Nuclear interactions of 340-GeV pions in emulsion

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Some results on heavy- and shower-particle multiplicities produced in interactions of 340-GeV pions in nuclear emulsion are presented and compared with similar results in proton-nucleus interactions at different energies. Values of $\langle N_g \rangle$ in $\pi^- A$ interactions are found to be less than its value in pA interactions at similar energies. This is understood in terms of additive quark model. The result on mean normalized multiplicity reveals that the values of R_{A1} are almost constant in the forward direction for all values of $\langle \nu(N_g) \rangle$ and R_{A1} increases with $\langle \nu(N_g) \rangle$ in the intervals $1.2 < \eta \leq 2.0$ and $\eta \leq 1.2$.

I. INTRODUCTION

Interest in the study of particle-nucleus interactions at high energies has increased in recent years[1-3] as new accelerator beams became available. An important feature noticed in these interactions is that the nucleus plays the important role of the target for the incident hadron as well as the newly produced hadronic systems. It is expected that an experimental investigation of hadron-nucleus interactions will not only help to explain the multiparticle production process but also reveal hadron structure.

From a survey of literature one finds that the pion-nucleus ($\pi^- A$) interactions have been comparatively less studied than proton-nucleus (pA) interactions. Therefore, such a study has been carried out using 340-GeV pions. This paper is a continuation of our earlier publication.[4] In this paper not only the statistics of the data have been improved but also new results have been discussed. The predictions of some of the models of multiparticle production[5-9] have been compared with the experimental results. Wherever possible the experimental results from proton interactions have also been compared.

II. EXPERIMENTAL DETAILS

A stack of Ilford-G5 emulsion pellicles each of size ($7.50\times 7.50\times 0.063$ cm^3) exposed to a 340-GeV negative-pion beam of flux $(0.5-1.5)\times 10^4$ particles/cm^2 at the CERN Super Proton Synchrotron, Geneva, has been employed for the present study. Plates were area scanned using M4000 Cooke's series microscopes with 15× eye pieces and 20× objectives. For measurement a 100× oil-immersion objective was used. Only those interactions lying 3 mm from the leading edges of the pellicles were picked up. The interactions caused by primaries making angles $>2°$ with the mean beam direction were excluded. Also the events lying within 35 μm from the top or bottom surfaces of pellicles were left. The primaries of the stars so selected were followed back up to the edges of the pellicles to make sure that the events chosen did not include any secondary interactions. Using the above criteria, a sample of 1582 clean events was collected.

In each event the tracks of different particles have been classified according to their specific ionization g^* ($=g/g_0$), where g is the ionization of the track and g_0 is the ionization of the primary. The tracks with $g^* < 1.4$, $1.4 \leq g^* \leq 10$, and $g^* > 10$ have been taken as shower, gray, and black tracks, respectively. The numbers of shower, gray, and black tracks in a star have been denoted by N_s, N_g, and N_b, respectively. The black and gray tracks together are referred to as heavily ionizing tracks and their number is denoted by N_h ($=N_g+N_b$).

III. EXPERIMENTAL RESULTS

A. Characteristics of heavily ionizing particles

Figures 1(a)–1(c) show N_h, N_b, and N_g distributions for the events with $N_h \geq 0$ at 340-GeV $\pi^- A$ interactions. The value of $\langle N_h \rangle$ at 340 GeV is found to be 7.83±0.17. For the sake of comparison the same distributions for 50-GeV $\pi^- A$, and 400- and 800-GeV pA interactions[10-12] are also given in the same figure. The figures show that the distributions are similar in nature. The dispersion of the N_h distribution, defined as $D(N_h)=(\langle N_h^2 \rangle - \langle N_h \rangle^2)^{1/2}$, is plotted in Fig. 2 as a function of incident energy for two groups of events, viz., $N_h \leq 20$ and $N_h \geq 0$ at different projectile energies.[13-22] Straight-line fits to the data have been carried out and the following equations are obtained:

$$D(N_h)_{\pi^- A} = (5.96\pm 0.84)-(0.09\pm 0.18)\ln E \qquad N_h \leq 20\,, \quad (1)$$

$$D(N_h)_{pA} = (5.86\pm 0.28)-(0.05\pm 0.06)\ln E \qquad N_h \leq 20\,, \quad (2)$$

$$D(N_h)_{\pi^- A} = (6.23\pm 0.92)+(0.17\pm 0.20)\ln E \qquad N_h \geq 0\,, \quad (3)$$

$$D(N_h)_{pA} = (6.37\pm 0.08)+(0.22\pm 0.02)\ln E \qquad N_h \geq 0\,, \quad (4)$$

