OBSERVATION OF THE $\pi^0 \to e^- + e^+ + e^- + e^+$ DECAY

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An event of charge-exchange scattering, $\pi^- + p \to \pi^0 + n$, with subsequent decay, $\pi^0 \to e^- + e^+ + e^- + e^+$, was detected on a photograph taken in a hydrogen diffusion chamber located in a magnetic field and bombarded with 160-Mev π^- mesons. One decay of this type was detected per 2500 π^0-meson decays of the usual $\pi^0 \to 2\gamma$ type. The π^0-meson mass is estimated as 141 ± 8 Mev. In the rest system of the π^0 meson, the angle between the electrons and positrons of the pairs are 7° and 12°, and the angle between the planes of the pair does not exceed 37°. Other possible explanations of the observed event seem to be very improbable.

INTRODUCTION

It is known that in addition to decaying in the usual manner

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

approximately one out of 80 π^0 mesons decays by the scheme proposed by Dalitz[1]

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

Such a decay can be interpreted as the internal conversion of one of the γ quanta in the field of the other γ quantum. Another possible process is double internal conversion of the gamma quanta, leading to the decay of the π^0 meson into two electron-positron pairs:

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

Kroll and Wada[2] theoretically estimated the probability of decay (3), relative to the usual decay (1), to be 3.47×10^{-5} (if the π^0-meson spin is zero). All particles produced when the π^0-meson decays according to (3) are charged, and are thus readily recorded by diffusion or bubble chambers. The observation of such decays in a chamber can therefore yield much important information on the properties of the π^0 meson. Thus, by measuring the momenta of all four particles (by measuring the radii of curvature in a magnetic field), we can determine the mass of the π^0 meson, while the spin and parity of the π^0 meson can be found by direct experiment from a study of the angular correlation between the planes of both pairs. However, in view of the exceedingly low probability, a systematic experimental investigation of process (3) involves certain difficulties. We know of only one description of such a decay in the literature. Hodson, Ballam, Arnold, et al.,[4] in a study of the production of heavy unstable particles in cosmic rays (by means of a controllable cloud chamber), discovered an event, the kinematics of which agrees with the decay $K^+ \to \pi^+(\mu^+) + \pi^0 + Q$, $\pi^0 \to e^- + e^+ + e^- + e^+$. Since only sixty $V^\pm$ decays were recorded in this investigation, and furthermore since π^0 mesons were produced only in some of these events, the probability of observing a decay of type (3) was very small. The authors themselves remark that the appearance of a decay of type (3) under the conditions of their experiment, in which not one event of the more probable decay (2) was observed, is an unusual statistical fluctuation. The angles between the electrons and positrons of the pairs, in the event described in reference 4, were so small (0.5 and 1.7 deg in the laboratory system), that the angle between the planes of the pairs could not be determined.

We describe in this article an event of charge-exchange scattering, $\pi^- + p \to \pi^0 + n$, with subsequent decay $\pi^0 \to e^- + e^+ + e^- + e^+$, registered in a diffusion chamber (Fig. 1).

CONDITIONS OF THE EXPERIMENT

A photograph of the decay described was obtained in an investigation of the scattering of π^- mesons by protons, using a diffusion chamber filled with hydrogen at a pressure up to 25 atmos.[5] The inside diameter of the chamber was 380 mm, and the height of the sensitive volume was 6 to 7 cm, at a temperature gradient of 7 deg/cm. The chamber was placed in a 9000-gauss dc magnetic field, uniform to within ±3.5% over the height of the sensitive volume and to within ±2.5% over the

