CHARACTERISTICS OF π^--NUCLEON COLLISIONS AT A PRIMARY ENERGY OF 4·4 GeV

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ABSTRACT

Eight hundred and sixteen nuclear interactions produced by 4·4 GeV π^--mesons in nuclear emulsion have been obtained by "along the track" scanning procedure. Favourable secondary particles from a selected 290 π^--N (pion-nucleon) collisions have been identified by blob-density and multiple scattering measurements. It is found that the pion often persists in these π^--N collisions, the average persistence is estimated to be 0·24 per collision. It is estimated that π-N and π-π collisions account for 60% and 28% respectively of the secondary particles. The average number of charged shower particles is $< n_s > = 2 \cdot 09 \pm 0 \cdot 12$, the average number of created charged particles is $<n_c\pm> = 1 \cdot 94 \pm 0 \cdot 12$, the average number of protons with energy greater than 300 MeV is $< n_p > = 0 \cdot 15 \pm 0 \cdot 05$ and the average number of charged kaons is found to be $<n_k\pm> = 0 \cdot 11 \pm 0 \cdot 06$. The integral energy spectra of pions in C-system as well as in L-system are well represented by exponential forms. The average inelasticity of the proton in C-system is found to be $0 \cdot 52 \pm 0 \cdot 10$. The charge retention probability for protons in π^--p collisions is $0 \cdot 45 \pm 0 \cdot 07$.

1. INTRODUCTION

DURING the last few years several investigations[1–24] have been carried out on π^--N (pion-nucleon) interactions at energies in the region of 1–16 GeV. In addition to these, there has also been an investigation[25] in which essentially π^--nucleus interactions have been studied in nuclear emulsion at 4·5 GeV. The only investigations carried out so far to study the characteristics of π^--N interactions at 4·5 GeV have been due to Maenchen *et al.*[3,5] Walker,[6] Femino *et al.*[23] and Bondár *et al.*[24]

In the present investigation, a detailed study of the characteristics of π^--N interactions has been carried out at 4·4 GeV in nuclear emulsion.

A special feature of this investigation is the identification of relativistic secondary particles from careful blob-density and scattering measurements. The important results that have emerged from this study concern (i) the 'persistence' of pions, (ii) the relative proportion of π-π and π-N collisions, (iii) the average multiplicity of particles other than protons, (iv) the angular distributions of secondary particles in laboratory system (L-system) and the centre of momentum system (C-system) as a function of multiplicity, (v) the nature of the energy spectra of secondary particles in L-system and C-system for events of different multiplicities, (vi) the inelasticity of the proton in the C-system, (vii) the probability of the proton to emerge as a proton in π^--p collisions, (viii) the distribution of transverse momentum of charged pions and (ix) the dependence of the average transverse momentum of charged pions on the angle of emission and on the multiplicity of the event. The results relating to the transverse momentum are under publication in a separate paper[26] and hence have not been discussed here.

Some of the features of π^--N collisions at 4·4 GeV are compared with those of p-N collisions at 6·2 GeV, since the available energy in the C-system in the two cases is same.

2. Experimental Procedure

In the present investigation, a stack* of 95 Ilford G5 emulsion pellicles of size 35 cm. × 25 cm. × 630 μm, exposed for 11 hours to a beam of π^--mesons at Berkeley have been employed. The momentum of the beam varied gradually across the beam from 4·8 GeV/c at one end to 3·8 GeV/c at the other end of the 35 cm. side of the stack. Only three pellicles were used in the present investigation. The thicknesses of the pellicles at the exposure time were checked by making range measurements on μ-mesons from π-μ decays at rest. The average thickness was found to be 635 μm., which agrees with the value of 630 μm. obtained from measurements made by the Paris group prior to the actual exposure.

The emulsions were scanned by the well-known "along the track" scanning procedure under a total magnification of about 1500 × (oil immersion) in the region where the energy of the beam pions is 4·4 GeV and the intensity of the beam is about 10^5/cm.^{2} (No attempt was made to note the lengths of the tracks followed.) In this way, a total of 816 interactions

* We are grateful to Professor Leprince-Ringuet of the Ecole Polytechnique, Paris, for kindly lending this stack to us. This stack was originally used by the Paris group[27] for work on K-mesons.

was recorded in the middle regions of the emulsions, excluding 50 μm. from either of the surfaces in the unprocessed emulsions; these include also events of the type $0 + 0 + 1$ in which the secondary track makes an angle greater than 5°. This criterion was adopted to exclude events resulting from diffraction scattering of the beam pions by emulsions nuclei. In all, three observers took part in the scanning and since they are the same observers who did the bulk of the scanning for the 6·2 GeV proton interactions,[28] it is believed that the scanning efficiency for events with $N_h \leqslant 1$ is nearly 100%. All the stars were assigned sizes according to the nomenclature described in the investigation[28] on 6·2 GeV *p*–N interactions.

The composition of emulsion is such that the number of collisions with free hydrogen is expected to be only a few per cent. of the total. However, a fair percentage of collisions with C, N and O nuclei and to a lesser extent with Ag and Br nuclei are of the extreme peripheral type, which result at most in one black or grey track (probably due to the recoiling proton) beside the shower particles. These inelastic events of the types $0 + 0 + n_s$, $1 + 0 + n_s$, and $0 + 1 + n_s$, in which the 'grey' proton is emitted in the forward hemisphere, will henceforth be denoted† as *class A*. Of the total 816 interactions, there are 109 (99 inelastic and 10 elastic) belonging to class A stars (there are two events of the type $0 + 1 + n_s$, in which the 'grey' proton is emitted in the backward hemisphere; these of course have not been included in class A).

For many considerations regarding π^--N collisions, it seems possible to justify the inclusion of even stars with a few black prongs associated with them. In an earlier investigation[28] on *p*–N collisions at 6·2 GeV, the behaviour of $\langle n_s \rangle$, the average multiplicity of shower particles, and θ_M, the median angle of the shower particles, has been studied as a function of N_h, the number of black *plus* grey tracks. It was then observed that N_g, the number of grey tracks associated with an event, is a better index of secondary interactions occurring within the target nucleus, than N_b, the number of black prongs, or N_h. It was further shown that the class of stars designated in the present paper as *class B*, with $N_h \leqslant 5$, but $N_g = 0$ or 1, (in a case where there is a grey track it should be in the forward hemisphere) have characteristics very similar to class A stars. It was therefore concluded

† The nomenclature used in our earlier paper[28] appears to be somewhat misleading. In the present investigation, we have denoted class A and class B stars as those called class B and class A respectively, in that paper.

that class B stars (which also includes class A) represent an extremely enriched sample of collisions in which only one target nucleon has taken part. There are in all 300 stars (290 inelastic and 10 elastic) belonging to class B. In this investigation, use has been made of class A and class B inelastic interactions to obtain information about various characteristics of π^--N collisions. However, for deducing information on the recoiling protons, only class A stars have been employed.

3. IDENTIFICATION OF SECONDARY PARTICLES

All secondary shower particles (defined as those with blob-density $\leqslant 1 \cdot 4$ times the plateau value) with projected length $\geqslant 3$ mm. in the same emulsion have been identified by blob-density and multiple Coulomb scattering measurements in a manner similar to that described in ref. 28 except for the fact that instead of using grain-density we have used in the present investigation blob-density as the ionisation parameter.

On the average 1,000 blobs and in no case less than 400 blobs were counted on each shower track. The blob-densities of all tracks were normalised to correspond to that at the middle of the emulsion.

In order to estimate spurious scattering in these emulsions, extensive measurements were made on the beam tracks using a basic cell size of 1 mm. It was found that the spurious scattering in these emulsions is constant in the region between 50 μm. from the air surface to 50 μm. from the glass surface of the unprocessed emulsion. These emulsions were found to have low spurious scattering; the mean sagitta for spurious scattering D_{SS} was found to be $0 \cdot 140 \pm 0 \cdot 011$ μm. for 1 mm. cell size (based on 1,645 cells). For 250 μm. and 500 μm. cell sizes, we have used values of $0 \cdot 046$ μm. and $0 \cdot 080$ μm. respectively, which were calculated from the value for 1 mm. on the assumption of $t^{0 \cdot 8}$ dependence of spurious scattering on cell size.[29] The total noise (reading, grain, etc.) was measured to be $0 \cdot 075$ μm. The contributions of spurious scattering and the total noise were subtracted quadratically from the observed mean second difference to yield that due to multiple Coulomb scattering.

