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An experimental study of angular distribution of fast secondaries in 50 GeV/c π^--Em collisions

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Abstract. The pseudo-rapidity distribution has been studied for 50 GeV/c π^--colliding with various groups of target nuclei in emulsion. These data are compared with the published data on p–A collisions. It is observed that leading component multiplicity in π^--Em collisions decreases with N_h in high η-region. It is also observed that nearly 20% of the interactions proceed via single cluster formation at this projectile energy.

Keywords. Multiparticle production; pseudo-rapidity; leading component; leading particle; η-dispersion and single clusters.

1. Introduction

Angular distributions of the fast secondaries produced in p–p and p–A collisions have widely been studied both at cosmic ray energies and the available machine energies. Amongst these studies, the ones worth noting are those of Berger *et al* (1973) and Dao *et al* (1973) in the case of p–p reactions up to $E_{\text{lab}}=300$ GeV and due to Busza *et al* (1975), Anderson and Otterlund (1975) Jain *et al* (1975), Florian *et al* (1976), Daftari and Roy (1976), Hebert *et al* (1977) and Otterlund *et al* (1977) in the case of p–A reactions up to FNAL energy $E_{\text{lab}}=400$ GeV.

In the case of pion-nucleus interactions the data available so far are mainly due to Kohli (1966) and Abdo *et al* (1973) using emulsion nuclei as targets at energies 17·2 GeV and 60 GeV respectively. Busza *et al* (1975) have also collected data on π^- interactions with various nuclei using counters as detecting devices. As compared to nuclear emulsion experiments, the experiments of the latter have two limitations—one on the detection range of particle velocities ($\beta \geqslant 0{\cdot}85$) and the other due to angular range of detection ($\theta \leqslant 110°$).

Our reasons to carry out this experiment using emulsion nuclei are due to (1) to provide data on angular distribution of shower particles in 50 GeV/c π^--Em collisions (2) to observe distinction if any, in the data of p–A and π^--A reactions (e.g. the average multiplicity of the leading particle in the two cases) and (3) to observe general features of the pseudo-rapidity with respect to the target mass and the projectile energy.

2. Experimental details

A NIKFI-R emulsion stack was exposed to 50 GeV/c π^--beam in a pulsed magnetic field of strength $\simeq 200$ k gauss at Serpukhov (USSR) in 1973. The irradiation pulse was fairly narrow containing $\simeq 10^5$ π^-, mesons/cm^2 and often passed through the middle of the pellicles. The pellicles of this stack were area-scanned at magnification $=40\times 15$X. A careful analysis for the selection of primaries was carried out by Kumar *et al* (1978). According to this the pellicle was mounted on the stage of the microscope such that the flux of beam* is nearly aligned to the x-motion of the microscope and then the primaries of the scanned events were followed backward by 500 μm on X-axis from the centre of the interaction. Y and Z coordinates were measured both at the centre of the star and at the point X$=$500 μm from it and opposite to beam-direction.

Projected angle θ_p and angle of dip δ of the primaries were evaluated from these measurements and histograms in θ_p and δ were plotted separately. The histograms so obtained were highly leptokurtic with a spread $\theta_p=\pm 0{\cdot}18^\circ$ in projected angle and $\delta=\pm 0{\cdot}34^\circ$ in angle of dip (in processed emulsion). The tracks lying simultaneously within these limits were taken to be primaries from the beam flux.

The angular measurements of the shower particles were made on MBE-9 (Russian) microscope by measuring projected angle and the angle of dip of the track with respect to primary beam track associated with the interaction. To measure the angle of dip of the track, the z-coordinate of the track at the centre of interaction and at $X=500$ μm towards the particle motion were noted. By adopting this method the angular resolution of the overlapping tracks and the collimated showers is possible. The least count of the goniometer used for measurement purposes of θ_p is $0{\cdot}6^\circ$ and this facilitated angular measurements on 445 interactions.