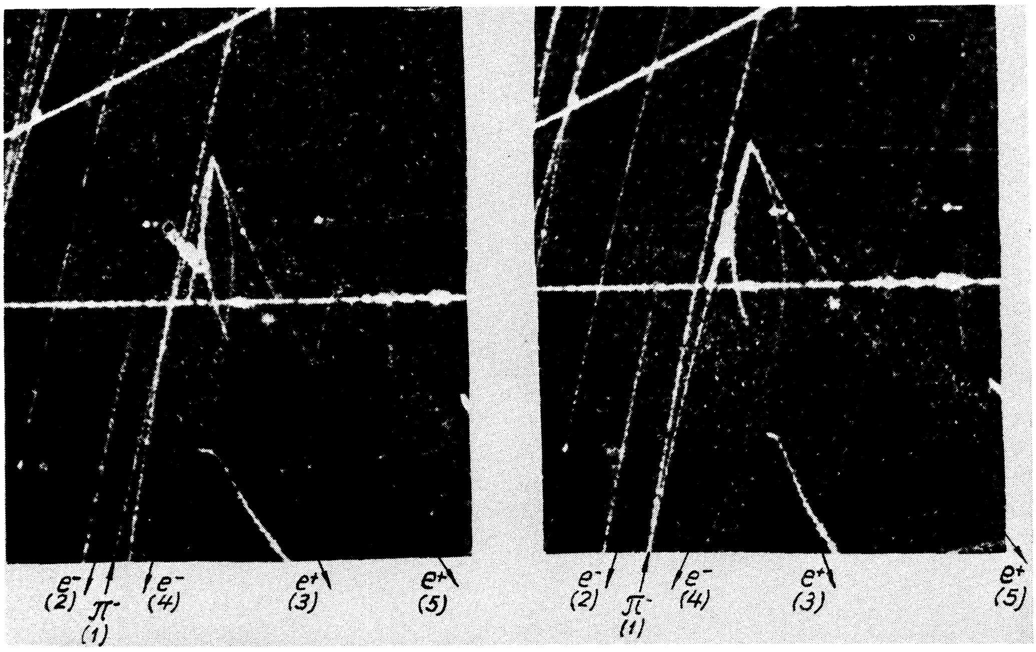

FIG. 1. Stereophotograph of an event of charge-exchange scattering $\pi^- + p \to \pi^0 + n$ with subsequent decay $\pi^0 \to e^- + e^+ + e^- + e^+$, obtained with the aid of a hydrogen diffusion chamber.

radius. The topography of the magnetic field was plotted with a magnetometer operating on the Hall-effect principle and calibrated by the proton-resonance method.* The photographs were taken with a stereo camera with two GOI (State Optical Institute) "Gelios-37" lenses of 62 mm focal length, on Pankhrom-Kh 35-mm film of speed 1000 GOST units. The "Gelios-37" objectives were corrected for the distortion arising when photographing through the 25-mm thick glass upper windows of the chamber; their resolution at the center of the field of view was 50 lines/mm. The base of the stero camera was 120 mm long, and the taking distance was approximately 1 m.

The camera was exposed in a beam of π^- mesons with an average energy of 160 Mev, obtained from the synchrocyclotron of the Joint Institute for Nuclear Research. The beam intensity was maintained such as to produce on each photograph an average of 30 to 40 π^--meson tracks. Approximately 90,000 stereo-photographs were obtained in the series of exposures. The scanning of these photographs disclosed the aforementioned case of $\pi^- + p \to \pi^0 + n$, $\pi^0 \to e^- + e^+ + e^- + e^+$, along with 1400 cases of elastic scattering of π^- mesons by protons and 26 cases of charge-exchange scattering with subsequent decay $\pi^0 \to e^- + e^+ + \gamma$. In a previous communication[6] we reported the results of processing 14 $\pi^0 \to e^- + e^+ + \gamma$ decay events.

PROCESSING AND RESULTS

As can be seen from Fig. 1, which is a stereo photograph of the analyzed case, the track (1) of one of the π^- mesons, passing through the chamber, stops inside the sensitive volume and four particles, with ionization close to minimum, are emitted into the rear hemisphere. Two of these (3, 5) are positively charged, and the other two (2,4) are negative.

We processed this case by the re-projection method. The construction and principal characteristics of the re-projector are analogous to those described in reference 7. The following were measured directly on the re-projector: 1) the radii of curvature of all five tracks, 2) the angles α between the incident π^- meson and each decay particle, 3) the azimuth angles β of each decay particle; 4) the depth angles γ, i.e., the angles between the direction of particle motion and the horizontal plane. Figure 2 shows schematically the angles α, β, and γ for one decay particle.

