# INVESTIGATION OF THE $\pi^- + n \rightarrow \pi^- + n + m\pi^0$ REACTION WITH A 2.8-Bev/c $\pi^-$ – MESON BEAM

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Production of mesons in the reaction $\pi^- + n \rightarrow \pi^- + n + m\pi^0$ is investigated with a freon bubble chamber. The momentum of the incident meson is 2.8 Bev/c. The results obtained are compared with the statistical theory and the peripheral interaction model.

At present there is very little information about the reaction

$$\pi^- + n \rightarrow \pi^- + n + m\pi^0, \qquad m = 1, 2, \qquad (1)$$

and about the isotopically symmetrical reaction

$$\pi^+ + p \rightarrow \pi^+ + p + m\pi^0.$$

A study of these reactions supplements the information on inelastic interaction between pions and nucleons at high energies, and in particular on the applicability of the statistical theory and also the model of peripheral collision between the incoming meson and a meson in the "jacket" of the nucleon.

## 1. EXPERIMENTAL PROCEDURE

To obtain data on reaction (1), we examined stereo photographs obtained with a 17-liter freon bubble chamber [1] 50 cm long. The $\pi^-$-meson beam had a momentum 2.8 ± 0.3 Bev/c. The bubble chamber operated without a magnetic field. The main feature that made this procedure feasible was the relatively high efficiency of registering the $\gamma$ quanta produced in the decay of the $\pi^0$ mesons.

In scanning the stereo photographs we selected the single-prong stars accompanied by electron-positron conversion pairs, directed towards the interaction point. It was assumed that the chosen single-prong stars are produced via reaction (1) when the incoming mesons interact with the quasi-free neutrons of the nuclei contained in the freon. Since the screening coefficient of the nucleon in the nucleus is not known for reaction (1), no absolute cross sections were determined.

Altogether 221 events were registered. In addition, we registered two single-prong stars in which the conversion pairs were accompanied by "forks" of two pions, produced in $K^0$ meson decay. The efficiency of registering reactions with production of neutral strange particles has been estimated previously [2] to be ~0.4. Consequently the contribution of such reactions to the investigated process can be estimated at $\lesssim 3\%$ and is disregarded.

## 2. ANGULAR DISTRIBUTIONS OF $\gamma$ QUANTA AND $\pi^-$ MESONS

The angular distribution of the registered $\gamma$ quanta accompanying the single-prong stars is shown by the dashed line of Fig. 1. The abscissas are the cosines of the angle of emission of the $\gamma$ quantum in the c.m.s. of the incoming meson and nucleon, while the ordinates are the numbers of the $\gamma$ quanta. The circles denote the angular distribution of the $\gamma$ quanta with account of the $\gamma$

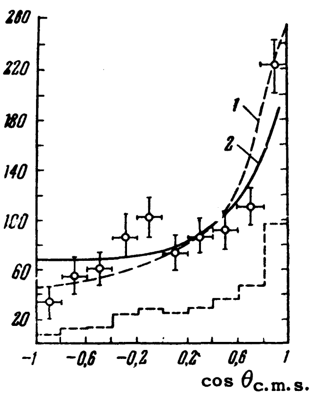


FIG. 1. Angular distribution of $\gamma$ quanta in the c.m.s. of the incoming meson and nucleon. Dashed histogram–distribution of registered $\gamma$ quanta without account of efficiency. The circles represent the same distribution with account of the $\gamma$ counting efficiency in the chamber. Curves 1 and 2 – calculated angular distributions assuming 50% (curve 1) and 30% (curve 2) contribution from peripheral collisions.

counting efficiency for the chamber. The errors are statistical.

The counting efficiency $\varepsilon$ was determined for each $\gamma$ quantum producing a pair directed towards the single-prong star. For this purpose we measured the distance L along the direction of $\gamma$-quantum motion from the point of interaction to the boundaries of that region of the chamber, where the conversion pair, if produced, would be registered in the scanning. The counting efficiency of a $\gamma$ quantum leaving a given point in a given direction is $\varepsilon = 1 - \exp(-L/L_k)$, where $L_k = 30$ cm is the known conversion length for the freon mixture in the bubble chamber.

As can be seen from Fig. 1, the angular distribution of the $\gamma$ quanta in the $\pi$N c.m.s. is anisotropic and asymmetrical. The ratio of the number of $\gamma$ quanta emitted forward and backward in the $\pi$N c.m.s. is $1.76 \pm 0.30$. It is possible that this ratio is underestimated compared with the data for the free nucleon, since it is known that the $\gamma$-quantum angular distribution for all the stars (including those accompanied by development of a nuclear cascade) is relatively large in $\gamma$ quanta emitted backward.