Figure 1 shows the plot of B/B_0, the ratio of the blob-density of the secondary track to that of the beam track, *versus* $p\beta$. The entire sample of 188 tracks, from a total of 607 shower particles associated with 290 interactions on which the blob-density and scattering measurements were made, has been divided into two categories, (i) 132 tracks on which a total of 700 or more blobs were counted (Fig. 1 *a*) and (ii) 56 tracks on which less than

700 but more than 400 blobs were counted (Fig. 1 *b*). The curve drawn is due to Johnston *et al.*[30] and is found to agree well with the curve one would draw through the centre of gravity of the distribution of points in Fig. 1 *a*. The particles have been identified as mentioned in the legend to Fig. 1. Tracks having $p\beta \geq 1 \cdot 5$ GeV/c have been arbitrarily assumed to be due to pions. This cannot be wrong because even if the proton is brought to rest in the C-system it will have a $p\beta = 1 \cdot 35$ GeV/c in the L-system; the proton should therefore have $p\beta \leqslant 1 \cdot 35$ GeV/c. The contamination due to K-mesons in this region is also expected to be small.

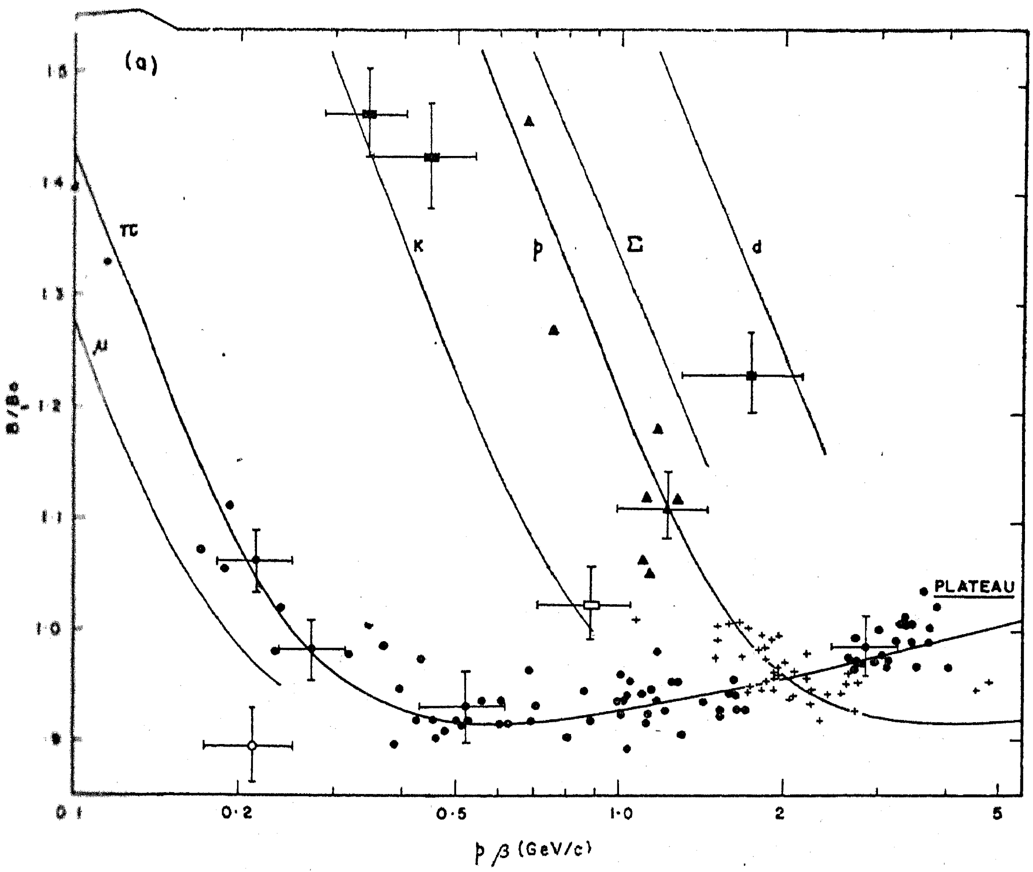

FIG. 1 (*a*). Plots of B/B_0 against $p\beta$ for 132 shower tracks on which $\geqslant$ 700 blobs were counted, ● Identified pions, + assumed pions, ▲ identified protons, ■ deuteron or sigma hyperon. ▬ identified kaon, □ assumed kaon and O muon (?).

The 188 tracks on which measurements have been made are classified as follows: 168 pions, 11 protons, 7 kaons (4 definite and 3 doubtful), 1 muon (?) and 1 possible deuteron or sigma hyperon.

Since measurements were made only on those shower tracks which had a projected length greater than 3 mm, in the emulsion plate, it introduces a certain amount of bias favouring tracks having small space angles. In order to study any parameter which depends on the emission angle of the track, proper corrections must be made to take this bias into account. For this purpose, we have assigned to each track a 'geometric factor' which depends on its emission angle and its location in depth of the emulsion. The degree of correctness of this assignment can be gauged from the fact that the sum of the geometric factors of 188 shower tracks which satisfied the selection criteria amounts to 627 as compared to a value of 607 for the total observed shower tracks from which the 188 tracks were selected for measurements.

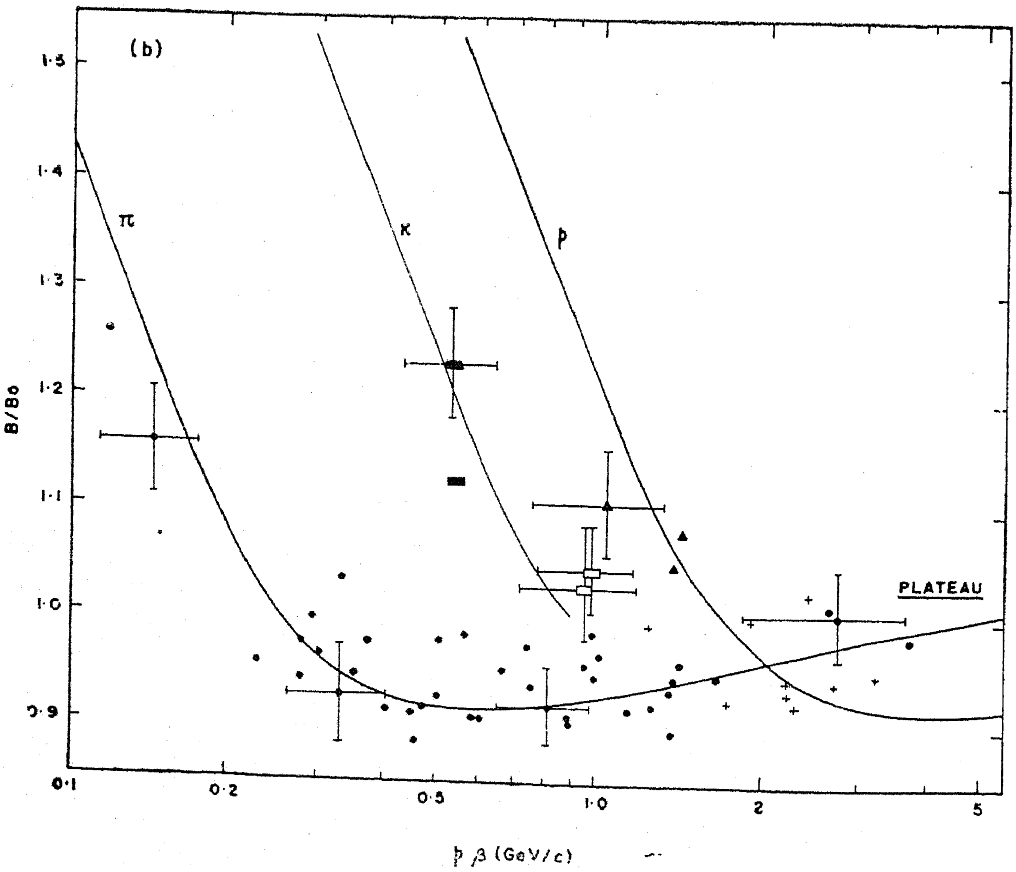

FIG. 1 (*b*). Plots of B/B_0 against $p\beta$ for 56 shower tracks on which < 700 blobs were counted. ● Identified pions, + assumed pions, ▲ identified protons, ▬ identified kaon and □ assumed kaon.