There are scanning losses in the groups $N_h=0$ and 1 which are assessed with the help of the line scanning data on hadron-nucleus collisions at various energies presented by Hebert *et al* (1974). According to this procedure the percentage contribution of $N_h=0$, $N_h=1$ and $N_h\geqslant 2$ group events at 50 GeV comes out to be 12·5%, 11·5% and 76% respectively. From the present data it is seen that $N_h=1$ group contains the ‘ regular in n_s ’ losses; therefore the direct enhancement of the number of events was made to the required level. The losses in $N_h=0$ group were ‘ irregular in n_s ’ in the range $n_s=1$ to 4 and were made up with the help of the data given by Bhowmik *et al* (1973) on 50 GeV π^--N collisions. Coherent events have been excluded from the data. The data with $N_h\geqslant 2$ is free from these losses. The total number of events after corrections is 507.

3. Results and discussions

In figure 1a the N_h-distribution of the events taken up in this study is presented. Figures 1b and 1c show the n_s-distribution of the shower particles associated with events in different categories of N_h. It may be noted that (a) the shape of the n_s-dis-

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*One track of the flux aligned along the X-axis is confirmed to be a beam track of 50 GeV/c momentum by (i) following it back upto the leading edge of the pellicle and (ii) by measuring its curvature and verifying its momentum.

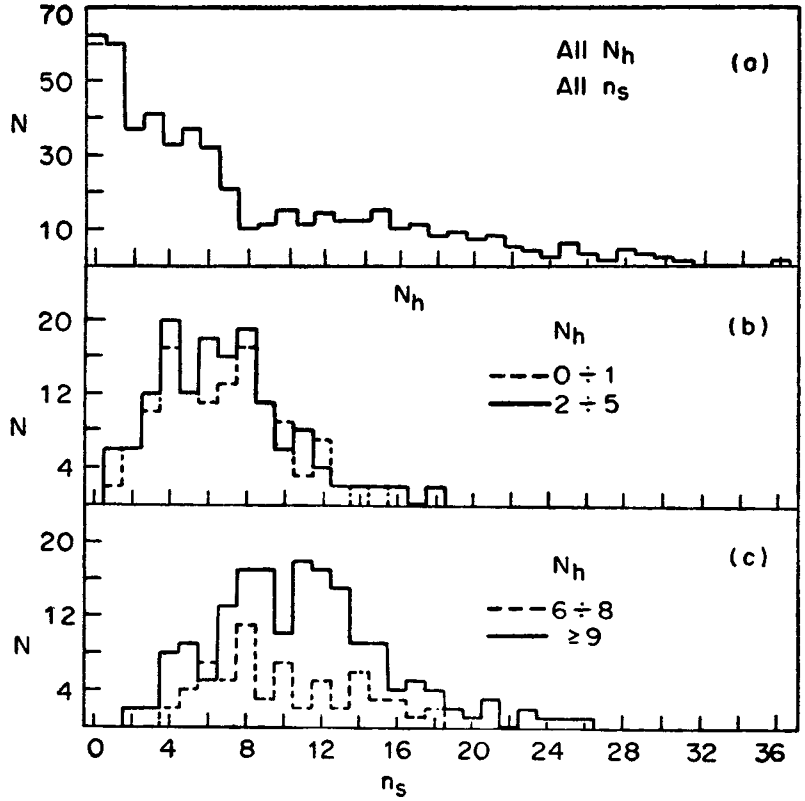


Figure 1 a. N_h-frequency plot of the corrected sample of events and **b.** n_s-frequency plot of events with $N_h=0\div1$ and $N_h=2\div5$. **c.** n_s-frequency plot of events with $N_h=6\div8$ and $N_h\geqslant9$

tribution does not show a significant change up to $N_h=5$, and (b) beyond $N_h=5$ the average value of n_s seems to increase with increasing N_h.

To study the longitudinal motion of the shower particles the rapidity variable, y, defined by Feynman (1969) and subsequently discussed by Lyon *et al* (1971) was chosen

$$y = \tanh^{-1}(P_L/E)$$

$$= -L_n \frac{(E-P_L)}{(P_t^2+m^2)^{1/2}}. \tag{1}$$

where, P_L and P_t are the longitudinal and transverse momenta of the φ articles.