Figure 2 shows the angular distribution of the $\pi^-$ mesons in the laboratory system (l.s.). The same figure shows for comparison the angular distribution of the $\gamma$ quanta in the l.s. Both distributions are normalized to the same area. It is seen that within the limits of statistical errors the angular distributions of the $\gamma$ quanta and of the $\pi^-$ mesons are the same. Figure 3 shows the angular distribution of the $\pi^-$ mesons for two groups of mesons: with momentum > 300 Mev/c (solid curve) and with momentum < 300 Mev/c (dashed curve). The choice of 300 Mev/c is based on the experimental feasibility of determining the momentum in the chamber. The momenta of the $\pi^-$ mesons were estimated from the ionization, multiple scattering, and also from the range if the $\pi^-$ meson stopped in the chamber. The abscissas in Fig. 3 are the cosines of the l.s. $\pi^-$-meson emission angle. The two distributions are likewise normalized to the same area. The experimental data indicate that the anisotropy increases with increasing $\pi^-$-meson energy.

The angular distributions of the $\gamma$ quanta in the $\pi$N c.m.s., as affected by the l.s. $\pi^-$-meson emission angle, $\pi^-$ meson momentum, and the number of counted $\gamma$ quanta all agree, within the limits of statistical errors. A tendency can be observed, however, towards increasing anistropy in the $\gamma$-quantum distribution with decreasing number of $\gamma$ quanta directed towards the point of interaction (Fig. 4). Thus, the anisotropy for $\gamma$ quanta from

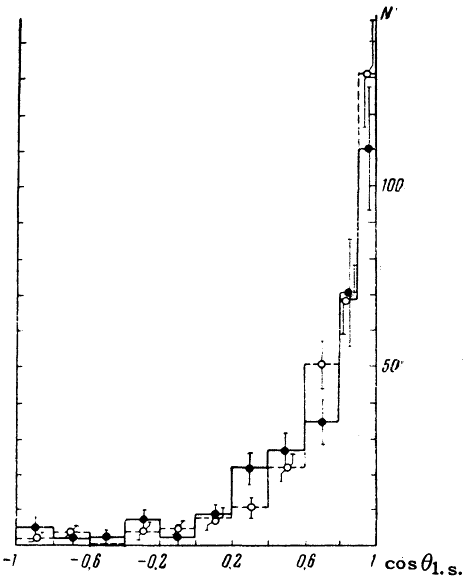


FIG. 2. Angular distributions of $\gamma$ quanta and $\pi^-$ mesons in the l.s., normalized to equal area. Solid curves – $\pi^-$ mesons, dashed curves – $\gamma$ quanta.

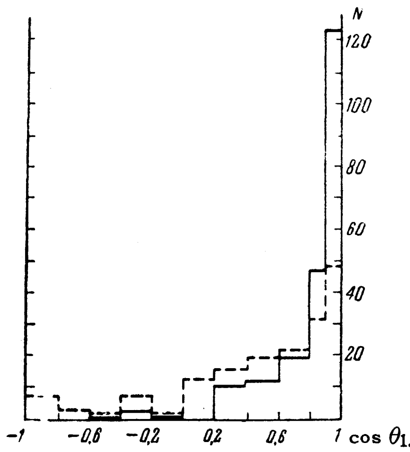


FIG. 3. Angular distributions of $\pi^-$ mesons in the l.s. as affected by the $\pi^-$-meson momentum $p_{\pi^-}$; solid curves – $p_{\pi^-}$ > 300 Mev/c, dashed – $p_{\pi^-}$ < 300 Mev/c.

stars with a single registered $\gamma$ quantum (histogram 1 of Fig. 4) is $1.7 \pm 0.4$, that for two registered $\gamma$ quanta (histogram 2 of Fig. 4) is $1.7 \pm 0.5$, while that for three to five $\gamma$ quanta (histogram 3, Fig. 4) is $1.5 \pm 0.7$.

We can also note that the anisotropy of the angular distribution of $\gamma$ quanta from stars with $\pi^-$-meson emission angle > 41° in the l.s. ($1.85 \pm 0.47$) exceeds that for < 41° in the l.s. ($1.68 \pm 0.39$).

