

MULTIPLE PION PRODUCTION IN 7.2-BeV  $\pi^-$ -p COLLISIONS

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Multiple pion production in  $\pi^-$ -p collisions is investigated for 7.2-BeV primary pions. The measurements are made with a hydrogen bubble chamber of 25-cm diameter. Angular and momentum distributions of pions and protons are presented for stars of different multiplicities. The existence of bound states with energies above 1 BeV is investigated for three- and four-meson systems.

## 1. INTRODUCTION

THE investigation of inelastic  $\pi^-$ -p collisions is of great interest in connection with the elucidation of the nature of strong interactions. During the last few years several resonances of two- and three-pion systems have been observed in  $\pi^-$ -p collisions and in the annihilation of antiprotons. [1-4] In [5] we showed that the formation and decay of these resonance states play an important part in the multiple production of pions. It was thus most reasonable to assume that multiple production proceeds mainly via the formation of complex bound systems consisting of several pions (or of several pions and a nucleon) subsequently decaying either to a lower resonance state or into several pions. The failure to account for multiple production on the basis of the existing statistical theory is evidently associated with the fact that an important part is played by the formation and subsequent decay of resonance states in the multiple production process. We present here spectra and angular distributions of pions and protons in inelastic  $\pi^-$ -p collisions produced with a 7.2-BeV proton beam. The formation of resonances in three- and four-pion systems was also investigated. The results were not compared with the statistical theory for the aforementioned reasons.

## 2. EXPERIMENTAL PROCEDURE AND RESULTS

Measurements were performed with a hydrogen bubble chamber placed in a 13.5-kOe magnetic field. The apparatus was arranged as shown in Fig. 1. A  $\pi^-$  beam produced in an internal beryllium target of a proton synchrotron was momentum-analyzed by a bending magnet, after which it

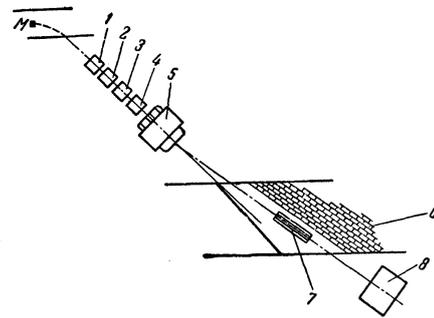


FIG. 1. Arrangement of measuring apparatus. M - target; 1-4 - quadrupole lenses; 5 - bending magnet; 6 - shield; 7 - collimator; 8 - hydrogen bubble chamber

was carefully collimated and guided to the input window of the hydrogen bubble chamber. A focusing system consisting of four quadrupole lenses was placed between the bending magnet and target. The mean  $\pi^-$  energy was 7.2 BeV; the primary  $\pi^-$  beam spread is represented satisfactorily by a Gaussian distribution of half-width  $\sim 0.8$  BeV/c.

Tracks on the photographic plates were measured by a graphic-analytic method. The radii of curvature of the tracks were obtained by measuring the coordinates of track points with a measuring microscope. Spatial angles were determined with accuracy  $\sim 0.7-1^\circ$ .

In 13,000 photographs we observed 1590 interactions between pions and protons; 192 events were identified as elastic scattering. We have previously [6] described our technique for determining the total interaction cross section and for investigating elastic scattering. The total cross section was  $\sigma_{\text{tot}} = 31.0 \pm 3.1$  mb. The total elastic and inelastic  $\pi^-$ -p cross sections were  $\sigma_{\text{el}} = 3.90 \pm 0.54$  and  $\sigma_{\text{inel}} = 27.1 \pm 0.3$  mb, respectively. Table I shows the distribution of charged particles in inelastic  $\pi^-$ -p collisions.

Table I

No. of prongs	Number of events	% of events	Cross section, mb
2	512	36.6	10.0
4	690	49.3	13.5
6	185	13.2	3.6
8	11	0.8	0.2

Because of the crowding of the chamber the number of stars with no charged particles was not determined. The upper limit of these stars is  $\sim 3\%$  of the inelastic interactions. The mean multiplicity of charged particles is  $\sim 3.6$ .