Here we consider the semi-inclusive distribution of the relativistic charged secondaries. According to Anderson and Otterlund (1975), about 95% of the shower particles correspond to pions with $\langle P_t\rangle = 0{\cdot}35$ GeV/c. By applying the following high energy approximations,

$$\langle P_t^2\rangle \gg m_\pi^2,$$

and $(p-p_L)/(E-p_L) \simeq 1$, one gets the approximate relationship

$$y \simeq \eta = -L_n \tan(\theta_L/2), \tag{2}$$

which enables one to estimate an approximate value of y by making only angular measurements. In the present paper we have used relation (2) for y-distributions and hence momentum measurements were not made to evaluate y from (1). η is the pseudo-rapidity of the emitted particle and has been very widely used, e.g. Lyon *et al* (1971); Abdo *et al* (1974), Busza *et al* (1975), Alekseeva (1976), Florian *et al* (1976) and Hebert *et al* (1977). Figure 2a shows the η-distribution of charged shower particles in different categories of N_h. In each category the distribution has been normalised to one interaction. The following may be noted from the figure;

(i) The distribution shifts rapidly towards the low η-values for higher N_h bins, and a larger part of multiplicity contributes to $\eta \leqslant 2{\cdot}0$ region and

(ii) at high pseudo-rapidities ($\eta \geqslant 3{\cdot}5$) the multiplicity decreases with increase of N_h.

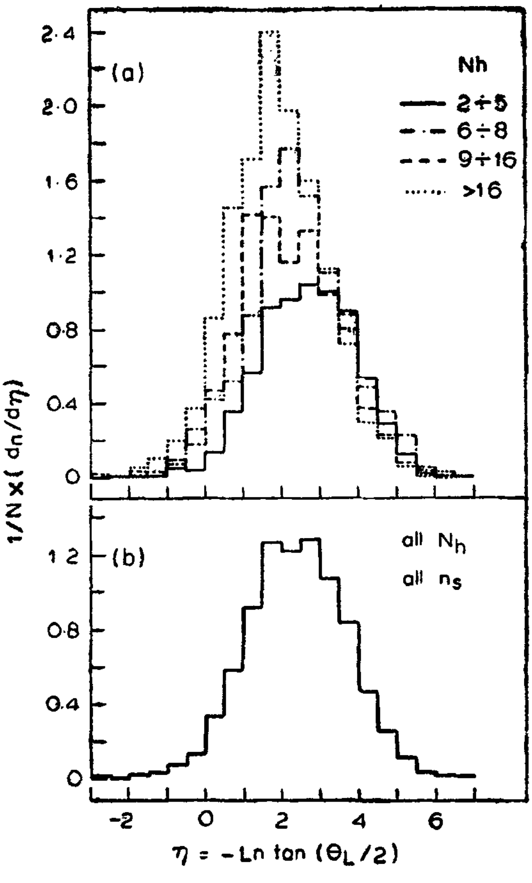


Figure 2a. η-distribution of the charged shower particles in various N_h-groups and **b.** η-distribution for all events ($\langle\eta\rangle = 2{\cdot}40 \pm 0{\cdot}04$, dispersion $D(\eta) = 1{\cdot}26 \pm 0{\cdot}02$, Kurtosis $a_4(\eta) = 3{\cdot}39 \pm 0{\cdot}05$)

In figure 2b the η-distribution for all N_h events has been displayed. The distribution seems to have developed a plateau from $\eta = 1{\cdot}5$ to $\eta = 3{\cdot}0$.

3.1. *Average leading particle multiplicity*

Probability distribution of existence of the projectile hadron among the fast secondaries plays a conclusive role in assessing the validity of numerous theoretical as well as phenomenological models of multiparticle production. Evidences have been provided by Hayakawa (1969), Buras *et al* (1973), Möller (1974), and in a compilation by Whitmore (1976) regarding the existence of leading particle in elementary collisions. In hadron-nucleus collision, it is difficult to be definite about the leading particle. Recently, some indirect observations have been made by Kaur *et al* (1977) (see appendix 1) showing depression of the leading particle in π^-—A collisions (by leading particle one essentially means the fastest moving hadronic matter amongst secondaries containing internal quantum numbers of the projectile hadron). In the present case one more trial is made with the help of η-distribution to know the characteristics of leading particle in π^--A collisions.

