mesons decayed in the chamber is equal to 2500. Thus, in our experiment, the probability of observation of both γ-rays conversion within I mm is equal to 5.5×10^{-9}.

b) If the π^o-meson decays via the scheme (2) and then γ-ray is converted within I mm from the decay point of π^o- meson, the probability of observation of such an event in our experiment amounts to 4.7×10^{-5}.

c) The kinetic energy of π^--meson 166 $\pm$ 14 Mev exceeds a little the threshold of the reaction $\pi^- + p \rightarrow \pi^o + \pi^o + n$ which is equal to 160 Mev. Therefore, when π^o-mesons produced in this reaction decay via the scheme (2) we can observe the event analogous to that under consideration. According to the rough estimation in which the use was made of the cross section for the above reaction 7×10^{-30} cm^2, calculated for the π^--meson energy 260 Mev [8], the probability of the detection of such events is much more less than 9×10^{-5}. The extremely good agreement of the kinematics of the event observed with that of the decay (3) contradict also this interpretation.

d) According to the estimation [2] only one π^o-meson out of 29000 decays via the scheme (3). Consequently, the probability of observation of such a decay from the experimental data electrons.

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d) According to the estimation [2] only one π^0-meson out of 29000 decays via the scheme (3). Consequently, the probability of observation of such a decay from the experimental data obtained here is about 0.09. The comparison of this value with those of a),b),c) as well as a good agreement with kinematics leave no doubt in the validity of observation of the decay $\pi^0 \to e^- + e^+ + e^- + e^+$.

Conclusion

As it was stated above, in decaying the π^0-meson into two electron-positron pairs, there exists a certain angular correlation between pair planes the investigation of which makes it possible to determine the spin and parity of the π^0-meson. The correlation function is

$$W(\varphi) \sim 1 + \lambda \cos 2\varphi,$$

where φ is the angle between pair planes. Kroll and Wada[2] have found that for π^0-meson spin 0 the coefficient of correlation λ is equal to $\pm$ 0.19. Here the sign "plus" reffers to an even π^0-meson, "minus" - to an odd one. The oorrelation is much more larger than that between planes of pairs produced by γ-rays from the reaction $\pi^0 \to 2\gamma$ [9,10]. In the paper by Joseph[3]*) the angular correlation for spin and parity of π^0-meson 2 $\pm$ was analyzed and it was shown that in this case $|\lambda| < 0.19$.

Thus, even in the most favourable case $|\lambda| = 0.19$ it is necessary to observe relatively large number of decays (3) (of the order of some hundreds) to draw definite conclusions concerning the spin and parity of π^0-mesons on the base of this experimental data. Although such an experiment takes a lot of time it can be performed if increasing the efficiency of the decay detection by observing $\pi^- p$ -capture in a liquid hydrogen bubble chamber.

In conclusion the authors express their gratitude to D.V. Shirkov for discussing this problem, L.I. Krasnoslobodtseva, T.S. Sazhneva and Yu.I. Saikina for scanning the photographs.

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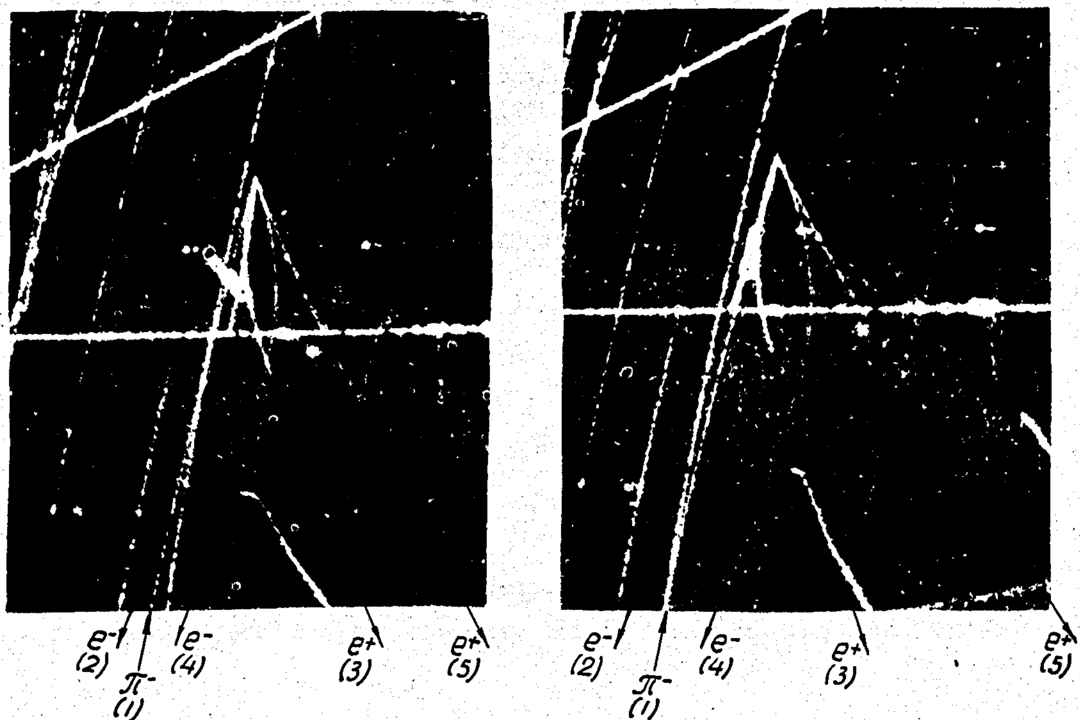