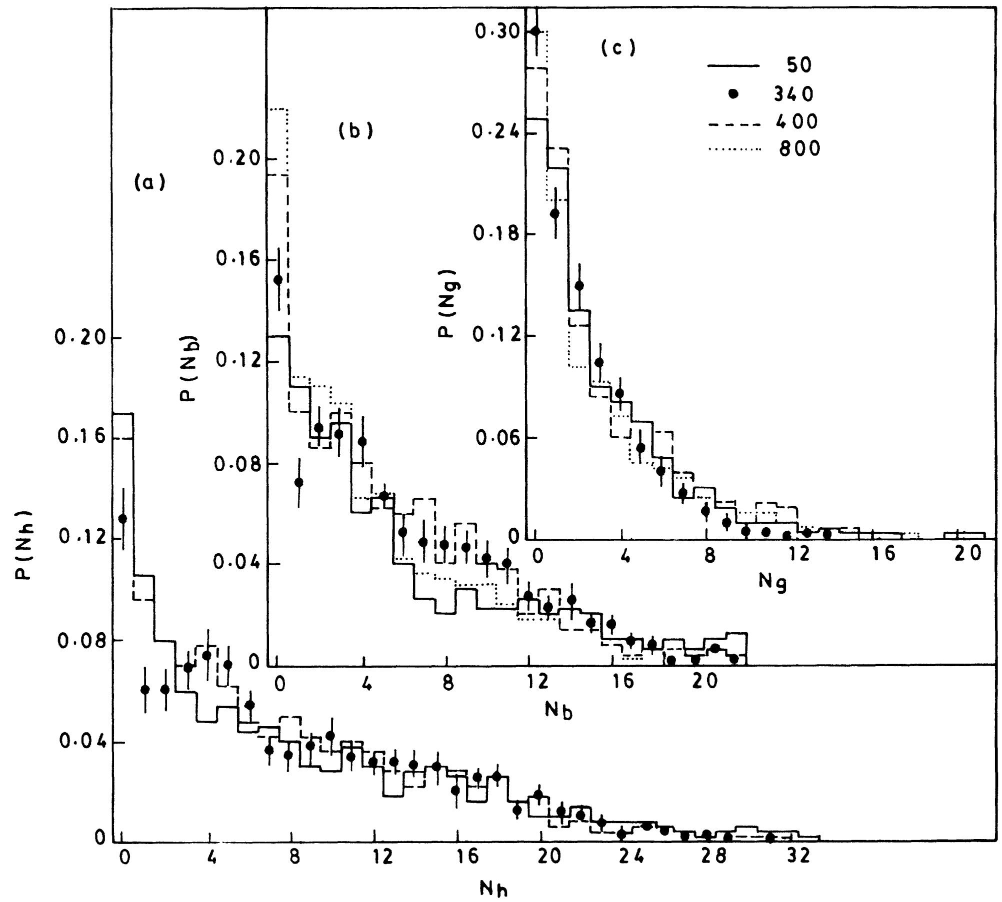

FIG. 1. Multiplicity distribution of (a) heavy, (b) black, and (c) gray tracks at 50, 340, 400, and 800 GeV.

where E is in GeV.

One may note from the above equations that the values of $D(N_h)$ for the events with $N_h \leq 20$ are almost the same in $\pi^- A$ and pA interactions and do not show any energy dependence, whereas the values of $D(N_h)$ seem to depend weakly on energy for the events with $N_h \geq 0$. The values of the ratio $\langle N_h \rangle / D(N_h)$ have also been plotted against the incident energy for pion and proton projectiles in Fig. 3 and the lines are best represented by the following equations:

$$[\langle N_h \rangle / D(N_h)]_{\pi^- A} = (0.98 \pm 0.12) + (0.01 \pm 0.01) \ln E \ , \tag{5}$$

$$[\langle N_h \rangle / D(N_h)]_{pA} = (1.10 \pm 0.05) - (0.01 \pm 0.01) \ln E \ . \tag{6}$$

The above ratio appears to be independent of the energy and projectile. This independence of $\langle N_h \rangle / D(N_h)$ on

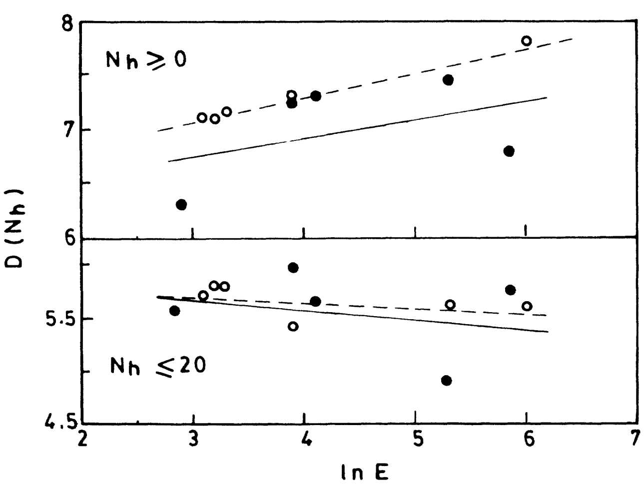

FIG. 2. Variation of $D(N_h)$ with incident energy (in GeV) for pion (● ——) and proton (○ — — —) projectiles.

