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AN INVESTIGATION OF THE $\pi^- + p \rightarrow n + \pi^0$ CHARGE EXCHANGE SCATTERING AND THE $\pi^- + p \rightarrow n + \eta (\eta \rightarrow 2\gamma)$ REACTION IN THE 1.55 – 4.5 BeV/c REGION

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The $\pi^- + p \rightarrow n + \pi^0$ charge-exchange scattering and the $\pi^- + p \rightarrow n + \eta\ (\eta \rightarrow 2\gamma)$ reaction were investigated in 1.55—4.5 BeV/c region in a 17-liter propane-xenon bubble chamber. The total cross sections of both reactions were measured in this region. The angular distributions of the π^0 mesons in the charge-exchange reaction were obtained. The backward exchange-scattering cross sections $d\sigma(\pi^- + p \rightarrow n + \pi^0)/d\Omega$ were estimated.

1. INTRODUCTION

THE information available to date on the exchange scattering process $\pi^- + p \rightarrow n + \pi^0$ is limited essentially to π^--meson energies up to ~ 1 BeV[1]. At higher energies there are very few experimental data on the cross section σ_e of this reaction. It was shown earlier[2] that $\sigma_e = 0.20 \pm 0.25$ mb for π^- mesons with 2.8 BeV/c momentum; estimates are given in [3,4] of the upper limits of σ_e for 6.1 BeV/c (< 0.14 mb), for 7—8 BeV/c (< 0.2 mb), and for 18.1 BeV/c (< 0.03 mb). Yet measurements of the exchange-scattering cross section at high energies are of great interest. As shown in the theoretical paper by Okun' and Pomeranchuk [5], a considerable decrease in the exchange scattering cross section should be expected with increasing π^--meson energy. This is connected with the fact that the total cross sections of the interaction of π^+ and π^- mesons with nucleons come close to each other at high energies ($\gtrsim 1$—2 BeV).

The purpose of the present paper is to investigate the exchange scattering

$$\pi^- + p \rightarrow n + \pi^0 \tag{1}$$

in the π^--meson momentum region from 1.55 BeV/c to 4.5 BeV/c and also to study the reaction

$$\pi^- + p \rightarrow n + \eta \quad (\eta \rightarrow 2\gamma). \tag{2}$$

Heretofore the cross section of reaction (2) was estimated only for 1.14 BeV/c when the decay $\eta \rightarrow 2\gamma$ was first established[6].

2. EXPERIMENTAL PART

Reactions (1) and (2) were investigated at π^--meson momenta 1.55 and 2.8 BeV/c using photographs previously obtained[7] in the 17-liter xenon bubble chamber with the π^--meson beam from the proton synchrotron of the Institute of Theoretical and Experimental Physics (20,000 and 60,000 stereo photographs, respectively). In addition, we have obtained for this investigation additional 20,000 stereo photographs for 4.5-BeV/c π^- mesons.

To identify the reactions (1) and (2) we made use of the fact that in the $X^0 \rightarrow 2\gamma$ neutral particle decay there exists a minimum angle φ_{min} between the outgoing γ quanta, defined by the relation

$$\sin (\varphi_{min}/2) = m/E, \tag{3}$$

where m and E is the mass and total energy of the X^0 particle. The distribution of the decay probability over the angle between the two γ quanta has a sharp peak near φ_{min} [8], so that an experimental determination of this distribution can yield φ_{min} and consequently the mass m of the particle, if its energy is known.

For the reactions (1) and (2), the momentum of the π^0 or η meson has in the pion-proton c.m.s. a constant value, independent of the angle of emission, which can be calculated from the known momentum of the π^- mesons in the laboratory system (l.s.). Thus, by finding the distribution over the angle φ' between the γ quanta from the π^0

Table I

π^- meson momentum, BeV/c	Number of cases with k γ-quanta								
	$N_{2\gamma}$	$N_{3\gamma}$	$N_{4\gamma}$	$N_{5\gamma}$	$N_{6\gamma}$	$N_{7\gamma}$	$N_{8\gamma}$	$N_{9\gamma}$	$N_{10\gamma}$
1.55	338	118	25	6	2	—	—	—	—
2.80	769	433	136	53	24	2	2	—	1
4.50	104	68	31	12	5	2	—	1	—

$\rightarrow 2\gamma$ or $\eta \rightarrow 2\gamma$ decay in the π^-p c.m.s., we can use the described method to identify the π^0 or η mesons [6]. The existence of the $\eta \rightarrow 2\gamma$ decay should by now be regarded as established [6,9].

