Characteristics of compound multiplicity in hadron-nucleus collisions

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A comparative study of compound multiplicity distribution at three different energies for pion-nucleus and proton-nucleus collisions is presented. The variation of the ratio \(D(N_c)/\langle N_c \rangle\) with black particle multiplicity shows a kind of scaling. The calculated values of \(R_{A1}\) and \(R_{A2}\) are found to be independent of energy and nature of the projectile. The variation of \(D(N_c)\) with \(\langle N_c \rangle\) supports Coherent Tube Model (CTM) for proton-nucleus collisions. Moments of the compound multiplicity distribution have also been studied.

Keywords: Compound multiplicity, Relativistic charged particles, Interactions, Mean normalized multiplicity, Dispersion, Moments

1 Introduction

In the present study, the phenomenon of multiparticle production in hadron-nucleus (hA) collisions at high energies using nuclear emulsion technique has been investigated. Nuclear emulsion is a material which memorises the tracks of charged particles. Emulsion consists of various elements like hydrogen (H), carbon (C), nitrogen (N), oxygen (O), silver (Ag) and bromine (Br). When high energy beam of particles, known as primary particles or projectiles, interact with the emulsion nuclei, secondary particles are produced. These secondary particles are classified into three categories viz., shower, grey and black particles. Shower particles are mostly relativistic pions emitted in the most forward cone. Similarly, grey tracks are produced, generally by recoiling protons and black tracks are due to evaporation of residual nuclei which consist mainly of protons and other light fragments. The selection criterion for shower, grey and black particles are discussed under experimental details.

The mechanism of production of relativistic charged particles in hA collisions1–3 has been extensively investigated in the past. However, little importance has been given to the grey particles. But the studies on the emission characteristics of grey particles may be of special interest because they are envisaged to be produced during or shortly after the passage of the leading hadron and hence, are expected to remember a part of the history of the reaction. For the first time Jurak and Linscheid4 investigated some interesting features of shower and grey particles, taking them together per event, without making any distinction between them, for hA interactions. Later on many researchers5–9 followed the same procedure in their analyses to study high energy interactions. The number of shower and grey particles taken together in an event has been termed as compound multiplicity \(N_c(=N_s+N_g)\). A survey of literature shows that the pion-nucleus (\(\pi^A\)) interactions are less studied in terms of compound multiplicity.

Various features of compound multiplicity in \(\pi^A\) collisions at 50 and 340 GeV and proton-nucleus (pA) collisions at 400 GeV have been investigated. In this way, the nature of the projectile and the energy both are compared.

2 Experimental Details

Three stacks of emulsion, two exposed to negative pion beams of energy 50 and 340 GeV and third one to a proton beam of 400 GeV, have been used in the present investigation. The search of primary interactions was carried out by the method of area scanning. The events were picked up after leaving 3 mm from the leading edges of the pellicles to avoid any distortion effects. The interactions, which were produced within 35 μm from the top or the bottom surface of the pellicles have been excluded from the data.
To avoid any contamination of primary events with secondary interactions, the primaries of all the interactions were followed back up to the edge of the plates and only those events whose primary remained parallel to the main direction of the beam and which did not show any significant change in their ionization, were finally picked up as genuine primary events.

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, grey and black tracks, respectively. The number of shower, grey and black tracks in an event have been denoted by \( N_s \), \( N_g \) and \( N_b \), respectively. The grey and black tracks taken together are referred to as heavy tracks and their number in an event is given by \( N_h (=N_g+N_b) \). The other details regarding the exposure of the stack, beam flux and the number of events etc. are presented in Table 1.