In figure 3 we display the integral average multiplicity $\bar{n}$ ($> \eta$, N_h) with respect to N_h of our present data for the entire range of η where $\bar{n}$ ($> \eta$, N_h) is defined as the total number of particles per event of particular N_h with angle of emission smaller

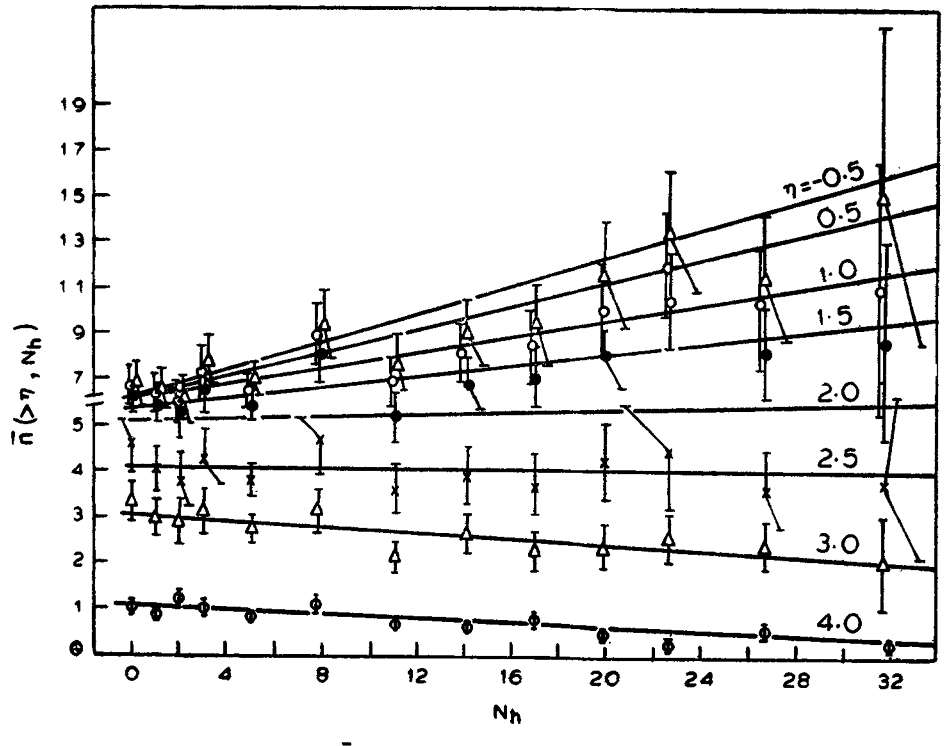


Figure 3. N_h versus $\bar{n}(>\eta, N_h)$ plots for various values of η. The straight lines across the data are the linear fits of the types of equation (3) (The data corresponding to the fits at $\eta>2{\cdot}0$ and $0{\cdot}5$ are not shown in the figure)

than the one characterised by $\eta = -L_n \tan(\theta_L/2)$ or with pseudo-rapidity greater than η. This relation was first used by Anderson and Otterlund (1975) to distinguish the 'leading particle component' to the 'repeated collision component' of the multiplicity. The following linear fits to the data are made.

$$\bar{n}(>\eta,\ N_h) = a(\eta) + b(\eta)\ N_h. \tag{3}$$

The error bars on data points shown in the figure correspond to the statistical errors.

The following points may be noted:

(i) $\bar{n}(>\eta,\ N_h)$ decreases with N_h in the range $\eta > 2{\cdot}5$.

(ii) $\bar{n}(>\eta,\ N_h)$ is almost insensitive to N_h at $\eta = 2{\cdot}5$ and increases with N_h in the range $\eta < 2{\cdot}5$.

Comparing the data in figure 3 with the p-Em data at 200 and 300 GeV/c presented by Anderson and Otterlund (1975) and Hebert *et al* (1977), the following can be stated.

