Signatures of Target Fragmentation of Nuclear Emulsion by Light Nuclei

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The interactions of a proton (3.7 GeV) with an emulsion can reveal the behavior of the nucleon–nucleus interactions. Furthermore, the interactions of $^4$He (2.1A GeV) and $^7$Li (2.2A GeV) with an emulsion introduce adequately a manner-representing nucleus–nucleus interactions. On the other hand, a major part of this work concerns the target fragmentation process. Thus, the yields of the target fragmentation (heavily ionizing particles $N_h$) have been studied on the basis of a comprehensive analysis of the data in the literature. The complete destruction of Ag nuclei (heaviest target in the emulsion) is achieved at a limiting value of $N_h$ ($N_h \geq 28$) for the nucleus–nucleus interactions. This study gives an indication of being a rich source of information on nuclear structure.

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I. INTRODUCTION

The investigation of the target fragmentation process through nucleon–nucleus or nucleus–nucleus interactions at high energy has been a field of active research for over three decades [1–7]. The difference between the projectile and the target spectator fragment is easily made. The projectile fragments corresponding to the spectator part are distinguished by being in a narrow forward cone. The angle of this cone is $\theta_{Lab} \leq 3^\circ$, while the produced particles and rescattering protons have a much broader distribution.

The target fragments are observed as highly ionizing particles, isotropically distributed. They can be black particles, which are essentially evaporation fragments from the target, or grey particles, which are knockout protons or slow mesons. Target fragmentation is sometimes called palliation.

At high energies, where the rapidity interval between the projectile and target are well separated, the physics of the two fragmentation regions must be similar. However the experimental techniques are often considerably different.

On the other hand, the synchrophasotron accelerator at Dubna enables equipping beams of $A \geq 1$ in the few GeV/nucleon range of energy.

Therefore, in the context of the present work, we can extract a bulk of data resulting from the interactions of protons (3.7 GeV), $^4$He (2.1A GeV), and $^7$Li (2.2A GeV) with an emulsion. Our lab group has previously investigated the different characteristics of such
interactions in several publications (summarized in [7–14]).

II. EXPERIMENTAL DETAILS

Three stacks of NIKFI–BR2 nuclear emulsion with dimensions of 10 cm × 20 cm × 600 µm were irradiated by P (3.7 GeV), \(^4\)He (2.1A GeV), and \(^7\)Li (2.2A GeV) beams at the synchrophasotron in Dubna, Russia. Along-the-track double scanning, fast in the forward direction and slow in the backward one, was carried out using a total magnification of about 1500X. Hence we could carefully extract a sufficient number of statistical events. They were 2649, 2066, and 1003 inelastic interactions belonging to p, \(^4\)He, and \(^7\)Li, respectively. The experimental mean free paths \(\lambda\) were found to be 30.20±0.70 cm, 20.76±0.46 cm, and 15.30±0.48 cm for the interactions of p, \(^4\)He, and \(^7\)Li with emulsion, respectively.

The tracks of the emitted secondary charged particles in each event were classified according to the traditional emulsion criteria [15, 16] as follows: (a) Shower tracks are singly charged relativistic particles with relative ionization \(I/I_0 \leq 1.4\), where \(I\) is the track ionization and \(I_0\) is the plateau ionization for singly charged minimum ionizing particles. Their multiplicity was denoted by \(n_s\). (b) Grey tracks have a range of \(L \geq 3\) mm in emulsion and relative ionization \(I/I_0 \geq 1.4\). These tracks are mostly due to protons with kinetic energy in the range 26 – 400 MeV. Their multiplicity is denoted by \(N_g\). (c) Black tracks are those having a range of \(L < 3\) mm, corresponding to protons with kinetic energy \(\leq 26\) MeV. They are mainly due to evaporated target fragments. Their multiplicity is denoted by \(N_b\). In each event, the black and grey tracks together are called highly ionizing tracks. Their multiplicity is denoted by \(N_h = N_g + N_b\). (d) Projectile Fragments, PF’s, are emitted with an angle \(\theta_{Lab} \leq 3^\circ\) with respect to the direction of incidence. They are characterized by no change in their ionization for at least 2 cm from the interaction point. In the present work they may be singly and doubly charged fragments stripped from the projectile nucleus, having velocity \(v \approx 0.97c\). The total charge of the stripped fragments in the forward cone per event is denoted by \(Q\). The single charged fragments emitted in the forward fragmentation cone were subjected to rigorous multiple scattering measurements for the momentum determination in order to distinguish them from the produced pions.