### 3 Results and Discussion

The compound multiplicity distributions at the three different energies are shown in Fig. 1. The values of mean compound multiplicities, \( <N_c> \), for \( N_h \geq 0 \) and the dispersion:

\[
D(N_c) = (<N_c^2> - <N_c>^2)^{1/2}
\]

of the compound multiplicity distributions are presented in Table 2. The CTM prediction\(^ {10-13} \) for variation of \( D(N_c) \) with \( <N_c> \) in \( hA \) collisions is shown in Fig. 2. The experimental results for \( D(N_c) \) versus \( <N_c> \) for the present data is also shown in Fig. 2. It is noted from Fig. 2 that \( pA \) interactions data satisfies the CTM but for \( \pi A \) data, a little deviation from CTM is observed.

The variation of the ratio \( D(N_c)/<N_c> \) with \( N_b \) is shown in Fig 3. Least squares fits to the data have been carried out and the following equations are obtained:

\[
D(N_c)/<N_c> = (0.40 \pm 0.05) - (0.01 \pm 0.00)N_b \quad \text{at 340 GeV} \quad \ldots(3)
\]

\[
D(N_c)/<N_c> = (0.46 \pm 0.07) - (0.003 \pm 0.01)N_b \quad \text{at 400 GeV} \quad \ldots(4)
\]

From Fig. 3 and slopes of the lines, same behaviour is observed at all the energies. Thus, we can say that the behaviour is independent of energy and this represents a kind of scaling. In the coherent tube picture, a collision with higher \( \nu \) (number of collisions) is equivalent to a hadron-nucleon collision at a higher energy and this leads to no variation of the ratio.

Figure 4 shows the variation of \( <N_c> \) with \( N_b \). Straight line fits to the data have been made and the equations obtained are as under:

\[
<N_c> = (5.13 \pm 0.89) + (0.63 \pm 0.09)N_b \quad \text{at 50 GeV} \quad \ldots(5)
\]

\[
<N_c> = (12.71 \pm 1.31) + (0.61 \pm 0.12)N_b \quad \text{at 340 GeV} \quad \ldots(6)
\]
Fig. 2 — Variation of $D(N_s)$ with $<N_s>$. The lines are due to least squares fittings.

$<N_c> = (10.01 \pm 1.02) + (1.43 \pm 0.19)N_b$

at 400 GeV  

...(7)

From Fig. 4 and Eqs (5-7), it is noted that $<N_c>$ depends linearly on $N_b$, thus, we can say that similar behaviour is observed here also. One more thing which is observed is that the compound multiplicity is energy dependent.

Table 3 — The values of $R_{A1}$ and $R_{A2}$

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>$R_{A1}$</th>
<th>$R_{A2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1.86±0.04</td>
<td>2.34±0.06</td>
</tr>
<tr>
<td>340</td>
<td>1.95±0.06</td>
<td>2.21±0.07</td>
</tr>
<tr>
<td>400</td>
<td>2.09±0.07</td>
<td>2.32±0.08</td>
</tr>
</tbody>
</table>

Another parameter which has been used to understand the multiparticle production process is the mean normalized multiplicity, $R_A$ (say $R_{A1}$). In the beginning this parameter was defined as:

$R_{A1} = <N_s>/<N_{ch}>$  

...(8)

where $<N_s>$ represents the average number of charged shower particles observed in $hA$ collisions and $<N_{ch}>$ is the mean number of charged particles observed in hadron-hadron(hh) interactions at the same energy. However, new definitions to the parameter have been given in terms of created charged particles. Thus, for example in $\pi A$ and $pA$ interactions, this has been taken as $^{14}$:

$<N_c> = (<N_s> - 0.50) / (<N_{ch}> - 1.40)$  

...(9)

$<N_c> = (<N_s> - 0.67) / (<N_{ch}> - 1.33)$  

...(10)

In the present analysis, $R_{A1}$ and $R_{A2}$ have been calculated using the following relations:

$R_{A1} = <N_c> / <N_{ch}>$  

...(11)
\((R_{A1}) \pi^A = (\langle N_c \rangle - 0.50) / (\langle N_{ch} \rangle - 1.40) \) ...(12)
\((R_{A2}) pA = (\langle N_c \rangle - 0.67) / (\langle N_{ch} \rangle - 1.33) \) ...(13)