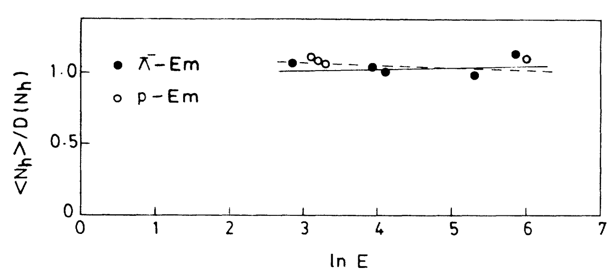

FIG. 3. Variation of $\langle N_h \rangle / D(N_h)$ as a function of energy for pion and proton projectiles.

the energy and the nature of projectile is in disagreement with the prediction of the cascade-evaporation model[9] and supports the double-step models.[5–8]

The variations of $\langle N_h \rangle$, $\langle N_b \rangle$, and $\langle N_g \rangle$ with the incident energy for $\pi^- A$ and pA interactions[11–22,23–27] have been given in Figs. 4(a)–4(c). The data points may be represented by the following lines:

$$\langle N_h \rangle_{\pi^- A} = (5.40 \pm 0.10) + (0.37 \pm 0.20)\ln E \ , \quad (7)$$

$$\langle N_h \rangle_{pA} = (7.59 \pm 0.29) + (0.00 \pm 0.06)\ln E \ , \quad (8)$$

$$\langle N_b \rangle_{\pi^- A} = (2.45 \pm 1.13) + (0.46 \pm 0.22)\ln E \ , \quad (9)$$

$$\langle N_b \rangle_{pA} = (4.35 \pm 0.32) + (0.07 \pm 0.06)\ln E \ , \quad (10)$$

$$\langle N_g \rangle_{\pi^- A} = (3.59 \pm 0.46) - (0.22 \pm 0.09)\ln E \ , \quad (11)$$

$$\langle N_g \rangle_{pA} = (3.20 \pm 0.24) - (0.06 \pm 0.05)\ln E \ . \quad (12)$$

It is observed from the above lines that in the case of proton interactions, $\langle N_h \rangle$ is almost constant in the entire energy range, whereas it seems to increase with energy for pion interactions. No saturation in $\langle N_h \rangle_{\pi^- A}$ is visible up to the energies considered here. $\langle N_b \rangle$ seems to be independent of energy in pA collisions, but increases with energy in $\pi^- A$ interactions.

Figure 4(c) shows that $\langle N_g \rangle$ remains almost independent of energy in the case of pA interactions whereas its value in the case of $\pi^- A$ interactions seems to decrease with energy. Similar results have been reported by Azimov *et al.*[20] and El-Nadi *et al.*[27] The average value of N_g in the present experiment is found to be 2.18 ± 0.06. Also the values of $\langle N_g \rangle$ in the case of $\pi^- A$ interactions are smaller than those in pA interactions. This smaller value of $\langle N_g \rangle$ in $\pi^- A$ interactions indicates that the number of collisions inside the nucleus for the pion projectile is smaller than that for the proton projectile. This difference in the values of $\langle N_g \rangle$ for $\pi^- A$ and pA collisions may be understood in terms of the additive quark model[28] (AQM). According to the AQM, when a hadron collides with a nucleon in a target nucleus, three types of of quarks are produced: viz., the spectator quark, the leading quark, and the sea quark. Spectator quarks are absorbed in nuclear matter with an absorption cross section:

$$\sigma_{qN}^{\text{inel}} = (1/n)\sigma_{hN}^{\text{inel}} \ , \quad (13)$$

where $\sigma_{hN}^{\text{inel}}$ is the inelastic hadron-nucleon cross section and n is the number of quarks in the incident hadron. For a pion $n=2$ and for a proton $n=3$, therefore, $\sigma_{pp}^{\text{inel}} > \sigma_{\pi^- N}^{\text{inel}}$. Thus a larger number of gray particles are expected to be produced in pA interactions as compared to $\pi^- A$ interactions, which agrees with experimental observations.

