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Investigation of the charge-exchange $\pi^- + p \to n + \pi^0$ and $\pi^- + p \to n + \eta$ $(\eta \to 2\gamma)$ reaction in the 1.25 - 4.5 BeV/c region

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NOTE

From photographs taken in the 17-litre propane-xenon bubble chamber, the reactions $\pi^- + p \to n + \pi^0$ and $\pi^- + p \to n + \eta$ $(\eta \to 2\gamma)$ were investigated with π^- at 1.25, 1.55, 2.8 and 4.5 BeV/c. Total cross-sections of both reactions were measured for the above momenta. Angular distributions of π^0 in charge-exchange were obtained. The $d\sigma(\pi^- + p \to n + \pi^0)/d\Omega$ at 180° (backward charge-exchange) was estimated.

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An investigation of charge-exchange $\pi^- + p \to n + \pi^0$ and $\pi^- + p \to n + \eta$ $(\eta \to 2\gamma)$ reaction in the 1.25 - 4.5 BeV/c region.

ABSTRACT

In 17-liter propan-xenon bubble chamber a charge-exchange $\pi^- + p \to n + \pi^0$ and $\pi^- + p \to n + \eta$ $(\eta \to 2\gamma)$ reaction were investigated in 1.25 - 4.5 BeV/c region. Total cross-sections of both reactions were measured in this region. Angular distributions of π^0-mesons in charge-exchange were received. Cross-section of charge-exchange backward around 180° was estimated.

1. Introduction

Until now, information about the $\pi^- + p \to n + \pi^0$ charge-exchange was to be found only in the π^--meson energy region up to about 1 BeV [1]. For higher energies, there is very little experimental data concerning the cross-section σ_c of the $\pi^- + p \to n + \pi^0$ reaction. In paper [2], it was shown that for π^--mesons at an energy of 2.8 BeV/c, $\sigma_e = 0.20 \pm 0.25$ mb; in papers [3,4] the upper limits of the cross-section σ_e are estimated as (<0.014 mb) at 6.1 BeV/c, (<0.2 mb) at 7-8 BeV/c and (<0.03 mb) at 18.1 BeV/c. Meanwhile, the measurement of the charge-exchange cross-sections in high-energy regions is of great interest. As shown in the theoretical work of Okun and Pomeranchuk [5], when the energy of the π^--mesons increases, a considerable reduction of the charge-exchange cross-sections is to be expected. This is due to the fact that the total cross-sections of π^+ and π^--meson interactions with nucleons become increasingly similar at high energies ($\gtrsim$ 1-2 BeV).

The purpose of the present paper is to investigate the charge-exchange

$$\pi^- + p \to n + \pi^0 \qquad (1)$$

in π^--meson energy region of 1.25 - 4.5 BeV/c, and also to study the reaction

$$\pi^- + p \to n + \eta \ (\eta \to 2\gamma) \qquad (2)$$

Until now the cross-section of reaction (2) was estimated only for 1.14 BeV/c in the paper establishing $\eta \to 2\gamma$ decay for the first time [6].

2. Experimental section

Reactions (1) and (2) were studied at π^--meson energies of 1.25, 1.55 and 2.8 BeV/c, in photographs obtained earlier by ourselves [7] with the 17-litre xenon-propane bubble chamber in a π^--meson beam of the

proton synchrotron of the Institute for Theoretical and Experimental Physics (11,000, 20,000 and 60,000 stereoscopic photographs respectively). In addition, 20,000 further stereoscopic photographs were taken for the above work at a π^--meson energy of 4.5 BeV/c.

In order to identify reactions (1) and (2), we took advantage of the fact that the decay of the neutral particle $X^0 \to 2\gamma$ corresponds to the minimum angle of flight between γ-quanta φ_{min} determined according to the equation

$$\operatorname{Sin} \frac{\varphi_{min}}{2} = \frac{m}{E} \qquad (3)$$

where m and E are the mass and total energy of the X^0-particle. The distribution of the probability of decay according to the angle between two γ-quanta φ has a sharp peak near to φ_{min} [8], and therefore obtaining this distribution experimentally can serve to determine the value of φ_{min} and, consequently, of the mass of the particle m, if its energy is known.