4. GENERAL CHARACTERISTICS

4.1. *Disappearing Tracks*

There are in all 5 events in which the tracks are found to disappear in the emulsion. Great care has been taken to see that none of these is due to spurious events and that there is no associated large angle track of minimum ionisation. These events are classified as $0 + 0 + 0$ and they presumably result from reactions of the type:

$$\pi^- + p \rightarrow \pi^\circ + n \qquad \text{(charge exchange)} \qquad (1)$$

$$\pi^- + p \rightarrow x\pi^\circ + n \qquad (x = 2, 3, 4 \ldots) \qquad (2)$$

and,

$$\pi^- + \text{nucleus} \rightarrow x\pi^\circ + \text{nucleus} \qquad (x = 1, 2, 3 \ldots) \qquad (3)$$

None of the 5 events has any recoil or slow electron associated with it and therefore it is not possible to classify any of them uniquely as due to a collision with a proton or a nucleus.

4.2 *Distributions of N_h and n_s*

The distribution of N_h for pion collisions with emulsion nuclei at 4·4 GeV is shown in Fig. 2. For comparison, the distribution for 6·2 GeV proton interactions,[28] normalised to the same number as that of

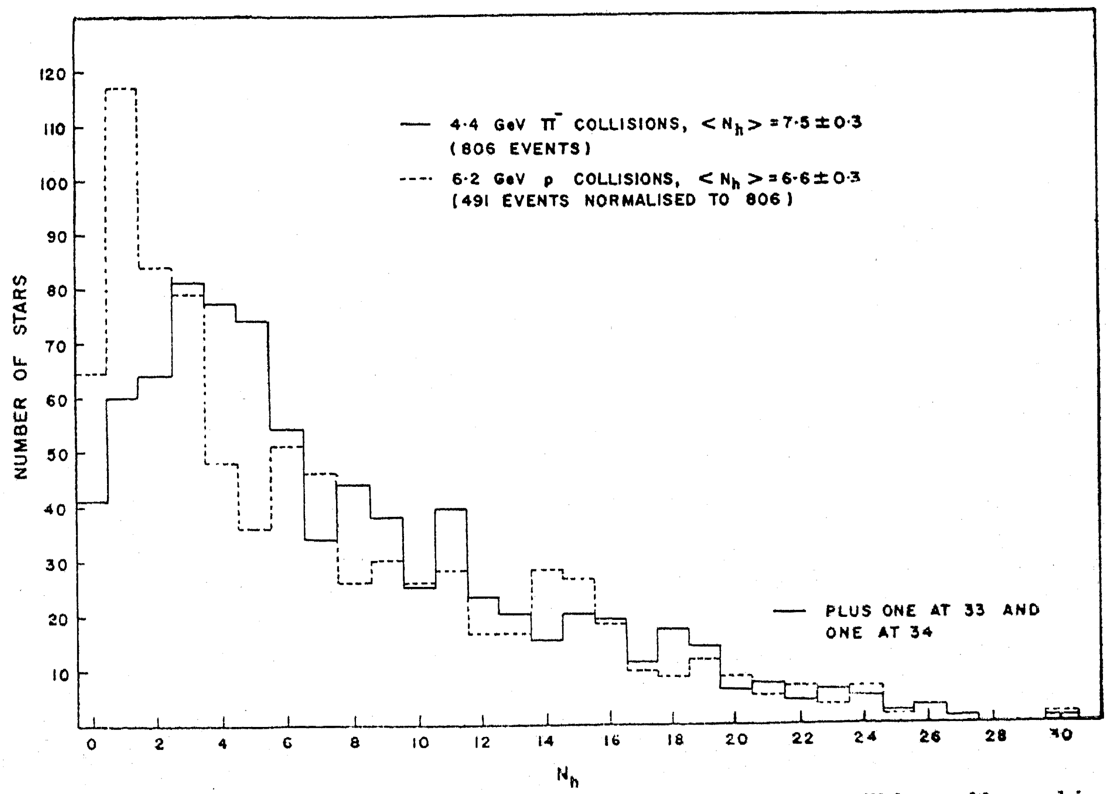

FIG. 2. Distributions of N_h for 4·4 GeV π^-- and 6·2 GeV proton collisions with emulsion nuclei. The latter distribution is normalised to a total number of 806 events, which is the total number of 4·4 GeV π^- inelastic interactions with emulsion nuclei.

pion interactions, is also shown in this figure. It may be mentioned that in this energy region the N_h-distribution for stars produced by protons in emulsion is extremely insensitive to primary energy and therefore any difference in the N_h-distribution for pions and protons will have to be attributed to genuine difference in the characteristics of pion and proton interactions. It is quite obvious from Fig. 2 that the two distributions are not quite the same. In particular, there is an appreciable excess of events with $N_h = 0$, 1 and 2 in the case of proton interactions (267 events) as compared to those of pion interactions (165 events) with emulsion nuclei. The mean and median values of N_h for π^--interactions in emulsion at 4·4 GeV are $7\cdot5 \pm 0\cdot3$ and $5\cdot1 \pm 0\cdot2$ respectively; the corresponding values for proton interactions[28] at 6·2 GeV are $6\cdot6 \pm 0\cdot3$ and $4\cdot3 \pm 0\cdot2$. In another investigation[31] on proton interactions in emulsion at 6·2 GeV, the average value of N_h has been found to be $8\cdot7 \pm 0\cdot3$. In view of this disagreement between the values of $<N_h>$ found in the two investigations in which proton inter-actions in emulsion have been studied at 6·2 GeV, it is difficult to draw any definite conclusion regarding any possible differences in imparting excita-tion energy to the emulsion nuclei by incident negative pions and protons at energies 4–6 GeV.

Figure 3 shows the distributions of n_s, the multiplicity of shower parti-cles, in π^--N collisions at 4·4 GeV and p-N collisions at 6·2 GeV; the latter is normalised such that the total number of events is 290, the number of inelastic π^--N events. It is apparent that these two distributions are very similar. This observation has great significance in view of the fact that the available energy in the C-system in π^--N and p-N collisions at these energies is same.

The average values of n_s for π^--N collisions at 4·4 GeV and p-N collisions at 6·2 GeV are $2\cdot09 \pm 0\cdot12$ and $2\cdot28 \pm 0\cdot16$ respectively. In both these cases the distribution of n is fairly broad, the standard deviation being 1·30 for π^--N collisions and 1·50 for p-N collisions.