The values of the ratio $\langle N_b \rangle / \langle N_g \rangle$ have also been plotted in Fig. 5(a) for $\pi^- A$ and pA interactions at different energies.[11–27] The following equations have been found to represent the data:

$$(\langle N_b \rangle / \langle N_g \rangle)_{\pi^- A} = (0.45 \pm 0.74) + (0.28 \pm 0.15)\ln E \quad 50 \le E \le 340 \text{ GeV} \ , \quad (14)$$

$$(\langle N_b \rangle / \langle N_g \rangle)_{pA} = (1.37 \pm 0.19) + (0.05 \pm 0.04)\ln E \quad 20.5 \le E \le 800 \text{ GeV} \ . \quad (15)$$

From the above equations, it may be noted that although the ratio $\langle N_b \rangle / \langle N_g \rangle$ is independent of energy in pA interactions, it shows an energy dependence in the case of $\pi^- A$ interactions.

The values of the ratio $\langle N_g \rangle / D(N_g)$ in $\pi^- A$ interactions at various energies are shown in Fig. 5(b) as a function of energy. The following line fits the data quite well:

$$\langle N_g \rangle / D(N_g) = (0.84 \pm 0.04) + (0.00 \pm 0.01)\ln E \ . \quad (16)$$

From the figure it is clear that the values of

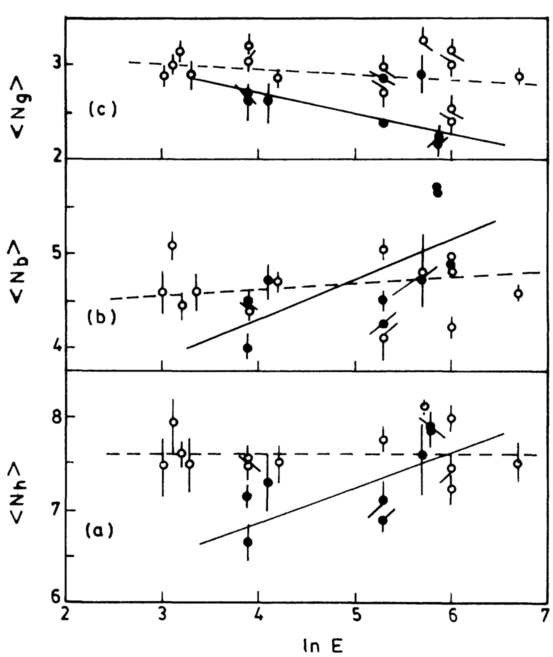

FIG. 4. Variation of (a) $\langle N_h \rangle$, (b) $\langle N_b \rangle$, and (c) $\langle N_g \rangle$ with incident energy for pion (●——) and proton (○ — — —) projectiles. The data points in $\pi^- A$ and pA interactions are in the energy range 50–340 and 20.5–800 GeV, respectively.

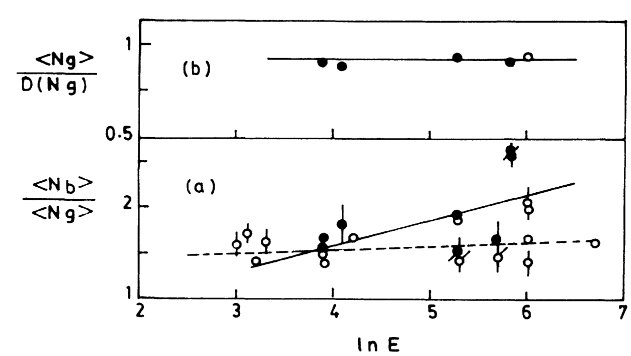

FIG. 5. Variation of the ratios (a) $\langle N_b \rangle / \langle N_g \rangle$ and (b) $\langle N_g \rangle / D(N_g)$ with energy for pion (●——) and proton (○ — — —) projectiles.