For reactions (1) and (2) in the π^--meson-proton centre of mass system, the momentum of the π^0- or η-meson has a constant value which is independent of the angle of flight, and can be calculated from the known momentum of the π^--mesons in the laboratory system. Thus, by finding the distribution according to the angle φ' between the γ-gamma from the $\pi^0 \to 2\gamma$ or $\eta \to 2\gamma$ decay in the π^--p centre of mass system, the above mentioned method can be used to identify the π^0 or η-meson [6]. The fact of $\eta \to 2\gamma$ decay in a given time can be considered as established [6,9].

In the photos obtained in the bubble chamber, the γ-quanta were observed through their conversion into electron-positron pairs. Events were sought with two or more pairs directed towards the stopping point of the π^--meson, provided that the stop was not accompanied by tracks of a nuclear interaction. The events found were interpreted as

resulting from such interactions of π^--mesons with free hydrogen or with protons of C or Xe nuclei, in which a proton charge-exchange occurs and one or more neutral particles are generated, which then decay into γ-quanta. It was considered that events with two pairs were due to reactions of the type $\pi^- + p \to n + X^0$ ($X^0 \to 2\gamma$), and also to processes with a number of γ-quanta of $k > 2$, when only 2 out of k γ-quanta were recorded in the chamber. For the reaction $\pi^- + p \to n + X^0$ ($X^0 \to 2\gamma$), such events formed a background which might be due, for instance, to the reaction $\pi^- + p \to n + \omega \to n + \pi^0 + \gamma \to n + 3\gamma$ or $\pi^- + p \to n + 2\pi^0 \to n + 4\gamma$, etc.

For events with 2 γ-quanta, measurement was made in a stereo-projector of two angles Θ_1 and Θ_2 between the γ-quanta and the direction of the π^--meson and of the angle φ between the γ-quanta. These data were used to transfer the angle φ into the π^--p centre of mass system. For events with 3-6 γ-quanta, the angles between every pair of γ-quanta and all the Θ_k angles were measured. The formation of such double combinations of events with 3-6 γ-quanta was used to find the background distribution according to the angle φ'. Furthermore, the potential lengths of ℓ_k were measured for each event and used to calculate the recording efficiency χ of the single γ-quanta. The mean values of $\bar{\chi}$ for events of given multiplicity and for a given π^--meson momentum, were used to calculate the probability of recording i out of k quanta. For the calculations, it was assumed that the conversion length $\ell_0 = 17.8 \pm 2.2$ cm [7]. The mean value of $\bar{\chi}$ was found to be between 0.5 and 0.7. The remaining details concerning the experiments and the processing of the results are contained in our paper on the "Evidence for $\omega \to \pi^0 + \gamma$ decay" [7].

3. Results obtained and interpretation

The distribution of the events found according to the number of conversion pairs is given in Table I.

Table I

Momentum of π^--mesons in BeV/c	Number of events with k γ-quanta								
	$N_{2\gamma}$	$N_{3\gamma}$	$N_{4\gamma}$	$N_{5\gamma}$	$N_{6\gamma}$	$N_{7\gamma}$	$N_{8\gamma}$	$N_{9\gamma}$	$N_{10\gamma}$
1.25	182	40	13	1	-	-	-	-	-
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	-

The majority of events were measured in a stereo-projector, after which the angles φ' in the π^--p centre of mass system were calculated for events with 2 γ-quanta and for double combinations of events with 3-6 γ-quanta. The distribution according to the angle φ' for events with 2 γ-quanta is shown in figure 1. When plotting these graphs, the recording efficiency of each separate event was taken into account, by taking the value $1/\chi_1$, χ_2 instead of one event along the Y-axis. The areas of the spectra were standardized for the number of events measured.

It is evident that the distributions shown in figure 1 are due not only to $\pi^- + p \to n + X^0$ ($X^0 \to 2\gamma$) reactions, but also to processes with higher γ-quanta multiplicity, i.e. they include background. Nevertheless, in all the distributions (figure 1) there is in the small angle region a clearly marked narrow peak corresponding to the formation of a π^0-meson in the $\pi^- + p \to n + \pi^0$ charge-exchange.

The background from the reaction $\pi^- + p \to n + k\gamma$ ($k \geq 3$) was deducted in a similar way to that mentioned in the previous paper [7]. The results are given in figure 2. The arrows show the value of the minimum angles of divergence between γ-quanta, φ'_{min}, calculated from expression (3), for the π^0-meson and the η-meson with a mass of 548 MeV.