In p-Em data $\bar{n}(>\eta,\ N_h)$ is insensitive to N_h in the region $\eta \geqslant 4$ while in the present data of π^--Em, $\bar{n}(>\eta,\ N_h)$ is insensitive to N_h at $\eta = 2{\cdot}5$ and decreases with increasing N_h in the range $\eta > 2{\cdot}5$.

To investigate the high pseudo-rapidity region of the present data, we plot in figure 4, $\langle \eta \rangle$ vs N_h for various ranges of η. Figure 4a shows the variation for all the produced particles, while figures 4b, c and d show the same variation for the particles produced in $\eta = -3$ to 2, $\eta = 2$ to 4 and $\eta = 4$ to 7 respectively. The error bars shown on the data points correspond to statistical errors. From figures 4 b, c and d it is easily noted that the tendency of decrease of $\langle \eta \rangle$ with N_h becomes slower as we move towards higher pseudo-rapidity regions and in figure 4d $\langle \eta \rangle$ becomes insensitive to N_h though the errors due to less statistics of particles in this region are quite large. If the 'projectile hadron' emerges out of the heavy nucleus with larger rapidity as it does in elementary collisions where the leading particle effect is much more pronounced,then the dispersion $D(\eta)$ will remain independent of N_h. In figure 4e we plot $D(\eta) = (\langle \eta^2 \rangle - \langle \eta \rangle^2)^{1/2}$ with respect to N_h in the range $\eta = 4$ to 7 and observe that $D(\eta)$ decreases with N_h.

3.2. *Cluster formation*

In figure 2b we have displayed the differential distribution of η variable which seems to have developed a plateau of length $\eta \simeq 1{\cdot}5$. To study the intermediate state of production of final state particles we analyse the data in terms of dispersion $D_1(\eta)$ of individual events for the entire range of η. It has been suggested by Berger *et al* (1973) that the events with the following dispersion limit,

$$D_1(\eta) = \left[\frac{1}{n_{\mathrm{ch}} - 1} \sum (\eta - \bar{\eta})\right]^{1/2} \leqslant 0{\cdot}9.$$

constitutes a purified sample of single cluster/nova events. Here n_{ch} is the charged particle multiplicity of the reaction. By adopting this way of analysing the events with single nova/cluster, Daftari and Roy (1976) have shown the substantial existence of the single cluster events in p-Em collisions at $P_{\mathrm{lab}} = 70$ GeV/c.