The radii of curvature of the tracks were measured with templates as well as by the coordinate method, using the UIM-22 microscope. Both methods yielded the same results, within the limit of errors. The accuracy of measure-

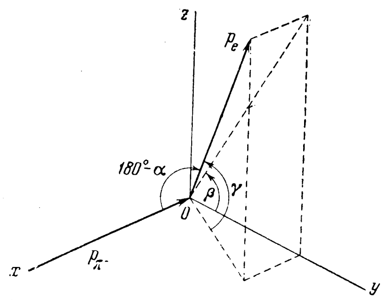

FIG. 2

*We are grateful to D. P. Vasilevskaya and Yu. N. Denisov for allowing us the use of this instrument.

ment of the radius of curvature of each track depends on the value of the curvature and on the length and direction of the track in space. The particle momenta, determined from the measured radii and depth angles γ, were corrected for the inhomogeneity of the magnetic field ($\sim 2\%$) and shrinkage of the film ($\sim 1\%$). In the coordinate method, corrections necessitated by the distortion of the optical system and by the fact that the image on the film is a conical projection of the actual track, were disregarded as small. Estimates have shown that the measurement results are practically unaffected by multiple scattering of particles by the gas in the chamber or by bremsstrahlung.

TABLE I

No. of track; particle	Radius of curvature, cm	Momentum, Mev/c
1, 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

Table I lists the values of the radius of curvature, averaged over measurements made by the re-projection and coordinate methods on two frames of a stereo pair; the corresponding particle momentum is also listed. The errors given for the radii are the maximum measurements errors. Total errors, which reflect both the inaccuracies in the measurements of the radii of curvature and depth angles, and the indeterminacies connected with the introduced corrections, are given for the momenta.

The ionization density produced by the particles in the chamber was estimated visually; it did not exceed $1\frac{1}{2}$ times minimum for all particles. Comparison of the obtained particle momenta with their ionization shows that all decay particles are electrons.

Table II gives the measured values of the angles α, β, and γ. The accuracy in the angle measurements is ±1%. The corrections necessitated by film shrinkage are negligibly small.

From the measured electron momenta and angles α and β, it is easy to calculate the direc-

TABLE II

No. of track; particle	α, deg	β, deg	γ, deg
2, e^-	138	84	42
3, e^+	138	94	42
4, e^-	127	−56	−41
5, e^+	128	−48	−36

tion and magnitude of the total momentum of all four electrons, $P_t = 147 \pm 26$ Mev/c; $\alpha = 153 \pm 2$ deg, and the total energy of all electrons is 202 ± 32 Mev. It follows from the kinematics of the process $\pi^- + p \rightarrow \pi^0 + n$ at a π^--meson kinetic energy of 166 ± 14 Mev (corresponding to a measured π^--meson momentum of 272 ± 16 Mev/c), that the π^0 meson emitted at an angle of 153 ± 2 deg should have a momentum of 163 ± 7 Mev/c and a total energy of 212 ± 6 Mev. Kinematically therefore, the four electrons are equivalent to the neutral pion from the reaction $\pi^- + p \rightarrow \pi^0 + n$, emitted at an angle 153 ± 2 deg.

The relatively large errors in the values of the total energy and total momentum of the four electrons permits only a rough estimate of the neutral-pion mass. However, taking into account certain kinematic relations between the neutral-pion mass and the measured values of momenta and angles, one can obtain a better value for the π^0-meson mass, namely 141 ± 8 Mev. Within the limit of measurement errors, this is in agreement with the presently accepted mass value, 135 Mev.

Table III gives the angles between the particles and the planes of the pairs, calculated in the laboratory system and in the rest system of the π^0 meson; the electron momenta in the rest system of the π^0 meson are also given. To calculate these quantities, we assumed accuracy limits for the particle-momentum measurements, within the limits indicated in Table I, to correspond kinematically to a π^0-meson mass of 135 Mev.