## 3. MULTIPLICITY OF $\pi^0$-MESON PRODUCTION

Table I lists the distribution of the single-prong stars relative to the number of electron-positron conversion pairs directed towards the point of in-

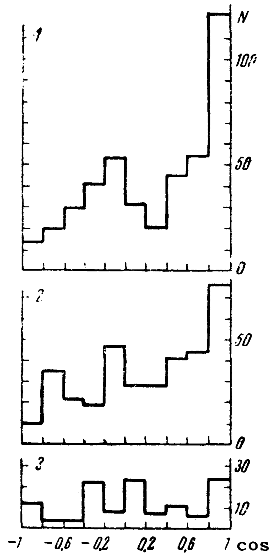


FIG. 4. Angular distributions of $\gamma$ quanta in the $\pi$N c.m.s. as affected by the number of registered $\gamma$ quanta emitted from stars: 1 – stars with single $\gamma$ quantum; 2 – stars with two $\gamma$ quanta; 3 – stars with 3, 4, and 5 $\gamma$ quanta.

teraction, and also as a function of the l.s. $\pi^-$-meson emission angle. In Table I, and further in the text, $N_1$—number of single-prong stars with one registered electron-positron conversion pair directed towards the point of interaction, $N_2$—the same with two pairs, etc, $N_0$—the total number of single-prong stars with pairs, and N—total number of registered conversion pairs. The last line of Table I lists the values of $N_1$—$N_5$, $N_0$, and N for all $\pi^-$-meson emission angles. The values obtained are determined by the multiplicity of $\pi^0$-meson production in reaction (1) and by the average conversion $\gamma$ counting efficiency in the chamber.

The average $\gamma$ counting efficiency was calculated from the formula

$$\bar{\varepsilon} = \left(\bar{n} / \sum_k \varepsilon_k^{-1}\right)^{-1},$$

where n—number of registered electron-positron pairs. It was shown that within the limits of statistical errors the average $\gamma$ counting efficiency does not vary with the $\pi^-$-meson emission angle. Nor do changes occur in the counting efficiency of $\gamma$ quanta accompanying single-prong stars with 1, 2, etc. counted conversion $\gamma$ quanta, i.e., the counting efficiency can be assumed constant for all the single-prong stars. We can therefore calculate the average counting efficiency of the $\gamma$ quanta produced in reaction (1) for the entire chamber, independently of the $\pi^-$-meson emission angle. The value obtained was 0.34 ± 0.02.

Starting from this value and the values of $N_4$ and $N_5$, and also from the fact that not a single event was registered with six electron-positron pairs, we can estimate the contribution of the cases with production of three $\pi^0$ mesons. The relative contribution to reaction (1) from processes involving the production of one and two $\pi^0$ mesons can be based on the ratios $N_1/N_0$, $N_2/N_0$, $N_3/N_0$, $N/N_0$. Knowing the contribution of the reactions with m = 1, 2, 3, we can readily determine the average multiplicity of $\pi^0$-meson production, which was found to be 1.47 ± 0.15. The error includes here the uncertainties in the contributions of the channels of reaction (1) with different m (see the last line of Table II).

Figure 5 shows the dependence of the average multiplicity (ordinates) on the $\pi^-$-meson emission angle (abscissas), calculated by the method indi-

**Table I**

| $\pi^-$ meson emission angles | Number of registered single-prong stars | | | | | | Total number of pairs, N |
|---|---|---|---|---|---|---|---|
| | $N_1$ | $N_2$ | $N_3$ | $N_4$ | $N_5$ | $N_0$ | |
| 0— 15° | 31 | 14 | 1 | — | — | 46 | 62 |
| 15— 30° | 33 | 15 | 1 | 1 | — | 50 | 70 |
| 30— 60° | 43 | 21 | 3 | 1 | — | 68 | 98 |
| 60— 90° | 25 | 10 | 3 | — | 1 | 39 | 59 |
| 90—180° | 10 | 6 | 1 | 1 | — | 18 | 29 |
| 0—180° | 142 | 66 | 9 | 3 | 1 | 221 | 318 |

**Table II.** Multiplicity of $\pi^0$ Production in the Reaction $n + \pi^- \rightarrow n + \pi^- + m\pi^0$ for $E_{\pi^-} = 2.8$ Bev

| | Percentage of cases with different m | | | Average multiplicity, $\overline{m}$ |
|---|---|---|---|---|
| | $m=1$ | $m=2$ | $m=3$ | |
| Statistical theory with account of the isobar (data of[3]) | 55 | 37 | 8 | 1.53 |
| Experimental data | ~63±5 | ~27±5 | ~10±5 | 1.47±0.15 |

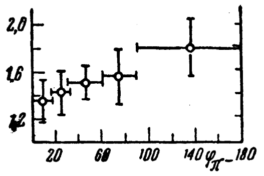


FIG. 5. Dependence of multiplicity of $\pi^0$-meson production on the l.s. $\pi^-$-meson emission angle.

cated above for five angle ranges. There is a tendency for the multiplicity to increase with increasing $\pi^-$-meson emission angle. The multiplicity of production of $\pi^0$ mesons in reaction (1) depends only on the $\pi^-$meson momentum, being $1.33 \pm 0.15$ for a meson with momentum > 300 Mev/c and $1.71 \pm 0.12$ when the momentum is < 300 Mev/c. The errors are statistical.