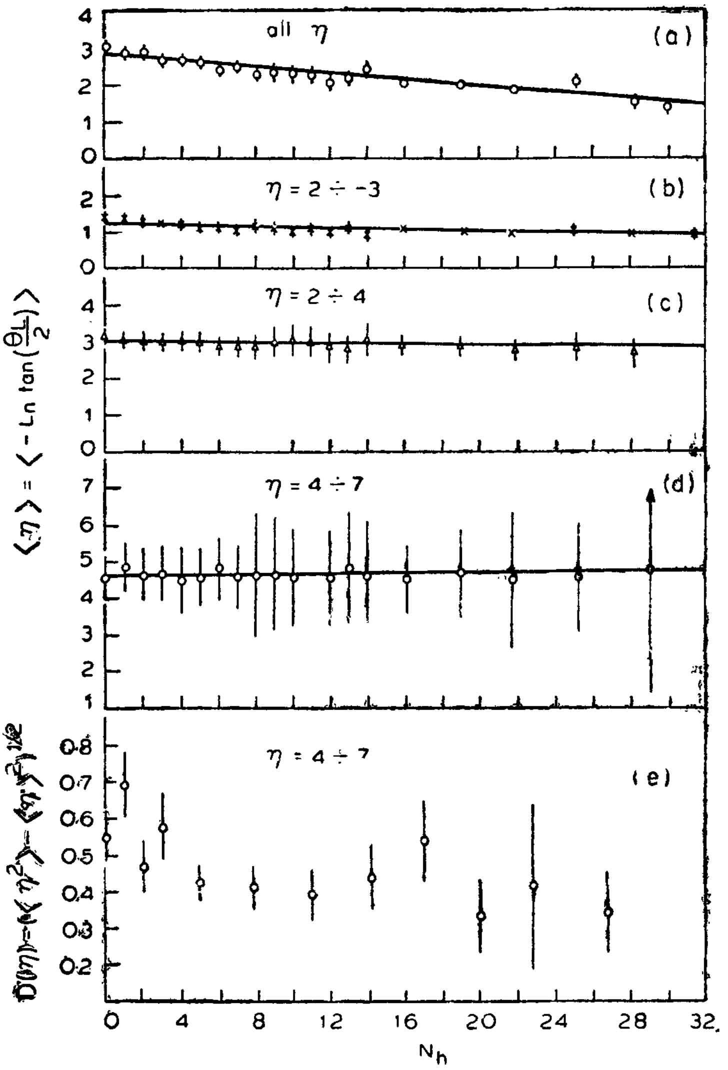


Figure 4. $\langle\eta\rangle$ versus N_h plot for all events a. for all η. b. $\eta=2$ to -3. c. $\eta=2$ to 4. d. $\eta=4$ to 7 and e. dispersion $D(\eta)$ of the tracks in the leading component range i.e. $\eta=4$ to 7

In figure 5a we display our data in terms of $\bar{D}_1$ (η) and n_s along with the predictions of various models as referred to by Dao *et al* (1973). Curves (1), (2) and (3) in the figure correspond to the predictions of the models (i) single and double nova production, (ii) multiperipheral production of clusters, and (iii) multiperipheral production of π's respectively.

In figure 5b the data of the present experiment have been displayed in terms of W_1 i.e. dispersion of $D_1(\eta)$'s. The crosses in the figure show a fitting of the type of $W_1=1{\cdot}22\,(n_s)^{-0\cdot 6}$, which is slightly different from the prediction of models of the type (ii) and (iii) i.e. $W_1=1{\cdot}22\,(n_s)^{-0\cdot 5}$ shown by Dao *et al* (1973) in order to fit the data of 300 GeV *pp* collisions.

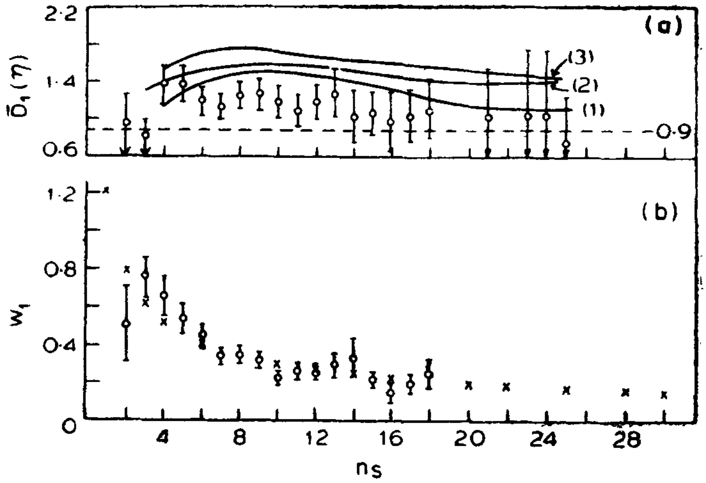
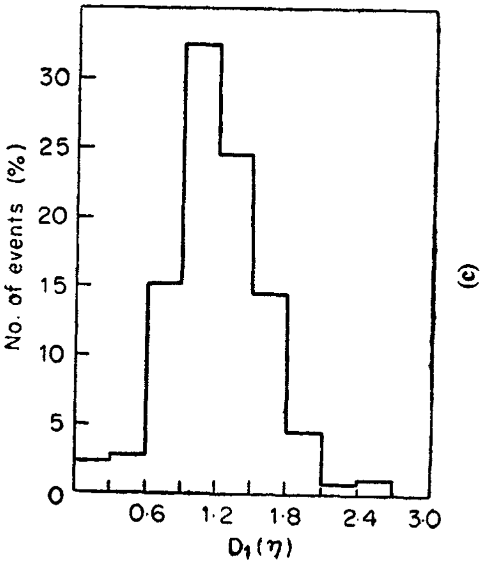


Figure 5a. Average dispersion $\bar{D}_1(\eta)$ versus n_s and b. W_1 versus n_s(W_1=dispersion of $D_1(\eta)$'s of showers with particular n_s) for all events of 50 GeV/c π^--Em collisions.



c. Percentage distribution of events with respect to $D_1(\eta)$.