III. RESULTS AND DISCUSSIONS

This experimental study has been performed on the interactions of p (3.7 GeV), \(^4\)He (2.1A GeV), and \(^7\)Li (2.2A GeV) with emulsion.

As given in the experimental details, the shower particles are mainly pions emitted due to the projectile fragmentation process. Therefore, to investigate the target fragmentation process, it is convenient to select those events with no relativistic charged particles (shower) in the laboratory frame, (i.e. with no pionization, \(n_s = 0\)). We use the criteria \(n_s = 0\) as an indicator of the target fragmentation in this work.

In Table I, the percentage probabilities of events having \(n_s = 0\) are given for our data,
TABLE I: The percentage probabilities of events having \( n_s = 0 \) and of those having \( N_h \geq 28 \) for the interactions of different projectiles with emulsion.

<table>
<thead>
<tr>
<th>Projectile</th>
<th>Energy A GeV</th>
<th>( P (n_s = 0) )( % )</th>
<th>( P (N_h \geq 28) )( % )</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p )</td>
<td>2.20</td>
<td>31.45\pm2.11</td>
<td>0.00\pm0.00</td>
<td>[17]</td>
</tr>
<tr>
<td>( p )</td>
<td>3.70</td>
<td>9.85\pm0.61</td>
<td>0.00\pm0.00</td>
<td>Present Work</td>
</tr>
<tr>
<td>( d )</td>
<td>3.70</td>
<td>2.60\pm0.40</td>
<td>1.58\pm0.31</td>
<td>[18–21]</td>
</tr>
<tr>
<td>( ^4\text{He} )</td>
<td>2.10</td>
<td>7.12\pm0.59</td>
<td>2.86\pm0.37</td>
<td>Present Work</td>
</tr>
<tr>
<td>( ^7\text{Li} )</td>
<td>2.20</td>
<td>10.37\pm1.02</td>
<td>3.69\pm0.61</td>
<td>Present Work</td>
</tr>
</tbody>
</table>

as well as for the data of other experiments [17–21].

One can observe that for protons (nucleon–nucleus interactions) at an incident energy of 2.2 GeV the value of \( P (n_s = 0) \)% is nearly three times that at 3.7 GeV. About 90.15% of the protons interactions at 3.7 GeV suffer the pionization process, while 68.23% do at 2.2 GeV. Thus, we can expect that the incident energy gives a chance for the pionization process to be more probable, where the impact parameter for protons has no effect in the collision with the target. For the other investigated projectiles (nucleus–nucleus interactions), we can observe that the value of \( P (n_s = 0) \)% rises systematically with projectile size. Therefore, one can say that in nucleus–nucleus interactions the projectile size may be an effective parameter in the target fragmentation process where the impact parameter effect begins to appear.

Fragmentation of a target nucleus is manifested by the emission of slow heavily ionizing particles. Hence the probabilities of the events with \( N_h \geq 28 \) are presented in Table I. These events result from the complete destruction of Ag nuclei [22, 23] in emulsion. This sample of interactions is located in the region of a very central collision. From the table it can be noted that for protons the destruction is not achieved, because the energy is not enough to reach the region of a very central collision. For the other projectiles used, the value of \( P (N_h \geq 28) \)% increases with the projectile mass. This increase will have a limiting behavior, where in Ref. [24] it was shown that the probability values of complete destruction of Ag nuclei give evidence for constancy with projectiles of \( A_p \geq 12 \).