## 4. DISCUSSION OF THE RESULTS

Table II shows comparisons of the average multiplicity and of the percentage ratio of different channels of reactions (1) with the statistical theory. The calculation was made by Maksimenko[3] using statistical theory with the isobar taken into account. The agreement between calculation and experiment is satisfactory. However, the statistical theory cannot explain the noted dependence of the multiplicity on the $\pi^-$-meson emission angle and on the momentum, nor the observed angular distributions of the $\gamma$ quanta and $\pi^-$ mesons.

We note that the $\gamma$-quantum angular distributions given in Figs. 1, 2, and 4 coincide with the angular distributions of the $\pi^0$ mesons from reaction (1) if the $\pi^0$-meson spectrum is sufficiently hard, as is apparently the case of 2.8-Bev $\pi^-$ mesons. At any rate, the angular distribution of the $\pi^0$ mesons is not broader than the given $\gamma$-quantum distributions.

The observed anisotropy in the angular distribution of the neutral and charged mesons in the $\pi$N c.m.s. can be explained by assuming, as is frequently done in the literature, the existence of peripheral $\pi\pi$ collisions along with the central $\pi$N collisions. If at the same time the angular distribution of the $\pi$ mesons produced by the central collision is assumed to be isotropic in the $\pi$N c.m.s. (in accord with the statistical theory), and the distribution of the $\pi$ mesons from the peripheral collisions is assumed to be isotropic in the $\pi\pi$ c.m.s., then the fraction of peripheral collisions is determined by the results obtained. To reconcile an anisotropy value $1.76 \pm 0.30$ we must assume $\gtrsim 30\%$ peripheral collisions (curve 2 of Fig. 1). The angular distribution of the $\gamma$ quanta is in good agreement with the assumed 50% contribution of the peripheral collisions (curve 1 of Fig. 1). It is easy to understand why the concept of an interaction between the incoming meson and the weakly bound meson in the "jacket" of the nucleon explains qualitatively the similarity in the angular distributions of the $\pi^0$ and $\pi^-$ mesons (Fig. 2) and the dependence of the multiplicity on the $\pi^-$-meson emission angle (Fig. 5).

The results of the present investigation do not contradict the assumed validity of the statistical theory (with account of the isobar, and possibly with account of the $\pi$-meson interaction in the final state) when a large number of mesons (> 2 or 3) is produced. The angular distribution of the $\pi^0$ mesons apparently becomes more isotropic with increasing multiplicity (Fig. 4).

These conclusions are in good qualitative agreement with those reached in investigations of the production of > 1-Bev mesons in $\pi$N interactions other than the reaction (1). Thus, to explain the angular distribution of charged pions produced in $\pi^-$p collisions at 4.5 Bev, Walker[4] considered first direct knock-out of pions from the nucleon. His data indicate an isotropic pion distribution in the pion c.m.s. From the value ~7 mb, given by Walker[4] for the cross section of inelastic $\pi$N collision via the $\pi\pi$ channel, we can estimate the fraction of the peripheral collisions to be about 30%. The notion of central and peripheral collisions was developed by V. S. Barashenkov many times. In his work[5], based on the data of Belyakov et al[6] concerning the production of charged 7-Bev mesons in emulsion, Barashenkov estimates the fraction of the peripheral collisions to be 50—60%. Grote et al[7], in an investigation quite similar to[6], deduced the presence of $\pi\pi$ interaction from an analysis of the target mass.[8] The contribution of peripheral collisions to scattering is also proposed by Shalamov and Shebanov[9] to explain the angular distribution of $\pi^0$ mesons produced in the reaction $\pi^- + p \rightarrow n + m\pi^0$ at 2.8 Bev.

The foregoing investigations and many other experiments[10,11] indicate that the statistical theory is applicable to an evaluation of the mean multiplicity of production of mesons and of the angular and momentum distributions of the secondary particles in processes having large multiplicity.

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