4.3. *Average Multiplicity $<n_s>$ and Median Angle θ_M as Functions of N_h*

The dependence of $<n_s>$ on N_h is shown in Fig. 4 (*a*) for all stars. It is found from this figure that $<n_s>$ is constant from $N_h = 0$ to about 10 and then decreases steadily as N_h increases; this effect is presumably due to the absorption of shower particles in the target nucleus resulting in higher excitation energy of the nucleus and hence in larger N_h. This is in contrast to the observations[28] made on proton collisions in emulsion at 6·2

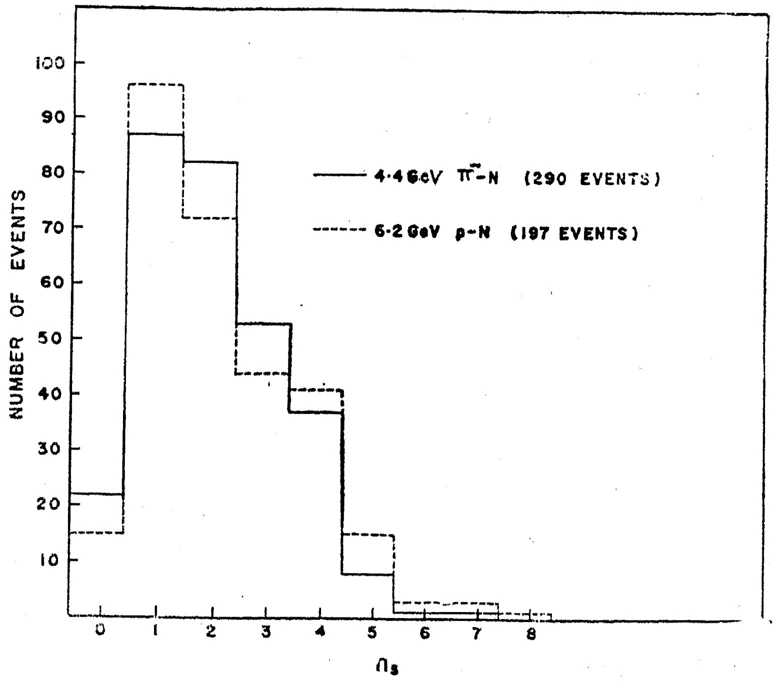

FIG. 3. The distributions of n_s for class B stars in the case of 4·4 GeV π^--N collisions (290 events) and 6·2 GeV p-N collisions (197 events), normalised to 290 events.

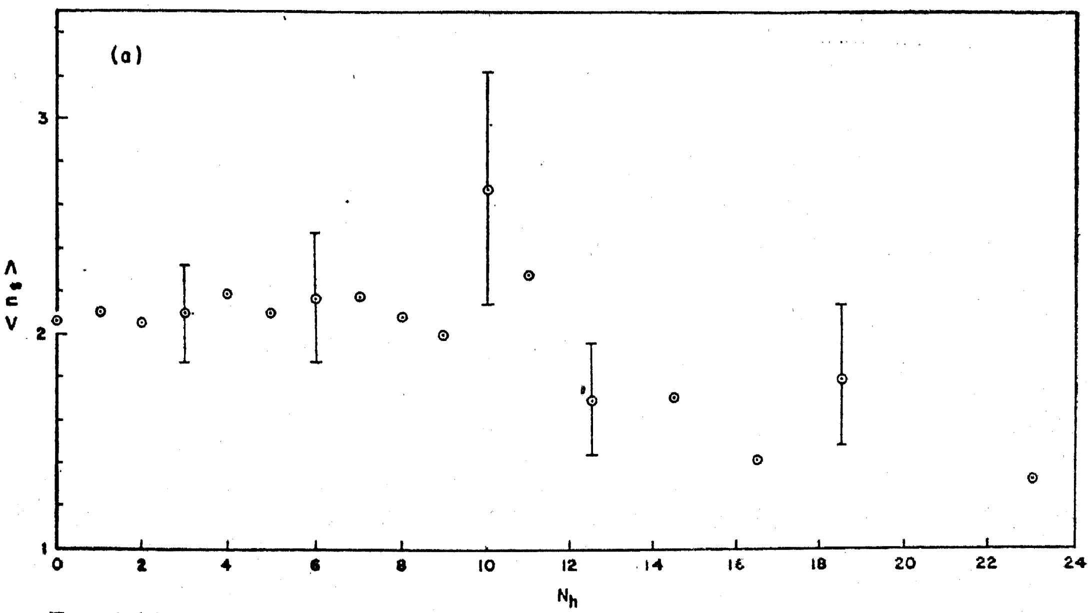

FIG. 4 (a). Dependence on N_h of the average multiplicity of shower particles $<n_s>$.

GeV, where it was found that $<n_s>$ increases as N_h increases till $N_h \sim 16$ and then decreases somewhat. The following explanation may be tentatively suggested for this difference. At the primary energies we are dealing with, the particles created in the first collision of a primary proton or a pion with one of the nucleons of the nucleus do not have enough energy to produce further mesons on suffering secondary interactions; their energy is rather converted primarily into excitation energy of the nucleus which manifests itself in the form of increased N_h. On the other hand, the surviving primary particle whether it be proton or pion still has enough energy (since the inelasticity is only $\sim 0 \cdot 5$) to produce mesons on suffering further interactions in the nucleus. The difference in the dependence of $<n_s>$ on N_h for collisions of protons and pions with emulsion nuclei can then be understood on the basis of the different cross-sections for *p-p* and π^--*p* collisions. The cross-section[32] for a π^--*p* collision is significantly less than that for *p-p* collision in the relevant energy region (3-6 GeV) and therefore the surviving proton (in a *p*-N collision within a nucleus) on the average suffers more secondary interactions as compared to the surviving pion (in a π^--N collision within a nucleus) and consequently the multiplicity for high values of N_h in the case of proton interactions with emulsion nuclei at $6 \cdot 2$ GeV is expected to be somewhat more than that of pion interactions with emulsion nuclei at $4 \cdot 4$ GeV, even though the average multiplicity in *p*-N and π^--N collisions at these two energies is found to be equal.

Figure 4 (*b*) shows the dependence of θ_M on N_h. It is found that θ_M increases with N_h till $N_h \sim 15$, in a manner very similar to that observed[28]

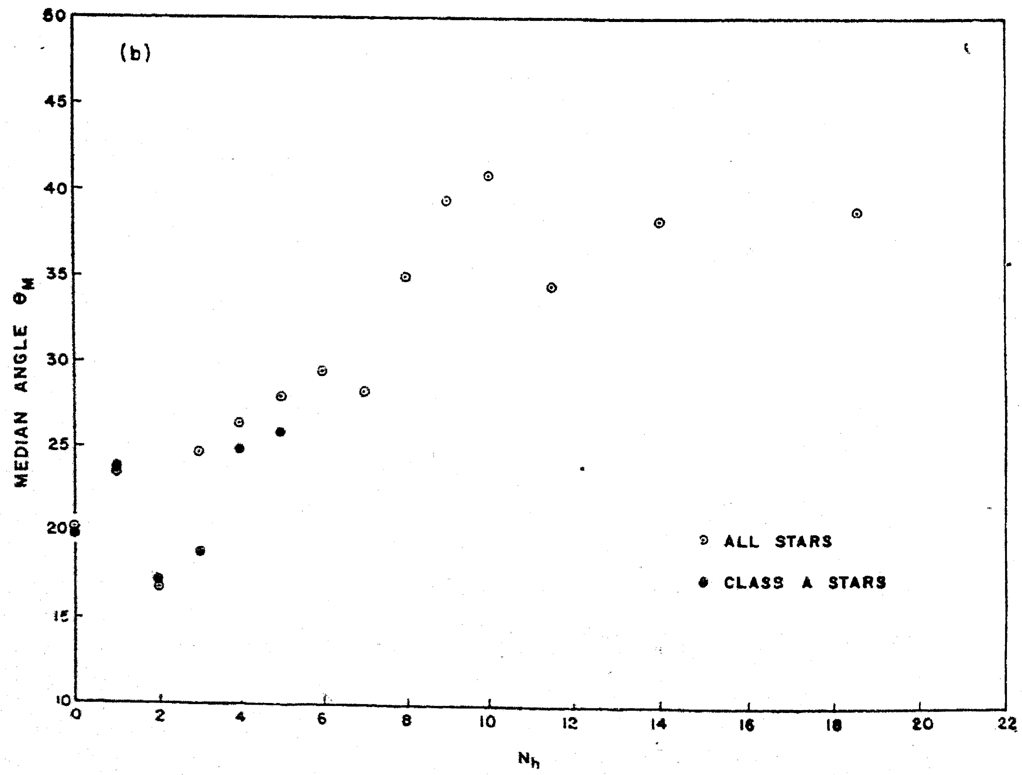

FIG. 4 (*b*). Dependence on N_h of the median angle of shower particles, θ_M.

in the case of proton collisions at 6·2 GeV. This, together with the behaviour of $<n_s>$ as a function of N_h, discussed above, indicates that at a primary energy of 4·4 GeV the secondary particles created inside the nucleus either suffer large angle scatterings or catastrophic collisions in which the secondary particle is absorbed and the energy is transferred to the evaporation particles.