The proton was identified whenever possible by a momentum measurement and an ionization calculation. The following check was performed to estimate the efficiency of proton identification. In  $\sim 3000$  photographs we selected two-prong stars having one heavily ionizing particle. Protons were identified by measuring the momenta of these particles. Among these same two-prong stars we selected elastic  $\pi$ -p scattering events; these were identified by selecting coplanar events in which the angles of both secondary particles agreed with the kinematics of elastic scattering. We found that all protons determined from the kinematics of elastic scattering and having momentum  $\leq 1.5$  BeV/c are included in the set of events for which protons were identified by momentum measurements and ionization calculations.

Figures 2 and 3 show the c.m.s. momentum and

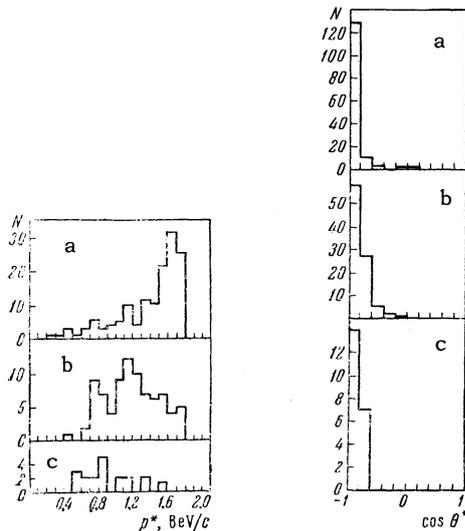


FIG. 2

FIG. 3

FIG. 2. Momentum distributions of protons in c.m.s. a - 2-prong stars; b - 4-prong stars; c - 6-prong stars.

FIG. 3. Angular distributions of protons in c.m.s. a - 2-prong stars; b - 4-prong stars; c - 6-prong stars.

angular distributions of protons in 2-, 4-, and 6-prong stars. In all instances the protons are emitted in a narrow backward cone. For 2-prong stars the proton momentum distribution exhibits a concentration of events about the value of proton momentum in elastic scattering. This peak in the momentum range 1.5-1.8 BeV/c is caused to a considerable degree by the two-particle kinematics of the formation of two-pion resonances  $\Pi$  with masses 550 and 760 MeV in the reaction  $\pi^- + p \rightarrow \Pi + p$  followed by the decay  $\Pi \rightarrow \pi^- + \pi^0$ .

Figures 4-7 show the momentum and angular distributions in the c.m.s. for  $\pi^+$  and  $\pi^-$  mesons in 2-, 4-, 6-, and 8-prong stars. The momentum distributions show a clear tendency toward a decrease of the mean pion momentum as the multiplicity increases. For low multiplicity the pion angular distributions are markedly asymmetric, pions being emitted predominantly in the primary-beam direction. The distributions agree with [7].

Table II shows the mean momenta and mean transverse momenta  $p_{\perp}$  for stars of different multiplicities. Neither protons nor pions show any appreciable dependence of  $p_{\perp}$  on multiplicity. The values of  $p_{\perp}$  also agree satisfactorily with data obtained both at higher [8] and lower energies.