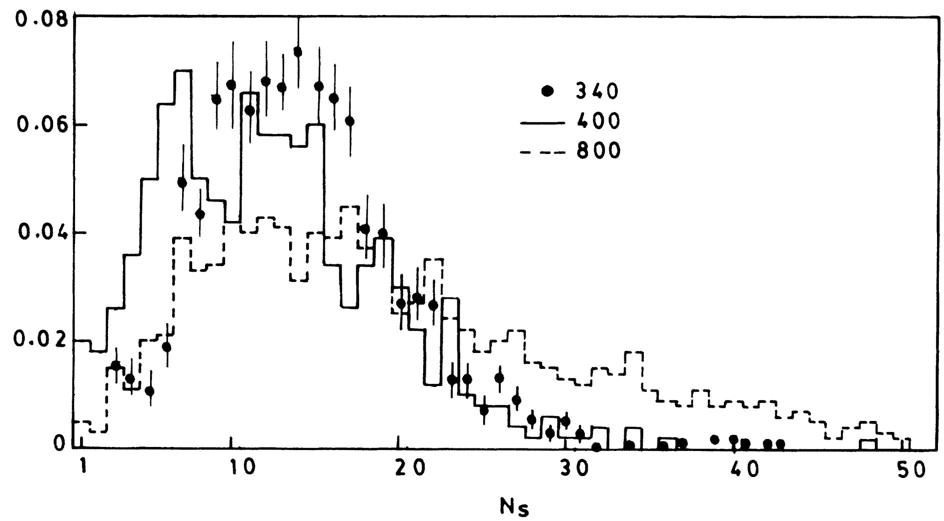

FIG. 6. Multiplicity distributions of shower particles at 340, 400, and 800 GeV.

$\langle N_g \rangle / D(N_g)$ are constant over a wide range of energy, which is inconsistent with the cascade-evaporation model[9] and agrees with the double-step models.[5-8]

The values of the ratios $\langle N_g \rangle_{\pi^- A} / \langle N_g \rangle_{pA}$ and $\langle N_h \rangle_{\pi^- A} / \langle N_h \rangle_{pA}$ at almost the same energy of pion and proton projectiles are found to be 0.91 ± 0.09 and 0.94 ± 0.07 which agrees well with results at other energies.[14-16,25] Thus one may say that the ratios are nearly equal and almost independent of energy. It may be mentioned here that the ratios are very close to the ratio $\langle \nu \rangle_{\pi^- A} / \langle \nu \rangle_{pA}$, where $\langle \nu \rangle$ is the average number of collisions made by the impinging hadron inside the target nucleus of mass number A. It may be determined as follows:

$$\langle \nu \rangle_{hA} = A \sigma_{hN}^{\text{inel}} / \sigma_{hA}^{\text{inel}} , \tag{17}$$

where $\sigma_{hN}^{\text{inel}}$ and $\sigma_{hA}^{\text{inel}}$ are, respectively, the hadron-nucleon and hadron-nucleus inelastic cross sections. Using the reported values of cross sections one gets[29] the relations

$$\langle \nu \rangle_{\pi^- A} = 0.744 A^{0.25} \tag{18}$$

and

$$\langle \nu \rangle_{pA} = 0.716 A^{0.326} . \tag{19}$$

From these relations, the value of the ratio $\langle \nu \rangle_{\pi^- A} / \langle \nu \rangle_{pA}$ comes out to be ~ 0.83. Therefore either of the quantities $\langle N_g \rangle$ and $\langle N_h \rangle$ may be taken to estimate the average number of collisions made by the incident particle inside a nucleus.

B. Characteristics of shower-particle multiplicity distribution

The multiplicity distributions of shower particles for 340-GeV/c $\pi^- A$ interactions along with pA interactions at 400 GeV/c (Ref. 11) and 800 GeV/c (Ref. 12) are shown in Fig. 6. The value of $\langle N_s \rangle$ in the present experi-

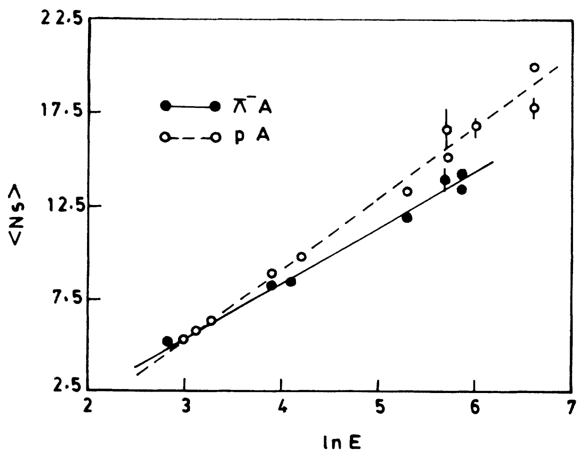

FIG. 7. Variation of $\langle N_s \rangle$ with energy for pion and proton projectiles.