4.4. *Multiplicity*

Favourable relativistic secondary particles have been identified according to the procedure outlined in Section 3.

4.4.1. *Average number of charged shower particles and created particles per interaction.*—The observed values for the average multiplicities for different classes of stars are summarised in Table I. The average multiplicity $<n_s>$ includes all pions (slow and fast) and protons of energy greater than 300 MeV.

TABLE I

Mean multiplicities for various classes of stars

Class of stars	$<n_s>$	$<n_c\pm>$
Class A	2·12±0·21	1·97±0·21
$N_h \leqslant 2$	2·07±0·17	1·92±0·17
Class B	2·09±0·12	1·94±0·12
π^--p	1·87±0·27	..
π^--n	2·48±0·48	..

The mean multiplicity of charged created particles, $<n_c\pm>$, has been obtained after subtracting from $<n_s>$ the contribution due to protons among shower particles (which has been estimated as 0·15 per interaction in Section 4.4.2). The created particles, at these low primary energies, are mostly pions with a small admixture of kaons and hyperons. It is estimated that the average number of charged kaons is 0·11 ± 0·06 (*see* Section 4.4.2). If one assumes that the production of charged hyperons is negligible at this energy, one can write $<n_c\pm> - 0{\cdot}11 = <n_\pi\pm>$.

It is concluded from the present investigation that in π^--N collisions at 4·4 GeV, $<n_s> = 2{\cdot}09 \pm 0{\cdot}12$ and $<n_c\pm> = 1{\cdot}94 = 0{\cdot}12$; the corresponding values in p-N collisions at 6·2 GeV are $2{\cdot}19 \pm 0{\cdot}17$ and $1{\cdot}60 \pm 0{\cdot}15$ respectively. The quantity $<n_c\pm>$ for π^--N collisions also includes the contribution of the 'persisting' pions which has been estimated to be $0{\cdot}24 \pm 0{\cdot}03$ per collision (*see* Section 5). These 'persisting' pions are akin to 'forward' protons in the investigation[28] on p-N interactions at 6·2 GeV. Thus, the average number of *created* particles in π^--N collisions is $1{\cdot}94 - 0{\cdot}24 = 1{\cdot}70 \pm 0{\cdot}12$. It is this number which should be compared with $<n_c\pm> = 1{\cdot}60 \pm 0{\cdot}15$ in p-N collisions. It can therefore be concluded that the multiplicities of the created particle in π^--N collisions at 4·4 GeV and p-N collisions at 6.2 Gev are equal. It should be noted that the available energies in the C-system in these two types of collisions are also equal.

An attempt has also been made to obtain information on multiplicity in π^--p and π^--n collisions; for this, events belonging to class A and having even or odd charged secondaries are assumed to be due to π^--p and π^--n collisions respectively. From a total of 48 (excluding the events of 0 + 0+ 0 type, *see* Section 4.1) π^--p events and 35 π^--n events, it is found that $<n_s> = 1{\cdot}87 \pm 0{\cdot}27$ and $2{\cdot}48 \pm 0{\cdot}48$ respectively.

4.4.2. *Average number of fast protons and kaons per interaction.*—Among the shower particles (blob-density $\leqslant 1{\cdot}4$ times the plateau value) associated with 290 class B interactions there are 11 protons and 4 charged kaons having total geometric weights of 43·3 and 30·5 respectively, thus giving $<n_p> = 0{\cdot}15 \pm 0{\cdot}05$ and $<n_K\pm> = 0{\cdot}11 \pm 0{\cdot}06$.

5. 'PERSISTENCE' OF PIONS AND RELATIVE PROPORTION OF π-N AND π-π COLLISIONS

An instructive way of studying the angular distribution of secondary particles is to plot the differential distribution in log tan θ (where θ is the angle of emission of the secondary particle with respect to the primary direction) in the L-system. If the emission of particles is symmertic in the C-system, it can be shown that this distribution will be a near gaussian centred at $-\log \gamma_c$, where γ_c is the Lorentz factor of the C-system. Further, an isotropic distribution in the C-system is characterised by a dispersion of 0·39, under the assumption that $m = \beta_c/\beta^* = 1$, *i.e.*, the ratio of the velocity of the C-system to that of the particles in the C-system is equal to unity. An anisotropic distribution has a dispersion greater than 0·39.

The magnitude of the dispersion is therefore a measure of the anisotropy. The anisotropy may be due to the fact that several systems moving with different relative velocities contribute to particle production. Thus, for example, if the pion-nucleon collisions are a mixture of π-π and π-N collisions, with isotropic emission in the respective C-systems, then the resultant distribution in log tan θ will be a superposition of two nearly gaussian distributions centred at two different values of $\log \tan \theta = -\log \gamma_C$, and consequently the dispersion of the resulting distiibution will be greater than 0·39. In the following, an attempt has been made to use these ideas to estimate the relative proportion of π-π and π-N types of collisions.

In Fig. 5 (*a*) is plotted $y = d\mathrm{N}/dx$, against $x = \log \tan \theta$ for the 607 shower particles associated with 290 class B interactions. [In Section 4.4.2 it is estimated that $(15 \pm 5)\%$ of these are protons, but here no attempt has been made to exclude them.] This distribution is found to have $< \log \tan \theta > = -0{\cdot}386$ and a dispersion of 0·528 as against the expected values of $-0{\cdot}240$* and 0·39 respectively for π-N collisions assuming isotropic distribution in C-system. Since the values actually obtained are significantly greater, the observed distribution can be attributed as due to a mixture of π-π and π-N types of collisions.

It can be shown that if the angular distribution in a system, having a Lorentz factor γ_C, is isotropic, and $\beta_C = \beta^*$, then the angular distribution in L-system is given by

$$\frac{d\mathrm{N}}{dx} = 2\left[\frac{10^{(x+\log \gamma_c)}}{1+10^{2(x+\log \gamma_c)}}\right]^2 \tag{5}$$

where $x = \log \tan \theta$. For primary pions of energy 4·4 GeV, $\gamma_C = 1{\cdot}78$ for a π-N collision and $\gamma_C = 4{\cdot}05$ for a π-π collision. Using the above

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* On the assumption that $m = 1$, we should have found $< \log \tan \theta > = -\log \gamma_c = -0{\cdot}250$ for π-N collision. We have tried to estimate the effect of the assumption $m = 1$ in the following way: The average kinetic energy of pions in the π-N C-system is found to be 346 MeV (*see* Sect. 6·2). Thus, the characteristic value of $m = \beta_c/\beta^* = 0{\cdot}826/0{\cdot}957 = 0{\cdot}863$. Further, it can be shown that if the angular distribution in the C-system is isotropic and $m < 1$, then the true value of the Lorentz factor, γ_{ct}, is related to the Lorentz factor γ_c, derived on the assumption $m = 1$, according to the relation

$$\gamma_{ct} = \gamma_c \frac{2(1-m)^{1-m/2}}{(1+m)^{1+m/2}}\,. \tag{4}$$

Using this relation, with $m = 0{\cdot}863$, it is found that $\gamma_{ct}/\gamma_c = 0{\cdot}977$. Since $\gamma_c = 1{\cdot}78$, one obtains $\gamma_{ct} = 1{\cdot}74$ and therefore the correct centre of the distribution should be located at $\log \tan \theta = -\log \gamma_{ct} = -0{\cdot}240$.

equation, the angular distributions in L-system were computed for π-N and π-π collisions, assuming isotropic emission in the respective C-systems. The experimental distribution shown in Fig. 5 (a) was then fitted by trial and error with varying contributions of π-N and π-π collisions till the observed distribution was well represented. In this way, it was found that π-N collisions account for 367 out of a total of 607 particles or 60% of