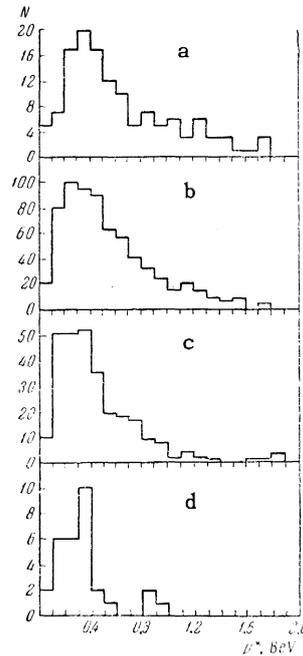


FIG. 4

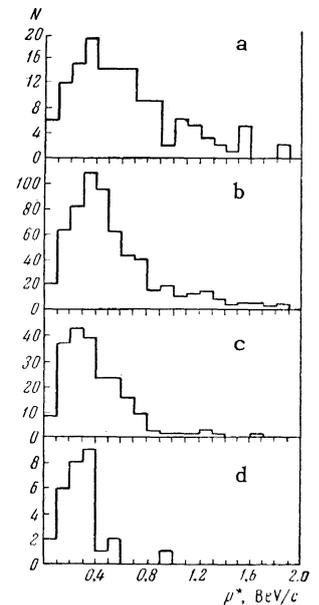


FIG. 5

FIG. 4. Momentum distributions of  $\pi^-$  mesons in c.m.s. a - 2-prong stars (reaction  $\pi^- + p \rightarrow \pi^- + \pi^+ + n + k\pi^0$ ); b - 4-prong stars; c - 6-prong stars; d - 8-prong stars.

FIG. 5. Momentum distributions of  $\pi^+$  mesons in c.m.s. a - 2-prong stars; b - 4-prong stars; c - 6-prong stars; d - 8-prong stars.

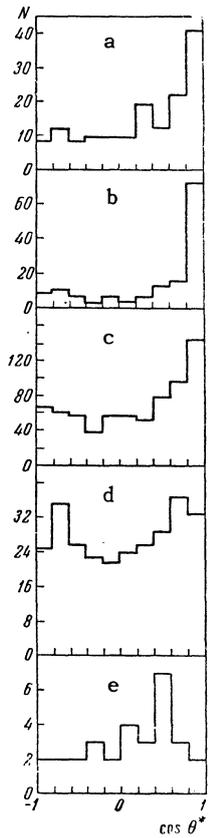


FIG. 6

FIG. 6. Angular distributions of  $\pi^-$  mesons in c.m.s. a and b—2-prong stars (a—reaction  $\pi^- + p \rightarrow \pi^- + p + k\pi^0$ ; b—reaction  $\pi^- + p \rightarrow \pi^- + \pi^+ + n + k\pi^0$ ); c—4-prong stars; d—6-prong stars; e—8-prong stars.

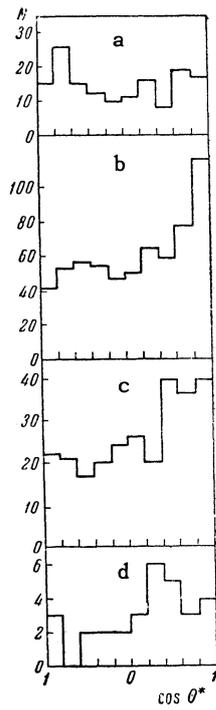


FIG. 7

FIG. 7. Angular distributions of  $\pi^+$  mesons in c.m.s. a—2-prong stars; b—4-prong stars; c—6-prong stars; d—8-prong stars.

### 3. DISCUSSION OF RESULTS

As already mentioned, the multiple production of pions is strongly affected by the formation of  $\pi\pi$  resonances. It is extremely likely that multiple production is accompanied by the formation of three- or four-pion resonance states which subsequently decay to lower resonance states or into pions. To test this hypothesis we searched for higher resonances in systems of three and

four pions. For this purpose we determined the effective masses of all possible pion combinations ( $\pi^-\pi^-\pi^+$ ,  $\pi^+\pi^+\pi^-$ , and  $\pi^-\pi^-\pi^+\pi^+$ ) for 4-prong stars. This was done by measuring the momenta and angles of the pions; the histograms are shown in Figs. 8—10. Figures 8 and 9 show the absence of a clear resonance structure for three-pion combinations. Considerable resonance structure is observed for four-pion combinations. However, the maxima in Fig. 10 do not possess sufficiently high statistical certitude and these maxima can possibly result from statistical fluctuations.