In figure 5c the fractional distribution of $D_1(\eta)$ of the present data is shown and from figures 5a, b and c the following may be noted:

(1) Owing to better fitting of the curve (1) of figure 5a with the data at low and high multiplicities, single clusters seem to have been produced in low as well as high multiplicity events.

(2) $W_1=1{\cdot}22\,(n_{ch})^{-0\cdot6}$ preferentially fits better at high multiplicities in comparison to low multiplicities. Along with conclusion (1) it may be said that while a substantial part of multiplicity events is due to single cluster formation it is also partly due to multiperipheral type of process.

(3) From the present data it is clear (figure 5c) that nearly 20% of the events correspond to $D_1(\eta) \leqslant 0{\cdot}9$ i.e. the events with single cluster/nova.

In figure 6 we observe the general features of η-distributions in terms of dispersion and moment coefficient of kurtosis (peakness) at various projectile energies and target masses. In figure 6a we plot $D(\eta)$ versus $\langle n_s \rangle$ (for all η, N_h and n_s) and it may be seen that $D(\eta)$ increases with the average multiplicity of charged particles. The following linear fit is made to the data i.e.

$$D(\eta) = \left(1{\cdot}09^{+0{\cdot}04}_{-0{\cdot}03}\right) + \left({\cdot}032^{+0{\cdot}001}_{-0{\cdot}001}\right) \langle n_s \rangle \qquad (4)^*$$

In figure 6b, the moment coefficient of kurtosis $a_4(\eta)$ (for all η, N_h and n_s) of various reactions is plotted with respect to $\langle n_s \rangle$. The data follow the following linear relation

$$a_4(\eta) = \left(3{\cdot}77^{+0{\cdot}12}_{-0{\cdot}11}\right) - \left({\cdot}046^{+0{\cdot}003}_{-0{\cdot}003}\right) \langle n_s \rangle \,. \qquad (5)^*$$