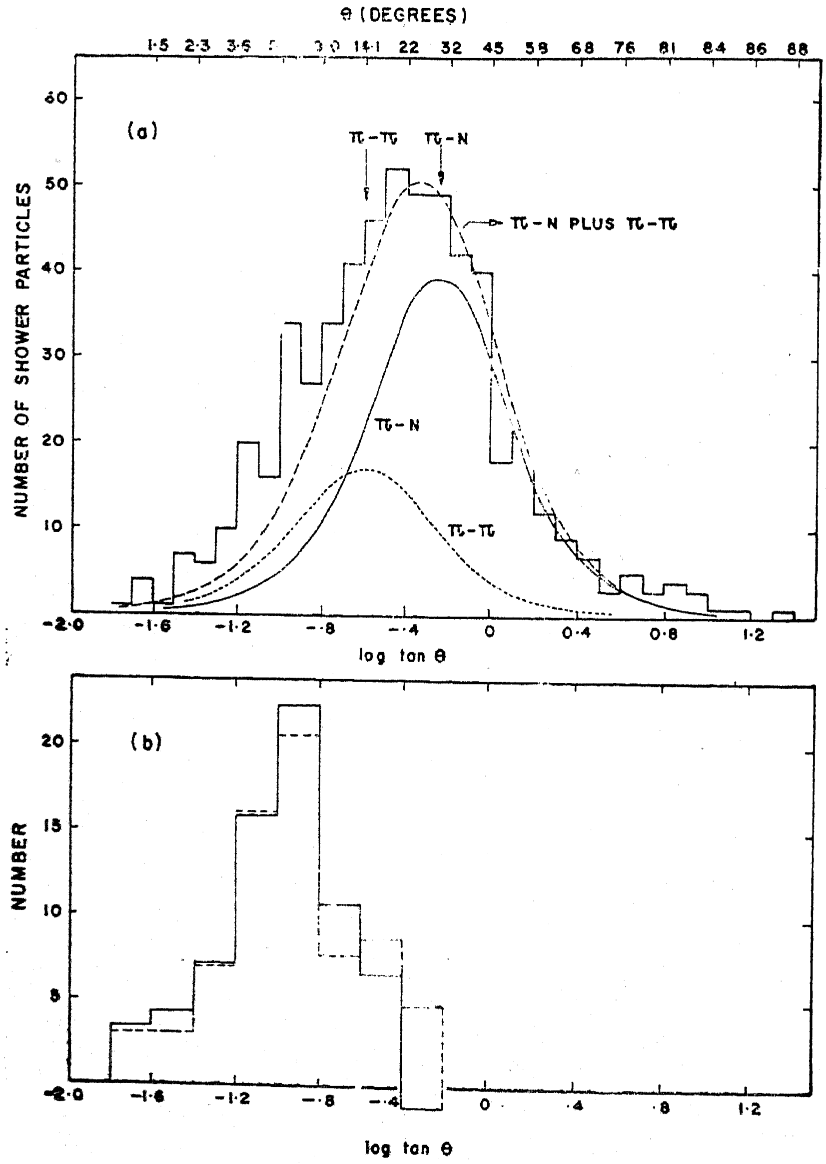

FIG. 5 (a). Log tan θ distribution of 607 shower particles associated with 290 class B 4·4 GeV π^--nucleon interactions. Curves drawn — and . . . . are calculated distributions for isotropic emission from π-N and π-π centre of momentum systems, respectively. The curve - - - is the sum of the curves —— and . . .

FIG. 5 (b). Log tan θ distribution for the difference of the experimental histogram and the curve - - - in (a). The dotted histogram is for the 70 highest energy identified pions.

all particles and π-π collisions account for 170 particles, or 28% of all the particles.

It is also seen (Fig. 5 *a*) that there are appreciable number of particles at small angles which could not be satisfactorily accounted for on the hypothesis of isotropic emission from π-N and π-π C-systems. We are therefore led to the natural explanation that these extra 70 tracks at relatively small angles are due to the 'persistence' of pions; this kind of effect has already been reported at 16 GeV.[21] The average value of 'persistence' in the present work is found to be $70/290 = 0 \cdot 24 \pm 0 \cdot 03$ per collision. In Fig. 5 (*a*) the solid line gives the log tan θ distribution of the persisting pions and is the difference between the experimental histogram and the combined π-N and π-π curves shown in Fig. 5 (*a*). Since these persisting pions have small angles of emission, they may be expected to have the highest energies. Therefore, of the 168 secondary particles identified as pions, those with the highest energies were selected such that the sum of their geometric factors amounted to 70. It is then found that the lowest energy of these is 1·8 GeV, *i.e.*, 41% of the primary pion energy. The log tan θ plot for these highest energy pions is shown with broken lines in Fig. 5 (*b*). As can be seen from this figure, there is very good agreement between this distribution and that deduced earlier for the persisting pions. It can therefore be concluded that almost all of the pions with energy greater than 1·8 GeV are due to the persisting pions. Further, in about 80% of these cases, they make angles less than 10° with respect to the primary direction. The average transverse momentum of these pions is 350 ± 50 MeV/c, which is within errors the same as the average value (300 ± 23 MeV/c) for all pions.[26] However, the average charged shower particle multiplicity $<n_s>$ of the events containing persisting pions is $1 \cdot 72 \pm 0 \cdot 25$ as compared to $2 \cdot 26 \pm 0 \cdot 14$ for all events with $n_s \geqslant 1$ (for events with $n_s \geqslant 0$, $<n_s> = 2 \cdot 09 \pm 0 \cdot 12$).

6. Angular and Energy Distributions

6.1. *Angular Distribution of Pions in the C-systems of π-N and π-π Collisions*

As described in Sect. 3, of the 188 shower particles identified, 168 are pions. Each of these have been assigned a 'geometric factor' depending on its space angle to take into account the bias against tracks at larger angles. A computer programme was run to carry out the Lorentz transformations from the L-system to the C-system.

Figure 6 shows the angular distributions of pions in the π-N C-system separately for events with n_s=1, 2, 3, $\geqslant$4, $\leqslant$2, $\geqslant$3 and $\geqslant$ 1. It is clear from

Fig. 6 (g) that the overall distribution is considerably asymmetric in the π-N C-system. The ratio of the number of tracks in the forward hemisphere to the number in the backward hemisphere is found to be 1·61. In order to see whether this is due to the fact that some of the pions result effectively, from a collision of the incident pion with a virtual pion of the nucleon cloud, transformations were also carried out from L-system to the π-π C-system. The distributions shown dotted in Fig. 6 refer to the angular distributions in the π-π C-system. From this figure, it is seen that in π-N C-system, there is considerable asymmetry in events with $n_S = 1$ and $n_s = 2$, whereas the distributions for events with $n_S = 3$ and $n_S \geqslant 4$ are almost isotropic. However, the angular distribution in π-π system is almost isotropic for