In the photographs obtained with the bubble chamber, the γ quanta were observed by their conversion into electron-positron pairs. Cases were selected in which two or more pairs were directed to the stopping point of the π^- meson, under the condition that the stopping was not accompanied by tracks due to nuclear interaction. The events obtained were interpreted as the result of such interactions between the π^- mesons and the free hydrogen or the protons from the C and Xe nuclei, in which proton charge exchange takes place and one or more neutral particles are produced, decaying subsequently into quanta. It was assumed that cases with two pairs are due to the reactions of the type $\pi^- + p \rightarrow n + X^0$ ($X^0 \rightarrow 2\gamma$), and also by processes with $k > 2$, when only two out of k γ quanta were registered in the chamber. For the $\pi^- + p \rightarrow n + X^0$ ($X^0 \rightarrow 2\gamma$) reaction, such cases served as a background due, for example, to the reaction $\pi^- + p \rightarrow n + \omega \rightarrow n + \pi^0 + \gamma \rightarrow n + 3\gamma$ or to the reaction $\pi^- + p \rightarrow n + 2\pi^0 \rightarrow n + 4\gamma$, etc.

For cases with two γ quanta we measured on the stereo projector the two angles θ_1 and θ_2 between the γ quanta and the direction of the π^- meson, and the angle φ between the γ quanta. These data were used to convert the angle into the π^-p c.m.s. For cases with three—six γ quanta, we measured the angles between any pair of γ quanta and all the angles θ_k. The formation of such combinations of two out of three—six γ quanta was used to determine the background distributions over the angle φ'. In addition, we measured for each case the potential length l_k, from which we calculated the efficiency κ of registration of single γ quanta. The average values of $\bar{\kappa}$ for events with a given multiplicity and for a given π^--meson momentum were used to calculate the probabilities for registering i out of k γ-quanta. In the calculations we assumed that the conversion length is $l_0 = 17.8 \pm 2.2$ cm [7]. The average value of $\bar{\kappa}$ was 0.5—0.7. The remaining details of the experiments and the data reduction are contained in our paper on the observation of the $\omega \rightarrow \pi^0 + \gamma$ decay [7].

3. RESULTS AND DISCUSSION

The distribution of the obtained events over the number of conversion pairs is listed in Table I.

Most cases were measured with the stereo reprojector, after which the angles φ' in the π^-p c.m.s. were calculated for the events with two γ quanta and for combinations of two out of three—six γ quanta. The distributions over the angle φ' for cases with two γ quanta are shown in Fig. 1. They were constructed with allowance for the registration efficiency of each individual case. Namely, in place of one case, the quantity $1/\kappa_1\kappa_2$ was laid-off on the ordinate axis. The areas under the spectrum were normalized to the number of measured cases.

It is obvious that distributions shown in Fig. 1 are due not only to the reactions $\pi^- + p \rightarrow n + X^0$ ($X^0 \rightarrow 2\gamma$), but also to processes with a larger multiplicity of the γ quanta, i.e., they contain a background. Nonetheless, in all the distributions (Fig. 1) we can see clearly a narrow peak in the small-angle region, corresponding to the production of the π^0 meson in the $\pi^- + p \rightarrow n + \pi^0$ charge-exchange reaction.

The background of the reactions $\pi^- + p \rightarrow n + k\gamma$ ($k \geq 3$) was subtracted by a procedure similar to that in an earlier investigation [7]. The results are shown in Fig. 2. The arrows indicate the values of the minimum angles φ_{min} between the γ quanta, calculated from relation (3) for the π^0 and η mesons. As follows from Fig. 2, in all three plots we can note, in addition to the well separated π^0-meson maximum, also groups of cases apparently corresponding to the η meson, i.e., due to the reaction (2). The statistics of the η-meson peaks are scanty, but we see that with increasing initial π^--meson momentum the maxima of the peaks shift towards the small angles, in good agreement with the calculated values φ_{min} for the η meson (arrows). This fact confirms the assumption that