Fig. 1, shows the dependence of the average shower particle multiplicity \( \langle n_s \rangle \), which is a parameter representing the projectile, on \( N_h \) for different projectiles.

From Fig. 1, one can observe that the dependence for all projectiles is linear. The correlations between \( \langle n_s \rangle \) and \( N_h \) can be fitted well by straight lines of the form \( \langle n_s \rangle = aN_h + b \). The fitting parameters are given in Table II.

From the table it can be shown that the heavier the projectile size, the larger are the slope values and the stronger is the dependence of \( \langle n_s \rangle \) on \( N_h \). However, the increase of the slopes with the projectile size indicates the strong dependence of the shower particles on the projectile. For protons, negative and weak dependences are observed.

The mean numbers of the recoil target protons (grey particles) \( \langle N_g \rangle \) and the evaporated target fragments (black particles) \( \langle N_b \rangle \) are good indicators representing target fragmentation. Hence Fig. 2 shows the dependence of the grey and black particle
FIG. 1: The dependence of $\langle n_s \rangle$ on $N_h$ in the interactions of $p$ (2.2 GeV) [17], $p$ (3.7 GeV), $d$ (3.7A GeV) [18–21], $^4$He (2.1A GeV), and $^7$Li (2.2A GeV) with emulsion, together with the linear fitting of the experimental data (lines).

TABLE II: The fitting parameters characterizing the dependence of $\langle n_s \rangle$ on $N_h$ throughout the interactions of different projectiles with emulsion.

<table>
<thead>
<tr>
<th>Projectile</th>
<th>Energy A GeV</th>
<th>$A$</th>
<th>$b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$</td>
<td>2.20</td>
<td>$-0.05 \pm 0.01$</td>
<td>1.14(\pm 0.16)</td>
</tr>
<tr>
<td>$p$</td>
<td>3.70</td>
<td>$-0.01 \pm 0.01$</td>
<td>1.64(\pm 0.12)</td>
</tr>
<tr>
<td>$d$</td>
<td>3.70</td>
<td>$0.07\pm 0.02$</td>
<td>2.44(\pm 0.13)</td>
</tr>
<tr>
<td>$^4$He</td>
<td>2.10</td>
<td>$0.17\pm 0.02$</td>
<td>2.38(\pm 0.18)</td>
</tr>
<tr>
<td>$^7$Li</td>
<td>2.20</td>
<td>$0.34\pm 0.02$</td>
<td>1.56(\pm 0.11)</td>
</tr>
</tbody>
</table>

average multiplicity on $n_s$.

From Fig. 2, one can show that the experimental data can be fitted well by the linear relation of the form $\langle N_{g,b} \rangle = \beta_{g,b}n_s + \alpha_{g,b}$, illustrated by the solid lines. The fitting parameters are given in Table III.

From the figure and the values of the slope parameters in the table, weak dependences for proton interactions are observed. However, the dependences are strong for $^4$He and $^7$Li.

If we define $A$ as the asymmetry parameter, where $A = \frac{\alpha_g - \alpha_b}{\alpha_g + \alpha_b}$, we can recognize the behavior of the system emitting grey particles and that emitting black ones with respect
FIG. 2: The dependence of $<N_g>$ and $<N_b>$ on $n_s$ for the interactions of $p$ (3.7 GeV), $^4\text{He}$ (2.1A GeV), and $^7\text{Li}$ (2.2A GeV) with emulsion, together with the linear fitting of the data (lines).

TABLE III: The fitting parameters characterizing the correlations between $<N_{g,b}>$ and $n_s$ for the interactions of $p$ (3.7 GeV), $^4\text{He}$ (2.1A GeV), and $^7\text{Li}$ (2.2A GeV) with emulsion.