In the reference system where the π^0 meson is at rest, the decay particles form two electron-positron pairs with small angles between the electrons and positrons (Table III) and with equal and opposite momenta; the momentum projections on the coordinate axes are balanced to a high degree of accuracy. (In principle, it is possible to con-

TABLE III

Number of track; particle	Laboratory system		π^0-meson rest system		
	Angle θ between particles, deg	Angle φ between planes, deg	Momentum Mev/c	Angle θ between particles, deg	Angle φ between planes, deg
2, e^-	6.5±1	75±10	56.1	7±2	<37
3, e^+			11.9		
4, e^-	6.5±1.5		9.0	12±4	
5, e^+			58.7		

sider the analyzed case as that of π^0-meson decay into two electron-positron pairs with angles of emission close to 180 deg. According to Dalitz,[1] however, that two such wide-angle pairs appear as the result of internal conversion is approximately 400 times less probable than the appearance of pairs with angles ~ 10 deg.)

In view of the effect that the angles of emission θ between the pair particles are relatively small, the angle between the planes of the pair can be determined only very roughly. Calculations show that in the rest system of the π^0 meson this angle does not exceed 37 deg, although angles close to 90 deg are more probable for the pseuco-scalar meson.

POSSIBLE EXAMPLES OF ANOTHER INTERPRETATION

Let us examine several other possible explanations for the observed event.

a) Let a π^0 meson, produced through charge-exchange decay, by the usual scheme (1), into two gamma quanta that are then converted into electron-positron pairs at so close a distance from the π^0-meson decay point, that this distance cannot be resolved on the photograph. The probability of both gamma quanta from the π^0-meson decay converting in the chamber hydrogen at a distance not exceeding 1 mm (width of track ~ 0.5 mm) is 2.2×10^{-12}. Since approximately 1400 events of elastic π^--p scattering have been registered in all the scanned films, and since the ratio of the cross sections of charge-exchange and elastic π^--p scattering is 1.8 at these energies,[6] the total number of π^0 mesons decaying in the chamber is 2500. Thus, the probability of observing the conversion of both gamma quanta at a distance less than 1 mm amounts to 5.5×10^{-9} in our experiment.

b) If the π^0 meson decays as in scheme (2) and then the gamma quantum is converted less than 1 mm from the point of π^0-meson decay, the probability of observing such an event in our experiments amounts to 4.7×10^{-5}.

c) The kinetic energy of the π^- meson (166 ± 14 Mev) exceeds somewhat the threshold of the reaction $\pi^- + p \rightarrow \pi^0 + \pi^0 + n$ (160 Mev). We can therefore observe an event analogous to that considered here if the two π^0 mesons produced in this reaction decay as per scheme (2). A rough estimate, in which the cross section of the foregoing reaction is taken to be 7×10^{-30} cm^2 and calculated for a π^--meson energy of 260 Mev,[8] shows the probability of observing such an event to be much less than 9×10^{-5}. Another argument against such an interpretation is the exceedingly good agreement between the kinematics of the observed event and the kinematics of decay (3).

d) According to the estimates of Kroll and Wada, only one π^0 meson in 29,000 decays by scheme (3). Consequently, the probability of observing such a decay in our experimental data amounts to approximately 0.09. A comparison of this value with estimates a), b), and c), and also the good agreement with the kinematics, leave no doubts regarding the reliability of observation of the $\pi^0 \rightarrow e^- + e^+ + e^- + e^+$ decay.

CONCLUSION

As noted previously, a definite angular correlation exists between the pair planes in the decay of a π^0 meson into two electron-positron pairs. A study of this correlation permits a direct determination of the spin and parity of the π^0 meson. The correlation function has the form

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

where φ is the angle between the pair planes. Kroll and Wada have found that for zero π^0-meson spin the correlation coefficient λ is ± 0.19, with the plus and minus signs pertaining to the even and odd π^0 mesons, respectively. The correlation is much stronger here than the correlation between the planes of the pairs produced by the gamma quanta from the decay $\pi^0 \rightarrow 2\gamma$.[9,10] Joseph[3] has analyzed the angular correlation for a π^0-meson spin and parity $2^{\pm}$, and has shown that in this case $|\lambda| < 0.19$.*

Thus, even in the most favorable case, $|\lambda| = 0.19$, one must observe a rather large number of decays as per scheme (3) (on the order of several hundred) if any definite conclusions are to be drawn from the experimental data regarding the spin and parity of the π^0 meson. Although such an experiment is unusually laborious, it can be made quite realizable by increasing the efficiency of recording such decays by observing the stopping of slow π^- mesons in a hydrogen bubble chamber.

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