Fig. 1. Stereophotograph of the event of charge-exchange scattering $\pi^- + p \rightarrow \pi^0 + n$ with the subsequent decay $\pi^0 \rightarrow e^- + e^+ + e^- + e^+$ taken in the hydrogen-field diffusion cloud chamber.

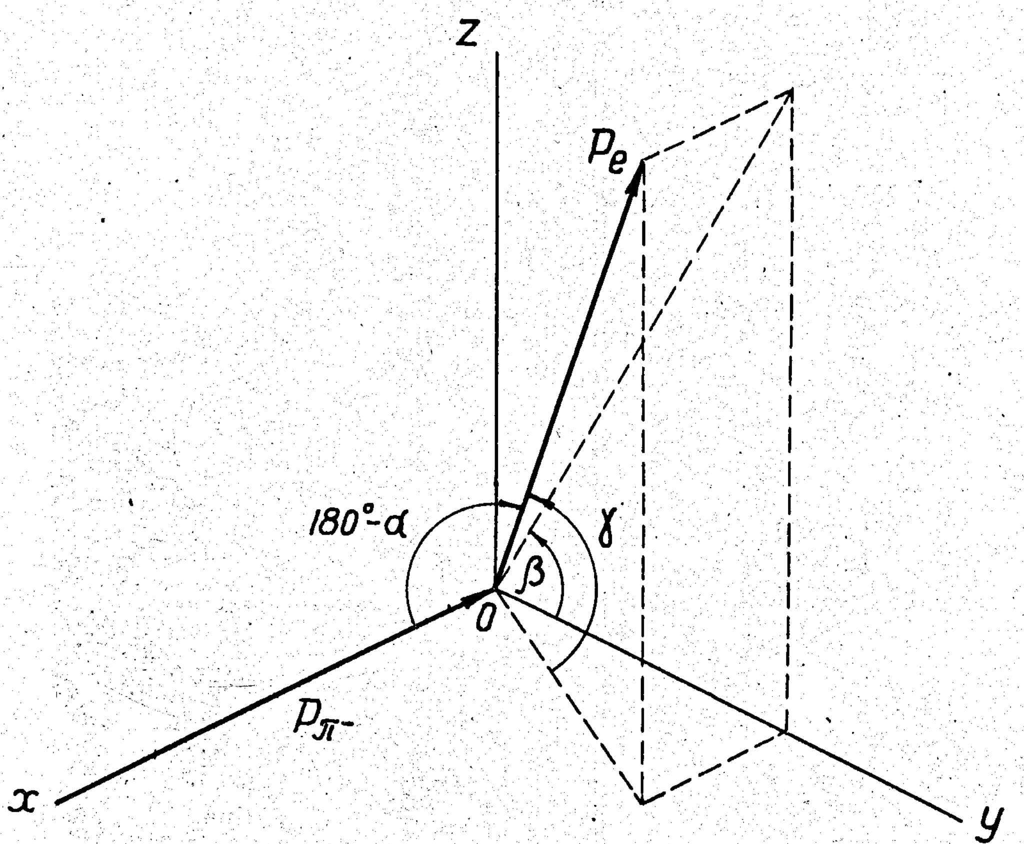

Fig. 2. Angles α, β and γ for one decay particle.