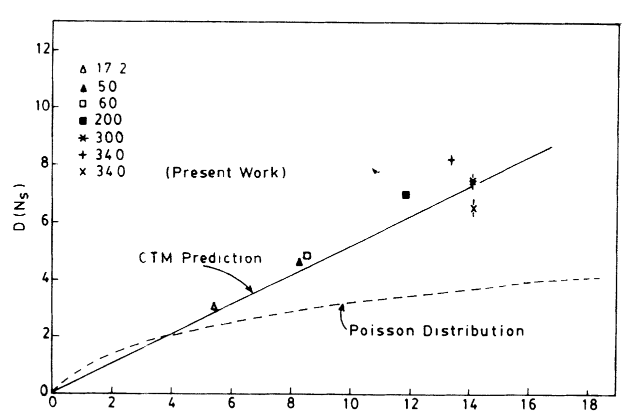

FIG. 8. Variation of $D(N_s)$ with $\langle N_s \rangle$ for pions. The solid line is due to the CTM prediction $[D(N_s) = 0.52 \langle N_s \rangle]$ and the dashed curve is the Poisson distribution $[D(N_s) = \langle N_s \rangle^{1/2}]$.

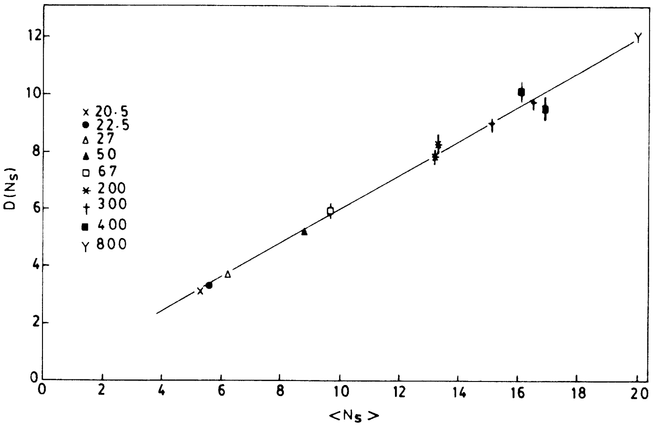

FIG. 9. Variation of $D(N_s)$ with $\langle N_s \rangle$ for protons.

ment is found to be 14.18 ± 0.16 for $N_h \geq 0$. Values of $\langle N_s \rangle$ for $\pi^- A$ and pA interactions as a function of energy[11–21,23–27,30–32] are plotted in Fig. 7. Least-squares fittings have been performed and the equations obtained are as follows:

$$\langle N_s \rangle_{\pi^- A} = (-3.34\pm0.61)+(2.97\pm0.12)\ln E \qquad 17.2 \leq E \leq 340 \text{ GeV}\,, \tag{20}$$

$$\langle N_s \rangle_{pA} = (-6.13\pm0.34)+(3.76\pm0.09)\ln E \qquad 20.5 \leq E \leq 800 \text{ GeV}\,. \tag{21}$$

It may be noted from Fig. 7 that at nearly the same energy of incident particle, the value of $\langle N_s \rangle$ in pA interactions is greater than that for $\pi^- A$ interactions. This difference in the values of $\langle N_s \rangle$ may be attributed to the fact that $\sigma_{pN}^{\text{inel}} > \sigma_{\pi^- N}^{\text{inel}}$. The dispersion $D(N_s)$ of N_s distribution, defined as $D(N_s) = [\langle N_s^2 \rangle - \langle N_s \rangle^2]^{1/2}$, is plotted in Fig. 8 as a function of $\langle N_s \rangle$ at several energies.[11–21,23–27,31] The prediction of the collective tube model[8] (CTM) and results of a Poisson distribution are also given in the figure. The CTM prediction agrees well with the experimental data especially at lower values of $\langle N_s \rangle$. A similar plot for pA collisions is given in Fig. 9.

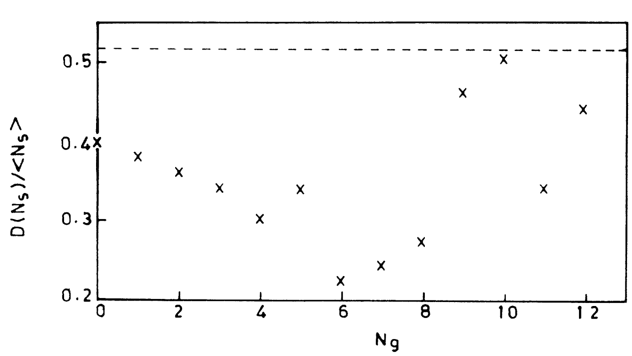

FIG. 10. Dependence of $D(N_s)/\langle N_s \rangle$ on N_g for pion-nucleus interactions at 340 GeV. The dashed line shows the prediction of the CTM (Ref. 8).