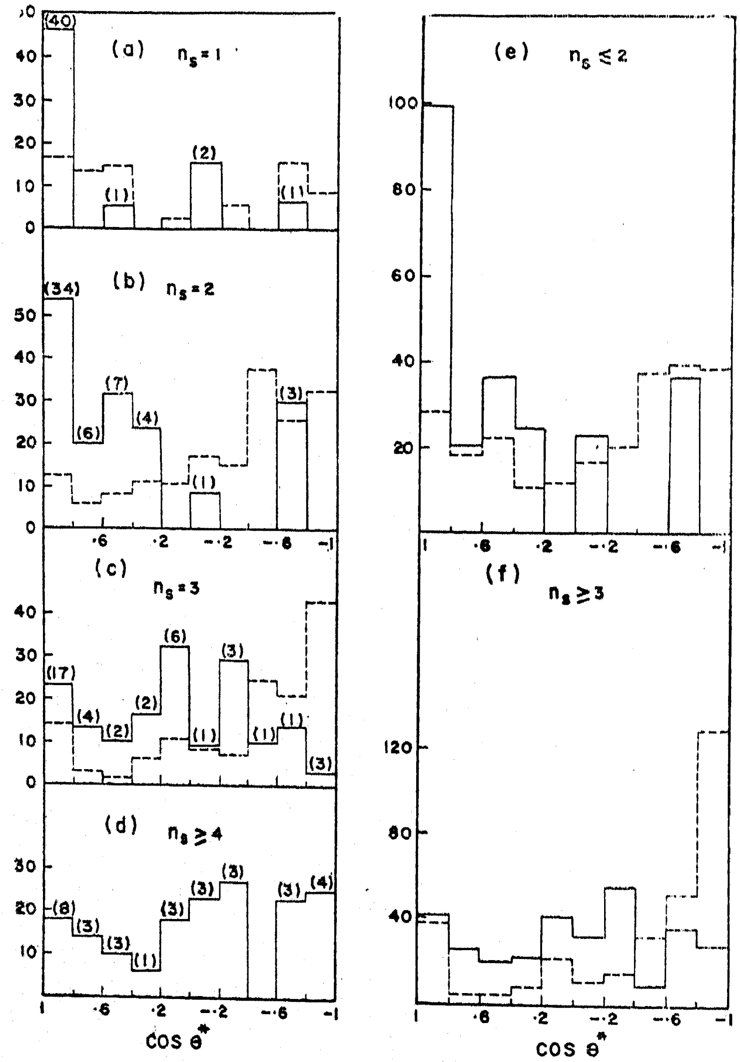

FIG. 6 (a–f). Angular distribution of pions (corrected for geometry) in C-systems, ——π-N C-system and - - - π-π C-system, for events with (a) $n_s = 1$, (b) $n_s = 2$, (c) $n_s = 3$, (d) $n_s \geq 4$, (e) $n_s \leq 2$ and (f) $n \geq 3$. The observed numbers are given inside parenthesis.

events with $n_s \leqslant 2$ and anisotropic for events with $n_s \geqslant 3$. This can be interpreted to mean that events with $n_s = 1$ and 2 result chiefly from π-π collisions and those with $n_s \geqslant 3$ mostly due to π-N collisions.

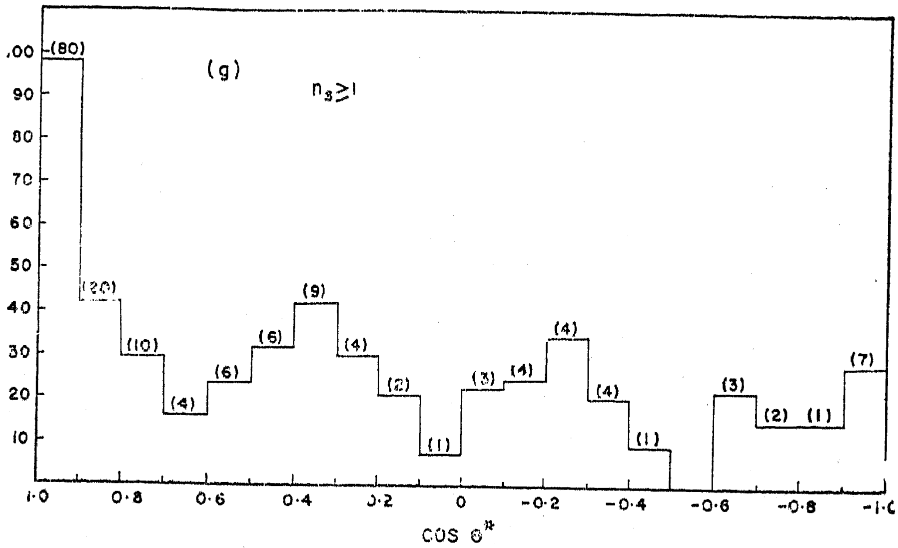

FIG. 6 (*g*). Angular distribution of pions (corrected for geometry) in C-systems,——π-N C-system, and - - - π-μ C-system, for events with (*a*) $n_s \geq 1$. The observed numbers are given inside parenthesis.

6.2. *Energy Distributions of Pions in the C-systems of* π-π *and* π-*N Collisions*

In Fig. 7 are shown the differential distributions of kinetic energy of pions in π-N and π-π C-systems for events with $n_s = 1, 2, 3, \geqslant 4$ and $\geqslant 1$. The average values of kinetic energy of pions in π-N C-system are 510 ± 78, 380 ± 52, 317 ± 51, 272 ± 47 and 346 ± 25 MeV, for events with $n_s = 1, 2, 3, \geqslant 4$ and $\geqslant 1$ respectively. This steady decrease with increasing multiplicity can be attributed as due to the decreasing effect of the persisting pions on the average energy as multiplicity increases.

The integral kinetic energy spectra of charged pions in the π-N C-system are shown in Fig. 8 for events with $n_s \geqslant 1$ and $n_s \geqslant 3$. Both are well represented by exponential form $e^{-\epsilon^*/T^*}$, where $T^* = 0\cdot32$ GeV and $0\cdot30$ GeV for events with $n_s \geqslant 1$ and $n_s \geqslant 3$ respectively. The value of T^* for events with $n_s = 1$ is howerer somewhat higher and is due to the fact that these have appreciable contribution from 'persisting' pions.

6.3. *Energy Distribution of Pions in the L-system*

The integral kinetic energy spectra of pions in the L-system for events with $n_s \geqslant 1$ and $n_s \geqslant 3$ are shown in curves A and B respectively of Fig. 9.

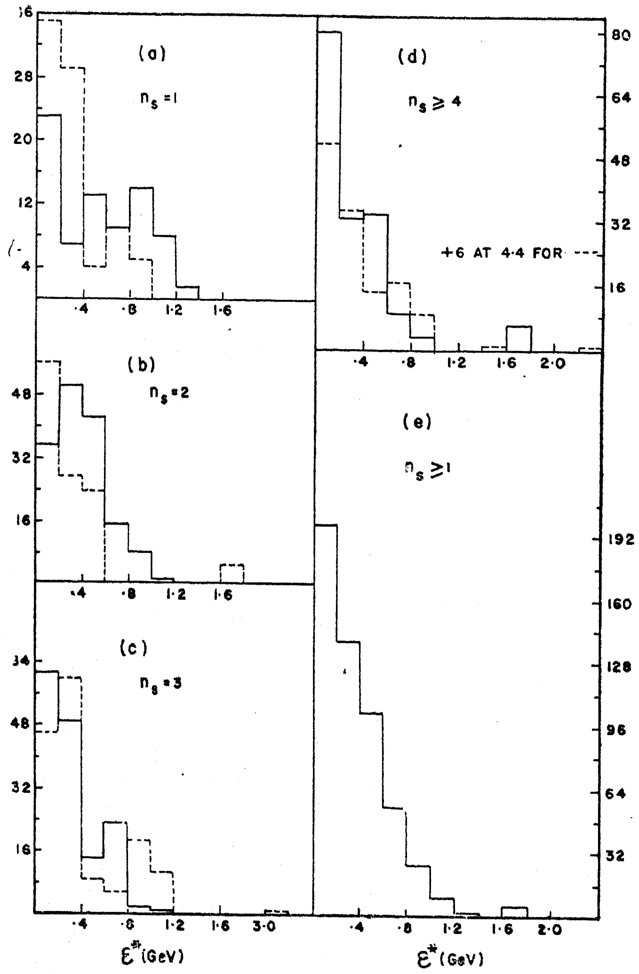

FIG. 7. Differential distributions of kinetic energy of pions in π-N C-system (——) and π-π C-system (- - -) for events with $n_s = 1, 2, 3, \geq 4$ and ≥ 1.

Both can be well represented by an exponential form $e^{-\epsilon/T}$, where $T = 0 \cdot 89$ GeV for events with $n_s \geqslant 1$ and $T = 0 \cdot 57$ GeV for events with $n_s \geqslant 3$. This difference once again is primarily due to the presence of 'persisting' pions in events with $n_s = 1$ and 2.