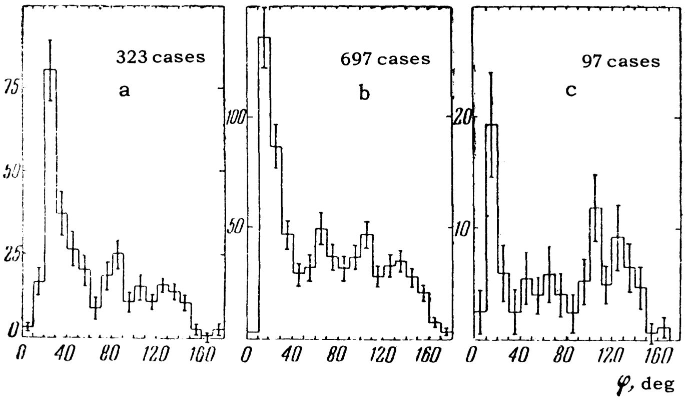

FIG. 1. Histograms of cases with two γ quanta—a—1.55, b—2.8, c—4.5 BeV/c.

we observed in addition to the $\pi^- + p \to n + \pi^0$ reaction also the reaction $\pi^- + p \to n + \eta\ (\eta \to 2\gamma)$.

The curves in Figs. 2 are the theoretical distributions for the $\pi^0 \to 2\gamma$ and $\eta \to 2\gamma$ decays,[8] normalized to the number of particles in the π^0 and η groups. We see that the experimental distributions are in satisfactory agreement with the theoretical ones, i.e., the measurement errors and the admixture of quasi-hydrogen events do not affect the results significantly.

Figure 2 may include a certain number of events due to the reactions $\pi^- + p \to K^0 + \Lambda(\Sigma^0) + m\pi^0 \to K^0 + \Lambda + k\gamma$ ($m \geq 1$, $k \leq 2$), when no K^0 or Λ are registered in the chamber, i.e., when such reactions imitate events like $\pi^- + p \to n + k\gamma$. To determine the magnitude of this background we scanned all the photographs for cases of stopped π^- mesons accompanied by K^0 and Λ particles and any number of γ quanta. The results are listed in Table II. From this table and from the known K^0 and Λ registration efficiencies we determined the contribution from these reactions with production of the strange particles to the numbers $N_{k\gamma}$ listed in Table I. For the cases with two γ quanta these contributions amounted to 2.0, 5.3, and 15.3% at 1.55, 2.8, and 4.5 BeV/c, respectively. The distribution of the strange-particle background relative to the angle φ, for cases with two γ quanta, is shown in Fig. 2 for 2.8 BeV/c with normalization corresponding to Fig. 2b. As follows from the figure, the background is distributed approximately uniformly over the entire 0—180° interval and constitutes a relatively small fraction of the area of the spectrum 2b (31 cases). For Figs. 2a and 2c, the contributions from the strange particles amount to 4 and 8 cases, respectively.

The cross sections for the charge-exchange (1) η-meson production (2) were calculated from the formula

$$\sigma(\pi^- + p \to n + X^0) = \frac{(S_x/S)\, n_2\sigma_0}{\sum\limits_{n=2}^{6} n_k}. \tag{4}$$

Here S_x is the area of the π^0 or η grouping on any of the spectra of Fig. 2; S is the area of the entire spectrum; n_k is the number of $\pi^- + p \to n$

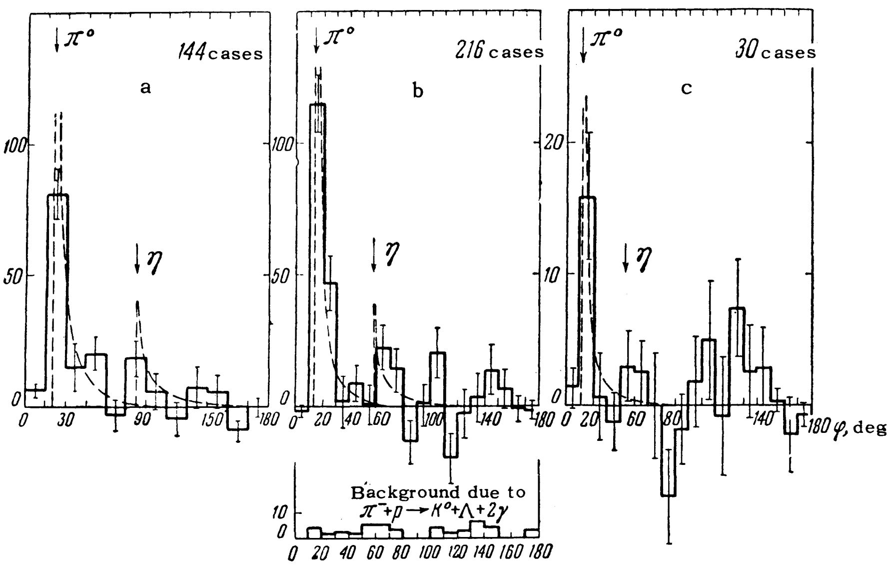

FIG. 2. Histograms of cases of the reaction $\pi^- + p \to n + X^0(X^0 \to 2\gamma)$ after subtracting the background: a — 1.55, b — 2.8, c — 4.5 BeV/c.