The values of \(R_{A1}\) and \(R_{A2}\) are presented in Table 3. The variations of \(R_{A1}\) and \(R_{A2}\) with energy are shown in Figs 5 and 6. \(R_{A1}\) and \(R_{A2}\) are independent of energy and nature of the projectile (Figs 5 and 6). Variations of \(R_{A1}\) and \(R_{A2}\) with \(N_b\) have also been studied and are shown in Figs 7 and 8. Least square fits to the data have again been performed and the following equations are obtained:

\[ R_{A1} = (0.91 \pm 0.15) + (0.11 \pm 0.02)N_b \]
\[ \text{at 50 GeV} \] ...(14)

\[ R_{A1} = (1.13 \pm 0.11) + (0.07 \pm 0.01)N_b \]
\[ \text{at 340 GeV} \] ...(15)
Table 4 — Values of central moments

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>$\sqrt[2]{\mu_2}$</th>
<th>$\sqrt[3]{\mu_3}$</th>
<th>$\sqrt[4]{\mu_4}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>7.39±0.17</td>
<td>7.27±0.16</td>
<td>10.43±0.23</td>
</tr>
<tr>
<td>340</td>
<td>8.15±0.21</td>
<td>7.41±0.25</td>
<td>11.37±0.29</td>
</tr>
<tr>
<td>400</td>
<td>11.17±0.37</td>
<td>11.38±0.35</td>
<td>16.18±0.45</td>
</tr>
</tbody>
</table>

Table 5 — Values of normalized moments

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>$C_2$</th>
<th>$C_3$</th>
<th>$C_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1.47±0.06</td>
<td>2.73±0.18</td>
<td>5.92±0.53</td>
</tr>
<tr>
<td>340</td>
<td>1.14±0.03</td>
<td>1.45±0.06</td>
<td>2.05±0.13</td>
</tr>
<tr>
<td>400</td>
<td>1.27±0.07</td>
<td>1.97±0.17</td>
<td>3.60±0.46</td>
</tr>
</tbody>
</table>

$R_{A1} = (0.99 \pm 0.18) + (0.14 \pm 0.11)N_b$

at 400 GeV ... (16)

$R_{A2} = (1.03 \pm 0.21) + (0.15 \pm 0.02)N_b$

at 50 GeV ... (17)

$R_{A2} = (1.37 \pm 0.13) + (0.07 \pm 0.01)N_b$

at 340 GeV ... (18)

$R_{A2} = (1.06 \pm 0.21) + (0.16 \pm 0.02)N_b$

at 400 GeV ... (19)

From Figs 7 and 8, it is noted that similar linear dependence of $R_{A1}$ and $R_{A2}$ on $N_b$ is observed.

Central and normalized moments of the compound multiplicity distribution have also been studied. The central moments are defined as:

$$\sqrt[k]{\mu_k} = \sqrt[k]{\langle (N_c - <N_c>)^k \rangle}$$

where $k$ may have values 1, 2, 3, 4 etc. The values of different moments are presented in Tables 4 and 5. From Table 4, we find that the central moments depend upon the energy and nature of the projectile, this supports CTM.

The normalized moments are defined as:

$$C_k = \frac{\langle N_c^k \rangle}{\langle N_c \rangle^k}$$

where $k = 1, 2, 3, 4$ etc.

The values of $C_2$, $C_3$ and $C_4$ are listed in Table 5. CTM says that the normalized moments are independent of energy but in the present case the model agrees with lower order of the moments only.

4 Conclusions

On the basis of the results presented, we conclude the following:

(i) A kind of scaling is observed in the variation of the ratio $D(N_c)/<N_c>$ with $N_b$ at three different energies.

(ii) Compound multiplicity is energy dependent.

(iii) $R_{A1}$ and $R_{A2}$ are found to depend almost linearly on black particle multiplicity at all the energies.

(iv) Central moments depend upon the energy and nature of the projectile whereas the normalized moments are found to be independent of energy particularly the lower orders of the moment.

References