The effective-mass distribution of all outgoing prongs was plotted for the reaction  $\pi^- + p \rightarrow 2\pi^- + \pi^+ + p + k\pi^0$ .  $M_{\text{eff}}$  was determined by measuring the proton angles and momenta. The results are shown in Fig. 11. A maximum is observed beyond the phase volume curve at  $\sim 2000$  MeV. An analysis of the lacking masses shows that this peak evidently pertains to the formation of a  $\pi^+\pi^+\pi^-\pi^0$  system, although the results do not completely eliminate the possibility that it belongs to a three-pion state. The smooth curve represents the invariant phase volume (normalized to the same area as the histogram).

We also attempted to find a bound state of a neutron and several pions. For this purpose in the case of 4-prong stars we plotted the distribution of effective masses lacking in the  $\pi^+\pi^-$  system (the effective-mass distribution of the system  $n + \pi^- + \pi^+ + k\pi^0$ ). Effective masses were obtained from the formula

$$M_{\text{eff}}^2 = (E_0 - E_1 - E_2)^2 - (\mathbf{p}_0 - \mathbf{p}_1 - \mathbf{p}_2)^2,$$

where  $(E_0, \mathbf{p}_0)$ ,  $(E_1, \mathbf{p}_1)$ , and  $(E_2, \mathbf{p}_2)$  are, respectively, the energy and momentum of primary  $\pi^-$  mesons and of secondary  $\pi^-$  and  $\pi^+$  mesons. The instrumental resolution determined by the energy spread of the primary beam was  $\sim 150$  MeV. The results are shown in Fig. 12, where the smooth curve represents the invariant phase volume normalized so that the area under this curve equals the area under the histogram. The peak observed at  $2230 \pm 80$  MeV is more than three times the standard error.

Table II

No. of prongs in stars	Mean $\pi^-$ momentum, BeV/c	Mean $\pi^+$ momentum, BeV/c	Mean transverse momentum of $\pi^-$ and $\pi^+$ mesons, BeV/c	Mean transverse momentum of protons, BeV/c
2	$0.62 \pm 0.5$	$0.59 \pm 0.06$	$0.4 \pm 0.07$	$0.29 \pm 0.03$
4	$0.52 \pm 0.03$	$0.48 \pm 0.02$	$0.33 \pm 0.03$	$0.35 \pm 0.04$
6	$0.43 \pm 0.04$	$0.39 \pm 0.04$	$0.32 \pm 0.02$	$0.37 \pm 0.09$
8	$0.34 \pm 0.06$	$0.30 \pm 0.08$	$0.27 \pm 0.04$	—

FIG. 8. Effective-mass distribution of 3-prong combinations in 4-prong stars:  $\pi^-\pi^-\pi^+$  combinations.

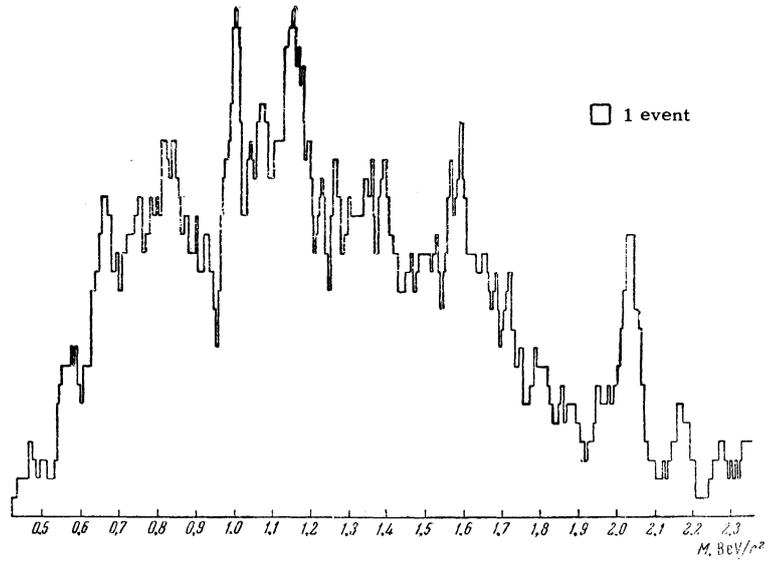


FIG. 9. Effective-mass distribution of 3-meson combinations in 4-prong stars:  $\pi^+\pi^+\pi^-$  combinations.