Table II

π^- meson momentum, BeV/c	Number of cases with k γ-quanta				Number of V-events
	1γ	2γ	3γ	4γ	
1.55	{ 20 2	6 —	2 —	— —	1 2
2.80	{ 94 12	37 6	8 1	6 —	1 2
4.50	{ 17 2	13 —	8 —	2 —	1 2

+ kγ reactions; σ_0 is the experimentally-known cross section of the reaction $\sigma^- + p \rightarrow n$ + neutral particles. The numbers n_k were determined, as described previously [7], from the data of Table I, corrected for the strange-particle contribution, with allowance for the probability of registration of i out of k γ-quanta. The values of σ_0 were assumed to be 4.0 and 2.0 mb for 1.55 and 2.8 BeV/c, respectively. These values were taken from [1,2] and were corrected for the strange-particle contribution. For 4.5 BeV/c, the value $\sigma_0 = 15$ mb was obtained by interpolating the data for 2.8 [2] and 6.1 BeV/c [3].

In using formula (4) it was assumed that the ratio $n_2/\Sigma n_k$ was the same for the interactions between π^- mesons and either free or bound protons of the nuclei. The fraction of quasi-hydrogen events for the employed xenon-propane mixture is 35%, as follows from the calculation. The calculated cross sections of reactions (1) and (2) are listed in Table III, which shows also data for 1.14 BeV/c from [6].

We were also able to obtain information on the angular distribution of the π^0 mesons in the charge-exchange reaction at 1.55 and 2.8 BeV/c. The results are shown in Fig. 3. The direction of motion of the π^0 meson was taken to be the bisector of the angle between the quanta from the $\pi^0 \rightarrow 2\gamma$ decay. The estimates show that the inaccuracy due to this assumption is small and depends on the angle θ between the bisector and the π^--meson direction. The values of the error in cos θ are shown in Figs. 3a and b. The background for

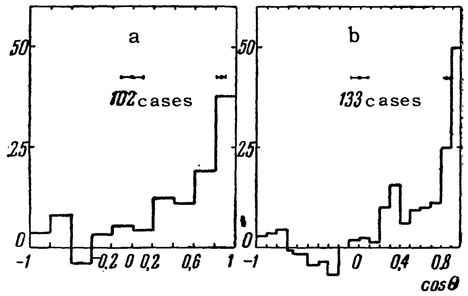

FIG. 3. Angular distribution of π^0 mesons in the reaction $\pi^- + p \rightarrow n + \pi^0$: a—1.55, b—2.8 BeV/c; θ—angle between the direction of motion of the π^- meson and the bisector of the angle between the γ quanta from the $\pi^0 \rightarrow 2\gamma$ decay.

Figs. 3a and b was subtracted in analogy with the procedure used for the distributions of Fig. 2.

Using the results of Fig. 3 and Table III, we can obtain information on the backward exchange scattering, i.e., the differential cross section of reaction (1) at 180°. In the calculations we used the cases contained within an angle of 1 sr around the 180° direction. We found that $d\sigma\,(\pi^- + p \rightarrow n + \pi^0)/d\Omega$ at 180° was 0.04 ± 0.02 mb/sr for 1.55 BeV/c and 0.008 ± 0.005 mb/sr for 2.8 BeV/c. The latter value agrees with the estimate of the upper limit given in [10] for the backward scattering exchange ($d\sigma_e/d\Omega < 0.01$ mb/sr).

Table III

π^- meson momentum, BeV/c	Cross section of the reactions (in mb)	
	$\pi^- + p \rightarrow n + \pi^0$	$\pi^- + p \rightarrow n + \eta$ $(\eta \rightarrow 2\gamma)$
1.14	3.0	0.5
1.55	1.54±0.37	0.32±0.22
2.80	0.36±0.09	0.08±0.07
4.50	0.19±0.12	0.05±0.07

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