<table>
<thead>
<tr>
<th>Projectile</th>
<th>$&lt;N_g&gt;$ versus $n_s$</th>
<th>$&lt;N_b&gt;$ versus $n_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\alpha_g$</td>
<td>$\beta_g$</td>
</tr>
<tr>
<td>$p$</td>
<td>1.64±0.07</td>
<td>0.06±0.02</td>
</tr>
<tr>
<td>$^4\text{He}$</td>
<td>0.61±0.10</td>
<td>0.53±0.04</td>
</tr>
<tr>
<td>$^7\text{Li}$</td>
<td>0.42±0.07</td>
<td>0.48±0.02</td>
</tr>
</tbody>
</table>

to the projectile size. Hence Fig. 3 displays the change of the asymmetry parameter with the projectile mass $A_p$.

The values of $A$ decrease with $A_p$ in the power relation $A = \mu A_p^\nu$, where $\mu = 0.40 \pm 0.00$, $\nu = -0.3 \pm 0.01$. Since the asymmetry is not constant, there may be a tendency of a symmetry trend between the system emitting grey particles and that emitting black particles. However, such a systematic change over the projectile size indicates a limiting behavior in the fragmentation system by light nuclei at the Dubna energy.

Now, it is convenient to scale or normalize the target parameters $<N_g>$ and $<N_b>$ with respect to the projectile parameter $<n_s>$. Hence Fig. 4 presents the ratios of $\frac{<N_g>}{<n_s>}$ and $\frac{<N_b>}{<n_s>}$ versus $N_h$ for the interactions of $p$ (3.7 GeV), $^4\text{He}$ (2.1A GeV), and $^7\text{Li}$ (2.2A GeV) with emulsion.

It is clear from Fig. 4 that the data are well fitted linearly using the relation of the
FIG. 3: The change of the asymmetry parameter $A$ with the projectile mass number $A_p$, for the interactions of $p$ (3.7 GeV), $^4\text{He}$ (2.1A GeV), and $^7\text{Li}$ (2.2A GeV) with emulsion, together with the linear fitting of the data (line).

FIG. 4: The dependences of the $\langle N_p \rangle / \langle n_s \rangle$ and $\langle N_b \rangle / \langle n_s \rangle$ ratios on $N_h$ for the interactions of $p$ (3.7 GeV), $^4\text{He}$ (2.1A GeV), and $^7\text{Li}$ (2.2A GeV) with emulsion, together with the linear fitting of the data (lines).
TABLE IV: The fitting parameters characterizing the dependences of $< N_g > / < n_s >$ and $< N_b > / < n_s >$ ratios on $N_h$ for the interactions of $p$ (3.7 GeV), $^4$He (2.1A GeV), and $^7$Li (2.2A GeV) with emulsion.

<table>
<thead>
<tr>
<th>Projectile</th>
<th>$&lt; N_g &gt; / &lt; n_s &gt;$ versus $N_h$</th>
<th>$&lt; N_b &gt; / &lt; n_s &gt;$ versus $N_h$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$</td>
<td>$c_g$ 0.10±0.01 $d_g$ −0.05±0.08</td>
<td>$c_b$ 0.40±0.02 $d_b$ −0.21±0.23</td>
</tr>
<tr>
<td>$^4$He</td>
<td>0.04±0.00 0.22±0.03</td>
<td>0.09±0.00 0.56±0.07</td>
</tr>
<tr>
<td>$^7$Li</td>
<td>0.03±0.00 0.25±0.02</td>
<td>0.05±0.01 0.64±0.06</td>
</tr>
</tbody>
</table>

FIG. 5: The change of the slope parameters $c_g$ and $c_b$ with the projectile mass in the interactions of $p$ (3.7 GeV), $^4$He (2.1A GeV), and $^7$Li (2.2A GeV) with emulsion, together with the fitting (lines).

form $< N_{g,b} > = cN_h + d$. The fitting parameters are shown in table IV.

From Fig. 4 and Table IV, one can note that the representative ratios of the grey particles on $N_h$ (target size) are stronger than the black. The values of the slope parameters decrease with increasing projectile mass. However, such values show a tendency for constancy with $N_h$ for nucleus–nucleus interactions. This indicates a limiting behavior of fragmentation over the different target sizes. The slope parameters change with the projectile size in a species represented diagrammatically in Fig. 5.