In order to obtain the number of charged pions of kinetic energy greater than ϵ per collision, divide the ordinate by 290 for curve A and 100 for curve B. It is interesting to note that for stars with $n_s \geqslant 0$, on the average, there are 0·02, 0·10, 0·15, 0·25 and 0·41 charged pions per collision which carry more than 80%, 60%, 50%, 40% and 30% of primary energy respectively, in the L-system.

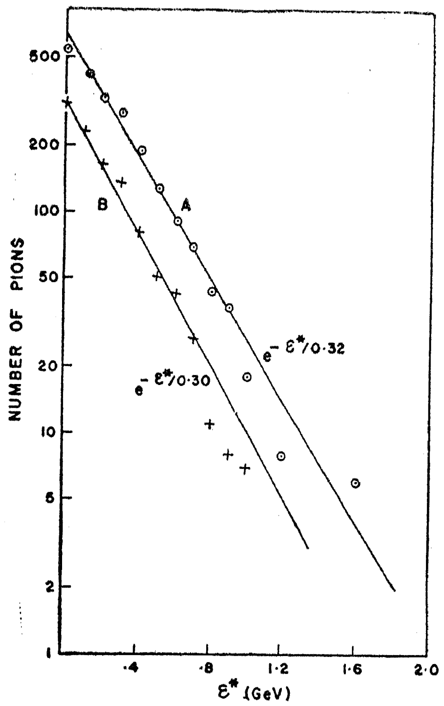

FIG. 8. Integral kinetic energy spectra of charged pions in the π-N C-system for events with $n_s \geq 1$ (Curve A) and $n_s \geq 3$ (Curve B).

6.4. *Inelasticity of Protons*

In order to obtain information about the characteristics of the recoiling protons one must use only the cleaner sample A. The total number of protons identified here is 23 with a total geometric weight factor of 28·8. This number being small, it is not meaningful to present its energy and angular distributions. However, it may be mentioned that the protons show significant backward collimation in the π-N C-system, and the average kinetic energy of the protons in the C-system is 372 ± 77 MeV.

Since in π-N collisions the primary pion after the collision cannot be uniquely distinguished from the created pions, it is not meaningful to talk of inelasticity in the usual sense of the term. However, what is meaningful is the inelasticity of protons, *i.e.*, the fraction of the initial energy lost by the proton in the C-system. The energy of the proton, before the collision, in the π-N C-system is 780 MeV and since the average energy of protons after the collision is 372 MeV, the average inelasticity of protons is found to be $k = 0\cdot52 \pm 0\cdot10$. This may be compared with a value of $0\cdot48 \pm 0\cdot05$ found in p-N collisions at 6·2 GeV.[28]

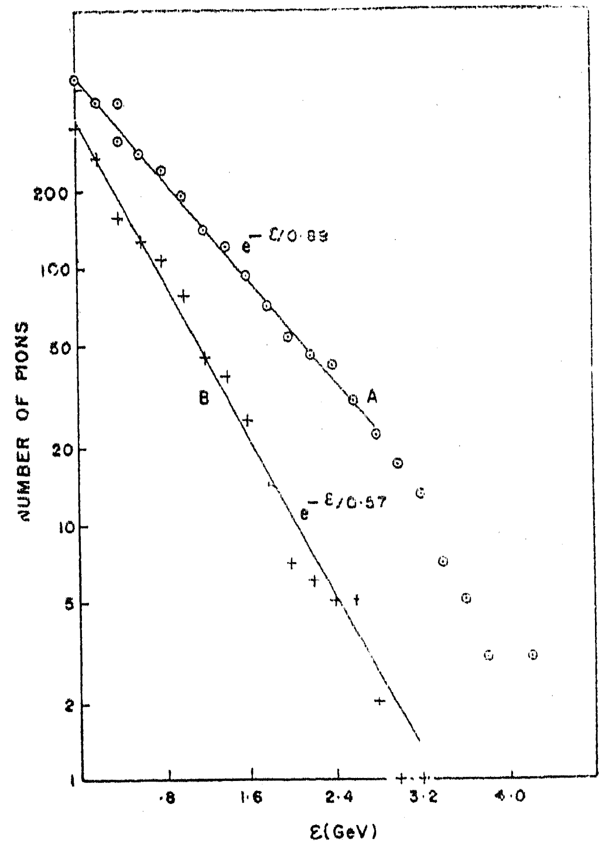

FIG. 9. Integral kinetic energy spectra of charged pions in the L-system for events with $n_s \geq 1$ (Curve A) and $n_s \geq 3$ (Curve B). In order to obtain the number of charged pions of kinetic energy greater than ϵ per collision, divide the ordinate by 290 for Curve A and 100 for Curve B.

Another quantity of interest is the average charge retention probability, *i.e.*, how often does the proton emerge as a proton in π^--p collisions. From our meagre data, we obtain a value of $0\cdot45 \pm 0\cdot07$ for the average charge retention probability for protons in π^--p collisions at 4·4 GeV. This may be compared with a value of $0\cdot51 \pm 0\cdot05$ found in p-N collisions at 6·2 GeV.[28]

7. SUMMARY

A total of 290 inelastic π^--N collisions in nuclear emulsion at a primary energy of 4·4 GeV have been analysed in detail. There are in all 607 shower particles associated with these interactions. By performing careful blob-density and scattering measurements, 188 shower particles have been identified. Important results obtained from this analysis may be summarised as follows:

(i) The angular distribution of charged pions in π-N centre of momentum system (C-system) is isotropic for events with multiplicity $n_s \geqslant 3$. But in the case of events with $n_s = 1$ and 2 there is appreciable peaking in the forward direction. However, if one considers the angular distribution in π-π C-system it is nearly isotropic for events with $n_s \leqslant 2$ and considerably anisotropic for events with $n_s \geqslant 3$. This indicates that whereas events with $n_s \geqslant 3$ result primarily from π-N collisions, most of the events with $n_s =$ 1 and 2 seem to result from π-π collisions, *i.e.*, the interaction of the primary pion with the virtual pion from the cloud of the target nucleon.

(ii) From an analysis of the differential distribution in log tan θ (where θ is the emission angle in the L-system) it is estimated that π-N and π-π collisions account for 60% and 28% respectively of the secondary particles. It is further deduced that there is an average 'persistence' of 0·24 per collision. These persisting pions are found to have energies greater than 1·8 GeV in all cases and angles less than 10° in 80% of the cases.

(iii) The average number of charged shower particle multiplicity in π^--N collisions is found to be $<n_s> = 2{\cdot}09 \pm 0{\cdot}12$. The average multiplicity of the created charged particles is $<n_c \pm> = 1{\cdot}94 \pm 0{\cdot}12$. The average value as well as the distribution of multiplicity in π^--N collisions at 4·4 GeV is essentially same as that in p-N collisions at 6·2 GeV. This is significant in view of the fact that the available energy in the C-systems in these two cases is same.

(iv) The average numbers of protons and kaons among the shower particles are found to be $<n_p> = 0{\cdot}15 \pm 0{\cdot}05$ and $<n_K \pm> = 0{\cdot}11 \pm 0{\cdot}06$ respectively.

(v) The integral kinetic energy spectrum of pions in π-N C-system is well represented by an exponential form $e^{-\epsilon^*/T^*}$, where $T^* = 0{\cdot}32$ GeV and 0·30 GeV for events with $n_s \geqslant 1$ and $n_s \geqslant 3$ respectively. The value of T^* for events with $n_s \leqslant 2$ is somewhat higher.

(vi) The integral kinetic energy spectrum of pions in the L-system can also be represented by an exponential form $e^{-\epsilon/T}$, where $T = 0{\cdot}89$ GeV and 0·57 GeV for events with $n_s \geqslant 1$ and $n_s \geqslant 3$ respectively. This difference is attributed to the presence of persisting pions in events with $n_s \leqslant 2$,

(vii) The inelasticity of protons, or the average fraction of the energy lost by the proton in the C-system is found to be $0 \cdot 52 \pm 0 \cdot 10$.

(viii) The charge retention probability for the proton in π^{-}-p collisions is found to be $0 \cdot 45 \pm 0 \cdot 07$.

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