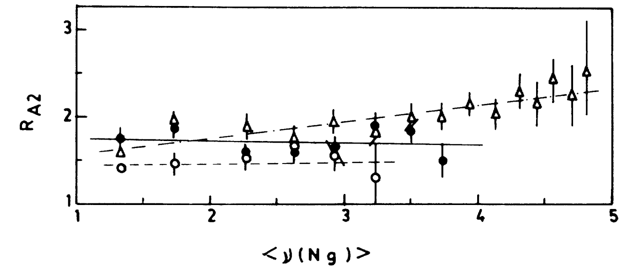

FIG. 11. Variation of R_{A2} with $\langle \nu(N_g) \rangle$, $2 \leq N_h \leq 6$ (○ — — —), $7 \leq N_h \leq 12$ (●——), and $N_h \geq 13$ (△ —·—·—·).

The data is best fitted by the line

$$D(N_s) = (0.59\pm0.01)\langle N_s \rangle + (0.04\pm0.15)\,, \tag{22}$$

which is very close to the $\pi^- A$ case.

However, when $D(N_s)/\langle N_s \rangle$ versus N_g is studied (Fig. 10) it is observed that the ratio varies with N_g. This does not agree with the prediction of CTM, since in the coherent tube picture a collision with higher ν or N_g is equivalent to a hadron-nucleon collision at a higher energy and this leads to no variation of $D(N_s)/\langle N_s \rangle$ with N_g.

C. Mean normalized multiplicity

An important parameter which has been used to understand the multiparticle production process is the mean normalized multiplicity, R_A (say R_{A1}). Initially this parameter was defined as

$$R_{A1} = \langle N_s \rangle / \langle N_{\text{ch}} \rangle\,, \tag{23}$$

where $\langle N_s \rangle$ represents the average number of charged

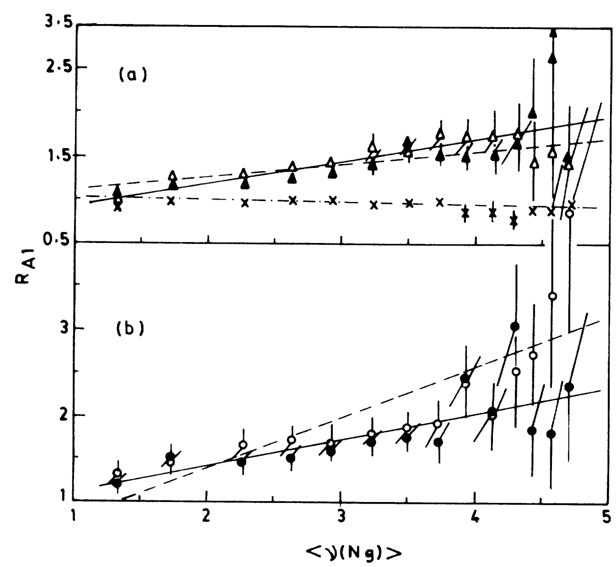

FIG. 12. Variation of R_{A1} with $\langle \nu(N_g) \rangle$ in different η intervals (a) $2.0 < \eta \leq 2.8$ (△ — — —), $2.8 < \eta \leq 3.6$ (▲——), $\eta > 3.6$ (× —·—·—·) and (b) $\eta \leq 1.2$ (○ — — —), $1.2 < \eta \leq 2.0$ (●——).

shower particles observed in hadron-nucleus interactions and $\langle N_{\mathrm{ch}} \rangle$ is the mean number of charged particles observed in hadron-hadron interactions at the same energy.

However, later on, new definitions to the parameter have been given in terms of the created charged particles. Thus, for example, $\pi^- A$ and pA interactions, this has been taken as[33]

$$(R_{A2})_{\pi^- A} = \langle N_s \rangle_{\mathrm{cr}} / \langle N_{\mathrm{ch}} \rangle_{\mathrm{cr}} = (\langle N_s \rangle - 0.50)/(\langle N_{\mathrm{ch}} \rangle - 1.40) \tag{24}$$

and

$$(R_{A2})_{pA} = (\langle N_s \rangle - 0.67)/(\langle N_{\mathrm{ch}} \rangle - 1.33) . \tag{25}$$

D. Variation of mean normalized multiplicity (R_{A2}) with the mean number of collisions [$\langle \nu(N_g) \rangle$]

The variation of R_{A2} with $\langle \nu(N_g) \rangle$ is being studied here. The values of $\langle \nu(N_g) \rangle$ have been calculated using the method given by Stenlund and Otterlund.[34] The variation of R_{A2} with $\langle \nu(N_g) \rangle$ for three groups of events ($2 \le N_h \le 6$, $7 \le N_h \le 12$, and $N_h \ge 13$) is shown in Fig. 11. Linear fits to the data have been carried out and the following equations are obtained:

$$R_{A2} = (1.44 \pm 0.20) + (0.01 \pm 0.08) \langle \nu(N_g) \rangle \qquad 2 \le N_h \le 6 , \tag{26}$$

$$R_{A2} = (1.79 \pm 0.19) - (0.02 \pm 0.06) \langle \nu(N_g) \rangle \qquad 7 \le N_h \le 12 , \tag{27}$$

$$R_{A2} = (1.41 \pm 0.12) + (0.18 \pm 0.03) \langle \nu(N_g) \rangle \qquad N_h \ge 13 . \tag{28}$$