As seen in Fig. 5, the slope parameters decrease with the projectile mass number $A_p$ in the shape of a power relation of the form $c_{g,b} = \gamma A_p^\eta$. The fitting parameters are $[\gamma = 0.10 \pm 0.00$ and $\eta = −0.63 \pm 0.03]$ and $[\gamma = 0.40 \pm 0.00$ and $\eta = −1.08 \pm 0.00]$ for the ratios of the grey and black particles, respectively.

Throughout the study of the target fragmentation, it is appropriate to visualize the distribution of the target fragments. Hence, Fig. 6(a) and (b) present the normalized $N_h$
FIG. 6: (a) $N_h$ – multiplicity distributions for the interactions of protons at 2.2 GeV [17] and 3.7 GeV with emulsion. (b) $N_h$ – multiplicity distributions for the interactions of $d$ (3.7A GeV) [18–21], $^4$He (2.1A GeV), and $^7$Li (2.2A GeV) with emulsion.

In Fig. 6(a) and (b), the distributions show an agreement and similarity between the data at the total sample and that having no pionization ($n_s = 0$) for each projectile, multiplicity distributions in the interactions of $p$ (2.2 GeV) [17], $p$ (3.7 GeV), $d$ (3.7A GeV) [18–21], $^4$He (2.1A GeV), and $^7$Li (2.2A GeV) with emulsion. The data are shown as a total sample of events compared with the sample of events having $n_s = 0$ (one of the target fragmentations criteria).

In Fig. 6(a) and (b), the distributions show an agreement and similarity between the data at the total sample and that having no pionization ($n_s = 0$) for each projectile,
FIG. 7: $N_g$ – multiplicity distributions for the interactions of different projectiles with emulsion.

regarding the tail of $N_b$ at the total sample.

Figs. 7 and 8 display the normalized distributions of $N_g$ and $N_b$ for the $p$ (3.7 GeV), $^4$He (2.1A GeV), and $^7$Li (2.2A GeV) interactions with emulsion.

Currently, the information in Figs. 7 and 8 is better understood. For nucleon–nucleus interactions (proton), the $N_g$ distributions are the same at the two criteria of $n_s$, as well as $N_b$ distributions. The distributions for nucleus–nucleus interactions are similar at the two criteria of $n_s$, and their behaviors have the same trend as that for nucleon–nucleus interactions.

IV. SUMMAR Y

The above study of nucleon–nucleus (proton), and nucleus–nucleus interactions ($^4$He and $^7$Li) at the Dubna energy can be summarized in the following way.

For nucleon–nucleus interactions the pionization process is more probable with the incident energy. In nucleus–nucleus interactions the projectile size may be an effective parameter in target fragmentation. The complete destruction of the Ag target nuclei in emulsion is achieved in nucleus–nucleus interactions. The destruction probability increases with the projectile size up to a critical mass ($A_p = 12$), where its value begins to saturate. The common feature characterizing the correlations between the different emitted particles always shows a linear dependence. There is a negative and weak correlation between $< n_s >$ and $N_b$ in the case of $p$ – emulsion interactions, while the correlations for nucleus–nucleus interactions are positive and moderate. The shower particles multiplicity depends signifi-
FIG. 8: $N_b$ – multiplicity distributions for the interactions of different projectiles with emulsion.

cantly on the size of the target in nucleus–nucleus interactions. Whereas the dependence for nucleon–nucleus interactions is not appreciable. This may reflect that the cascading process is more pronounced and, consequently, the energy deposition within the interaction volume is large in nucleus–nucleus interactions. In the case of $p$ – emulsion interactions there is practically no dependence of $\langle N_g \rangle$ and $\langle N_b \rangle$ on $n_s$, signifying the fact that the number of shower particles produced in events is independent of target excitation. However, in the case of nucleus–nucleus interactions their dependence is appreciable.

Therefore, the above observations are essential for a better understanding of the fragmentation mechanism in high energy collisions.

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References

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