As is clear from figure 2, in all 4 graphs, apart from the clearly distinguished π^0-meson maximum, groups of events can also be noted corresponding apparently to the η-meson, i.e. due to reaction (2). The statistical certainty of η-meson peaks is not considerable, but it can be seen that, when the initial momentum of the π^--mesons increases, the maxima of the peaks move towards the smaller angle side in good agreement with the calculated values of φ'_{min} for the η-meson (arrows). This confirms the hypothesis that, in addition to the reaction $\pi^- + p \to n + \pi^0$, the reaction $\pi^- + p \to n + \eta$ $(\eta \to 2\gamma)$ is also occurring.

The curves shown in the graphs of figure 2 are theoretical distributions for $\pi^0 \to 2\gamma$ and $\eta \to 2\gamma$ decays [8], normalized according to the number of particles in the π^0 and η-groups. It can be seen that the experimental and theoretical distributions are in good agreement, i.e. the errors of measurement and the inclusion of quasi-hydrogen events do not affect the results to any considerable extent.

In the graphs of figure 2, there must be a certain number of events due to the reactions $\pi^- + p \to K^0 + \Lambda\ (\Sigma^0) + m\pi^0 \to K^0 + \Lambda + k\gamma$ $(m \geq 1,\ k \geq 2)$, with no K^0 and Λ recorded in the chamber, namely when such reactions simulate $\pi^- + p \to n + k\gamma$ events. In order to establish the value of this background, all photographs, except those at 1.25 BeV/c, were scanned in search of π^--meson stops accompanied by K^0 and Λ particles and any number of γ-quanta. Results are given in Table II. From the data of this table and the known recording efficiency of K^0 and Λ, an estimate was made of the contribution of the above mentioned reactions with formation of strange particles to the numbers $N_{k\gamma}$ shown in Table I. For events with two γ-quanta, these contributions are 2.0%, 5.8% and 15.3% for 1.55 BeV/c, 2.8 BeV/c and 4.5 BeV/c respectively. The distribution of background from strange particles according to the angle φ' for events with 2 γ-quanta is shown in figure 2 for 2.8 BeV/c with normalization corresponding to graph 2c. As follows from the figure, the background is distributed approximately evenly over the whole range from 0 to 180° and represents a comparatively small part of the area of the

spectrum 2c (31 events). For graphs 2b and 2d, the contributions from strange particles are 4 and 8 events respectively.

Table II

Momemtum of π^--mesons in BeV/c	Number of events with k γ-quanta				Number of V-events
	1γ	2γ	3γ	4γ	
1.55	20	6	2	-	1
	2	-	-	-	2
2.80	94	37	8	6	1
	12	6	1	-	2
4.50	17	13	8	2	1
	2	-	-	-	2

The cross-section of charge-exchange (1) and the formation of η-mesons (2) was calculated according to the formula

$$\sigma\,(\pi^- + p \to n + X^0) = \frac{S_x}{S} \cdot \frac{n_2}{\sum_{n=2} n_k}\ \sigma_0 \qquad (4)$$

where S_x is the area of π^0 or η-groups in any of the spectra in figure 2, S is the area of the whole spectrum, n_k is the number of $\pi^- + p \to n + k\gamma$ reactions, σ_0 is the cross-section of the reaction $\pi^- + p \to n +$ neutral particles found experimentally. The number n_k was determined as already described [7] from the data of Table I, corrected for the contribution from strange particles, taking into account the probability of recording i out of K γ-quanta. The values of σ_0 were taken as : 4.6 mb for 1.25 BeV/c, 4.0 mb for 1.55 BeV/c and 2.0 mb for 2.8 BeV/c.

These values were taken from the papers[1,2] with correction for the contribution from strange particles. For 4.5 BeV/c, the value of σ_0 = 1.5 mb was obtained by interpolating data for 2.8 BeV/c and 6.1 BeV/c [3].

When using formula (4), the ratio $n_2/\Sigma n_k$ was assumed to be identical for interactions of π^--mesons with free protons and bound protons of the nuclei. The proportion of quasi-hydrogen events for the xenon-propane mixture used was 35%, as shown by calculations. The results of the calculation of the cross-section of reactions (1) and (2) are shown in Table III. It should be noted that an approximation of our data concerning the cross-section σ_e of $\pi^- + p \to n + \pi^0$ charge-exchange may be obtained from the dependence $\sigma_e \sim 1/p^n$, where p is the momentum of the π^--mesons in the laboratory system and $n = 2.10 \pm 0.16$.