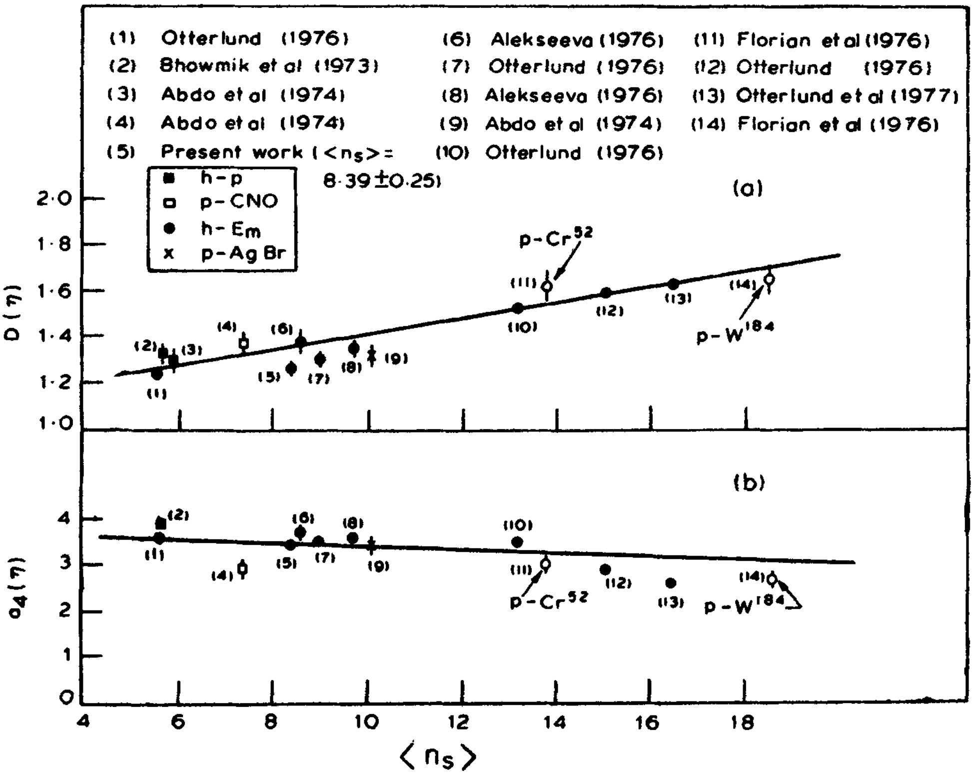


Figure 6 a. $D(\eta)$ versus $\langle n_s \rangle$ plot. **b.** $a_4(\eta)$ versus $\langle n_s \rangle$ plot of various hadron-nuclei reactions.

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*Errors shown in the fitted parameters correspond to the statistical errors in y-axis variable i.e. $D(\eta)$ in (4) and $a_4(\eta)$ in (5). While making the fits (4) and (5) the data point corresponding to $\langle n_s \rangle = 16{\cdot}5 \pm 0{\cdot}02$ could not be taken into account because of lack of statistics.

The increase of $D(\eta)$ and decrease of $a_4(\eta)$ with $\langle n_s \rangle$ infers that the η distributions flatten with the increase of multiplicity.

4. Conclusions

From the present study the following conclusion may be drawn, that

(1) In 50 GeV π^--Em reactions the gradual decrease of $\bar{n}(>\eta, N_h)$ with respect to N_h (figure 3) in the regions $\eta > 2{\cdot}5$ is in sharp contrast to the observation made in case of 200 and 300 GeV p-Em reactions where $\bar{n}(>\eta, N_h)$ remains constant with respect to N_h in the region $\eta \geqslant 4{\cdot}0$. This behaviour of π^--A reactions suggests that the probablity of emerging out of the leading particle in the high rapidity region goes on decreasing with the star size.

(2) Nearly 20% of the multiparticle production in π^--Em reactions at 50 GeV takes place through the formation of single nova or cluster while it has been pointed out by Berger *et al* (1973) that in all reactions at energies $E_{\text{lab}} \leqslant 30$ GeV, 90 to 100% events, at $E_{\text{lab}} = 200$ GeV 10% events and at ISR energies 1% event, are with $\bar{D}_1(\eta) \leqslant 1{\cdot}0$.

(3) From the general features of η-distributions as studied with the help of the data displayed in figure 6, one observes that η-distributions flatten with the increase of $\langle n_s \rangle$. In the case of elementary collisions it has been shown by Ganguli and Malhotra (1972) and also Ammosov *et al* (1973) and in case of h-A reactions by Takagi (1975), Berlad *et al* (1976) and Kohli (1976) that energy available in CMS is a variable to explain multiplicities in reactions at very high energies. It is thus concluded that $D(\eta)$ and $a_4(\eta)$ depend upon the energy available in CMS. A similar idea has also been pointed out by Bali *et al* (1971) and Bhowmik *et al* (1973).

(4) The present experiment suggests that further work is necessary on identification of the leading particle and its existence in leading component of multiplicity.

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Appendix 1

In the case of elementary collisions in the range of $p_{\text{lab}} = 6{\cdot}2$ GeV/c to 300 GeV/c, Buras *et al* (1973) have shown by plotting various moments of multiplicity with respect to $\langle n_s \rangle$ that there exists a linear relation between the individual moment and $\langle n_s \rangle$. The lines fitted to such data show a constant intercept on the axis of $\langle n_s \rangle$. The intercept is inferred as the average multiplicity of leading particle (α) i.e. the projectile emerging amongst the showers. In the case of p-p and π^--p reactions α is evaluated as 0·9 and 1·2 respectively. Kaur *et al* (1978) adopting the same way as that of Buras *et al* (1973) have shown that the values of α in case of p-Em (p_{lab}=6·2 to 400 GeV/c) and π^--Em reactions (p_{lab}=17·2 to 50 GeV/c) are 0·7 and zero respectively.

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