The diffractive excitation model[5] and energy flux cascade (EFC)[6] model predict that R_A should vary with ν as $R_A = a + b\nu$; $a = b = \frac{1}{2}$ (in the diffractive excitation model) and $a = \frac{2}{3}$ and $b = \frac{1}{3}$ (in the EFC). The CTM[8] predicts that $R_A \propto \nu^{1/4}$. None of these predictions agree with experimental results.

E. Variation of R_{A1} with $\langle \nu(N_g) \rangle$ in different η intervals

To study the behavior of R_{A1} with $\langle \nu(N_g) \rangle$ at small and large space angles, the data has been divided into different η intervals, viz., $\eta \le 1.2$, $1.2 < \eta \le 2.0$, $2.0 < \eta \le 2.8$, $2.8 < \eta \le 3.6$, and $\eta > 3.6$. Here η is pseudorapidity parameter defined as $\eta = -\ln \tan\theta/2$, where θ is the space angle of the secondary particle with respect to the primary. The variation of R_{A1} with $\langle \nu(N_g) \rangle$ for these η intervals is shown in Figs. 12(a) and 12(b). The data is represented by the equations

$$R_{A1} = (0.11 \pm 0.48) + (0.61 \pm 0.13) \langle \nu(N_g) \rangle \qquad \eta \le 1.20 , \tag{29}$$

$$R_{A1} = (0.77 \pm 0.32) + (0.32 \pm 0.09) \langle \nu(N_g) \rangle \qquad 1.2 < \eta \le 2.0 , \tag{30}$$

$$R_{A1} = (0.95 \pm 0.12) + (0.16 \pm 0.03) \langle \nu(N_g) \rangle \qquad 2.0 < \eta \le 2.8 , \tag{31}$$

$$R_{A1} = (0.60 \pm 0.25) + (0.27 \pm 0.07) \langle \nu(N_g) \rangle \qquad 2.8 < \eta \le 3.6 , \tag{32}$$

$$R_{A1} = (1.05 \pm 0.04) - (0.03 \pm 0.01) \langle \nu(N_g) \rangle \qquad \eta > 3.6 . \tag{33}$$

From Eq. (33) it is clear that in the very forward direction, i.e., small space angles ($\eta > 3.60$), the values of R_{A1} are almost constant for all $\langle \nu(N_g) \rangle$ values. One may further note from Fig. 12(b) as well as from Eqs. (29)–(31) that R_{A1} increases slowly with decreasing η intervals (i.e., increasing space angles) and the increase of R_{A1} with $\langle \nu(N_g) \rangle$ is quite appreciable in the intervals $1.2 < \eta \le 2.0$ and $\eta \le 1.2$. Thus one may conclude that particle production is independent of target size in the forward cone whereas the particle production depends on target size in the region of large space angles. Similar kinds of results have been observed by Vegni.[35]

IV. CONCLUDING REMARKS

On the basis of the results presented in the paper the following conclusions may be drawn.

(i) The independence of $\langle N_h \rangle / D(N_h)$ on energy and the nature of the projectile supports the double-step models[5–8] and disagrees with cascade-evaporation model.[9]

(ii) The values of $D(N_h)$ for the events with $N_h \le 20$ are independent of energy in $\pi^- A$ and pA interactions, whereas the values of $D(N_h)$ for the events with $N_h \ge 0$ seem to increase with energy.

(iii) The values of the ratios $\langle N_g \rangle_{\pi^- A} / \langle N_g \rangle_{pA}$ and $\langle N_h \rangle_{\pi^- A} / \langle N_h \rangle_{pA}$ are very much close to the ratio $\langle \nu \rangle_{\pi^- A} / \langle \nu \rangle_{pA}$. This indicates that $\langle N_g \rangle$ or $\langle N_h \rangle$ may be taken as the average number of collisions made by the incident particle inside a nucleus.

(iv) The values of R_{A1} are almost constant in the forward direction for all values of $\langle \nu(N_g) \rangle$, whereas in the intervals $1.2 < \eta \le 2.0$ and $\eta \le 1.2$ it increases slowly with $\langle \nu(N_g) \rangle$. This indicates that particle production is independent of target size in the forward cone and depends on target size in the region of larger space angles (backward cone).

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