Table III

Momentum of π^--mesons in BeV/c	Cross-sections of the reactions (in mb)	
	$\pi^- + p \to n + \pi^0$	$\pi^- + p \to n + \eta$ $(\eta \to 2\gamma)$
1.25	2.12 ± 0.60	1.61 ± 0.60
1.55	1.33 ± 0.32	0.32 ± 0.22
2.80	0.38 ± 0.09	0.08 ± 0.07
4.50	0.19 ± 0.12	0.05 ± 0.07

We were also able to obtain information concerning the angular distribution of π^0-mesons in charge-exchanges at 1.25 BeV/c, 1.55 BeV/c and 2.8 BeV/c. The results are given in figure 3. The direction of motion of the π^0-meson was assumed to be that of the bisector of the angle between γ-quanta from $\pi^0 \to 2\gamma$ decay. Estimates showed that the inaccuracy resulting from this assumption was slight and depended on the

angle Θ between the bisector and the direction of motion of the π^--meson. The error in the value cos Θ is shown in graphs 3a-3c. The background for 3b and 3c was deducted in a similar way to that used when plotting the distributions in figure 2. The background for 3a was not taken into account, owing to its smallness (about 10%) and the scantiness of information about the number of background reactions.

As can be seen from figure 3, the character of angular distribution of the π^0-mesons changes as the energy of the π^--mesons increases. As in the case of $\pi^+ p$ and $\pi^- p$ elastic scattering, the forward stretch increases as the energy grows. It is noted that the angular distribution obtained for 1.25 BeV/c (figure 3a) is close to the distribution for 1.14 BeV/c obtained in the paper [11].

By using the results in figures 3a and 3c and Table III, information can be obtained about backward charge-exchange, namely the differential cross-section of reaction (1) at 180°. The results are given in Table IV. For the calculations events were used which fell within an angle 1 sterad around the 180° direction. The value obtained by us for 2.8 BeV/c was found to agree with the estimate of the upper boundary for backward charge-exchange given in paper [12] ($d\sigma_0/d\Omega < 0.01$ mb/sterad).

Table IV

Momentum of π^--mesons in BeV/c	1.25	1.55	2.80
$d\sigma (\pi^- + p \to n + \pi^0)/d\Omega$ at 180° m mb/ster	0.15±0.08	0.04±0.02	0.008±0.005

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BIBLIOGRAPHY

1. P. Falk-Vairant, G. Valladas, Rev. Mod. Phys. 33, 362, 1961.
2. Ya.Ya. Shalamov, V.A. Shebanov, JETP 39, 1232, 1960.
3. G. Bellini, E. Fiorini, A. Orkin-Lecourtois, Phys. Lett. 4, 164, 1963.
4. R.A. Aripov, V.G. Grishin, L.V. Silvestrov, V.N. Streltsov, JETP 43, 394, 1962.
5. L.B. Okun, I.Ya. Pomeranchuk, JETP 30, 424, 1956.
6. M. Chrétien, F. Bulos, H.R. Crouch, R.E. Lanou, J.T. Massimo, A.M. Shapiro, J.A. Averell, M.E. Law, C.A. Bordner, A.E. Brenner, D.R. Firth, E.E. Ronat, K. Strauch, J.C. Street, J.J. Szymanski, A. Weinberg, B. Nelson, I.A. Pless, L. Rosenson, G.A. Salandrin, R.K. Yamamoto, L. Guerriero, F. Waldner, Phys. Rev. Lett. 9, 127, 1962.
7. V.V. Barmin, A.G. Dolgolenko, Yu.C. Krestnikov, A.G. Meshkovskij, Yu.P. Nikitin, V.A. Shebanov, ITEP preprint N° 161, 1963. JETP in publication.
8. B. Rossi, High Energy Particles, Gostekhizdat, 1955, p. 236.
9. L. Behr, P. Mittner, P. Musset, Phys. Lett. 4, 22, 1963.
10. V. Cook, B. Cork, W. Holley, M. Perl, Phys. Rev. 130, 762, 1963.
11. A. Weinberg, A.E. Brenner, K. Strauch, Phys. Rev. Lett. 8, 70, 1962.
12. Yu.D. Bayukov, G.A. Leksin, Ya.Ya. Shalamov, JETP 41, 2016, 1961.