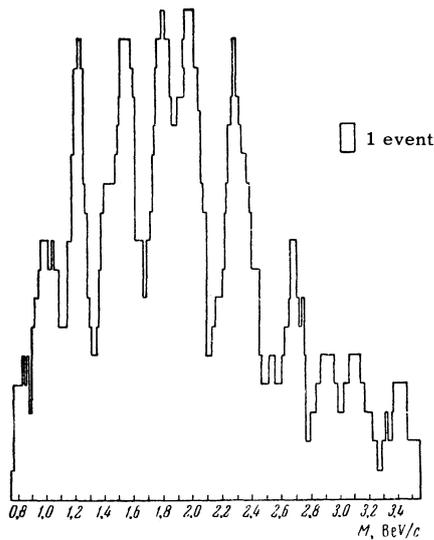
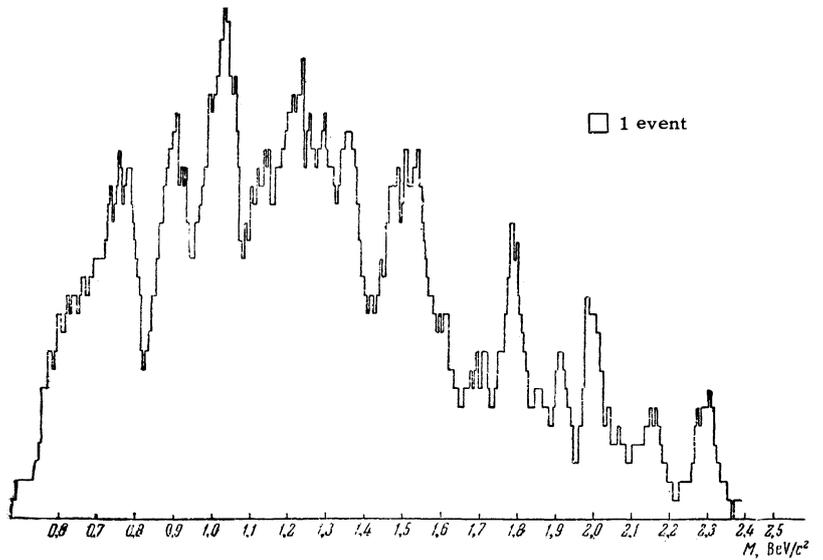


FIG. 10. Effective-mass distribution of 4-meson combinations in 4-prong stars:  $\pi^+\pi^+\pi^-\pi^-$  combinations.

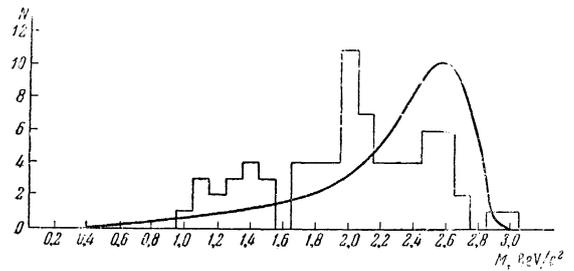


FIG. 11. Effective-mass distribution of all pions in the reaction  $\pi^- + p \rightarrow 2\pi^- + \pi^+ + p + k\pi^0$ .

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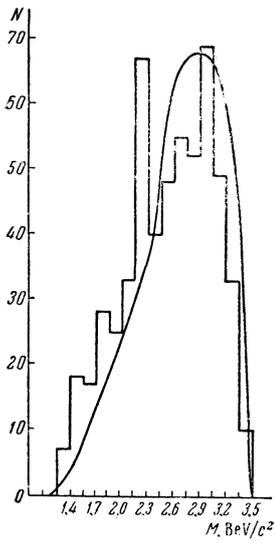


FIG. 12. Effective-mass distribution in neutron-pion combinations for 4-prong stars.

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