

ABOUT TARGET FRAGMENTATION IN NUCLEAR EMULSION AT RELATIVISTIC ENERGY

A. Abdelsalam⁽¹⁾ and B. M. Badawy⁽²⁾

(1) *Physics Department, Faculty of Science, Cairo University, Giza, Egypt*

(2) *Reactor Physics Dpt., Nuclear Research Center, A. E. A., Egypt*

E. Mail: badawyfathalla@hotmail.com

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The interaction of proton with nuclear emulsion at 3.7 GeV reveals the picture of hadron – nucleus collision. The nucleus – nucleus collisions are given in the interactions of ^4He and ^7Li with emulsion nuclei at nearly the same energy ($2A$ GeV). On the other hand, the relativistic energy (a few GeV/nucleon) is a special energy, at which the nuclear limiting fragmentation applies initially. Therefore, the target fragmentation is studied by selecting samples of inelastic interaction events having no emission of relativistic hadrons. The multiplicity characteristics of the produced target fragments are studied. The dependence of the target fragments on the projectile size has been analyzed. The complete destruction of Ag target nuclei has been observed in nucleus – nucleus interactions at number of heavily ionizing particles (N_h) ≥ 28 .

Keywords: *Interactions of p , ^4He , and ^7Li with nuclear emulsion, target fragmentation, complete destruction of Ag nuclei.*

INTRODUCTION

The investigation of target fragmentation process through nucleon – nucleus or nucleus – nucleus interactions at high energy has been a field of active research over the last three decades [1 – 7].

The difference between the projectile and the target spectator fragment is easy to make. The projectile fragments corresponding to the spectator part are distinguished in forward narrow cone. The angle of this cone is $\theta_{\text{Lab}} \leq 3^\circ$, 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. The target fragmentation is sometimes called spallation.

At high energies, where the rapidity interval between 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 synchrotron 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 resulted from the interactions of proton (3.7 GeV), ^4He (2.1A GeV), and ^7Li (2.2A GeV) with emulsion. Our Lab. Group have previously, investigated the different characteristics of such interactions throughout several publications, (summarized in [7 – 14]).

EXPERIMENTAL DETAILS

Three stacks of NIKFI-BR2 nuclear emulsion with dimensions of 10 cm x 20 cm x 600 μm were irradiated by p (3.7 GeV), ^4He (2.1A GeV), and ^7Li (2.2A GeV) beams at synchrotron 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 sufficient number of statistical events. They were, 2649, 2066, and 1003 inelastic interactions belonging to p, ^4He , and ^7Li , respectively. The experimental mean free paths λ 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, ^4He , and ^7Li 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 range of $L < 3$ mm, corresponding to protons with kinetic energy ≤ 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 heavily ionizing tracks. Their multiplicity is denoted by ($N_h = N_g + N_b$), and (d) Projectile Fragments, PF's are emitted with an angle $\theta_{\text{Lab}} \leq 3^\circ$, 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.

RESULTS AND DISCUSSION

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

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 (1), the percentage probabilities of events having $n_s = 0$, are given for our data, as well as for the data of other experiments [17 – 21].

Table 1. 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.

Projectile	Energy A GeV	P ($n_s = 0$) %	P ($N_h \geq 28$) %	Ref.
p	2.2	31.45±2.11	0	17
p	3.7	9.85±0.61	0	Present Work
d	3.7	2.60±0.40	1.58±0.31	18 – 21
^4He	2.1	7.12±0.59	2.86±0.37	Present Work
^7Li	2.2	10.37±1.02	3.69±0.61	Present Work

One can observe that, for protons (nucleon – nucleus interactions), at 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 proton interactions at 3.7 GeV suffer pionization processes, while at 2.2 GeV the percentage was 68.23 %. Thus, we can expect that, the incident energy gives a chance for 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 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 (1). These events results from the complete destruction of Ag nuclei [22, 23] in emulsion. This sample of interactions is located in the region of 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 very central collision. For the other used projectiles, 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.

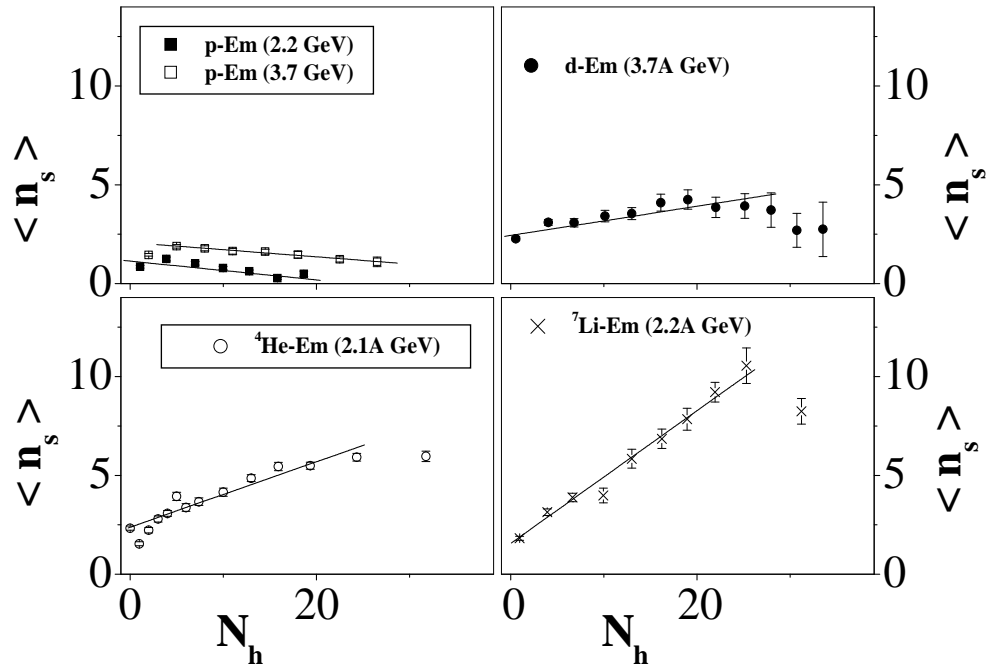


Figure 1. The dependence of $\langle n_s \rangle$ on N_h in the interactions of p (2.2 GeV) [17], p (3.7 GeV), d (3.7A GeV) [18 – 21], ^4He (2.1A GeV), and ^7Li (2.2A GeV) with emulsion, together with the linear fitting of the experimental data [lines].

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 (2).

From the table it can be shown that, the heavier the projectile size, the larger are the slope values, 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

the target fragmentation. Hence, Fig. (2) shows the dependence of the grey and black particle average multiplicity on n_s .

Table 2. The fitting parameters characterizing the dependence of $\langle n_s \rangle$ on N_h throughout the interactions of different projectiles with emulsion.

Projectile	Energy A GeV	a	b
p	2.20	-0.05 ± 0.01	1.14 ± 0.16
p	3.70	-0.01 ± 0.01	1.64 ± 0.12
d	3.70	0.07 ± 0.02	2.44 ± 0.13
^4He	2.10	0.17 ± 0.02	2.38 ± 0.18
^7Li	2.20	0.34 ± 0.02	1.56 ± 0.11

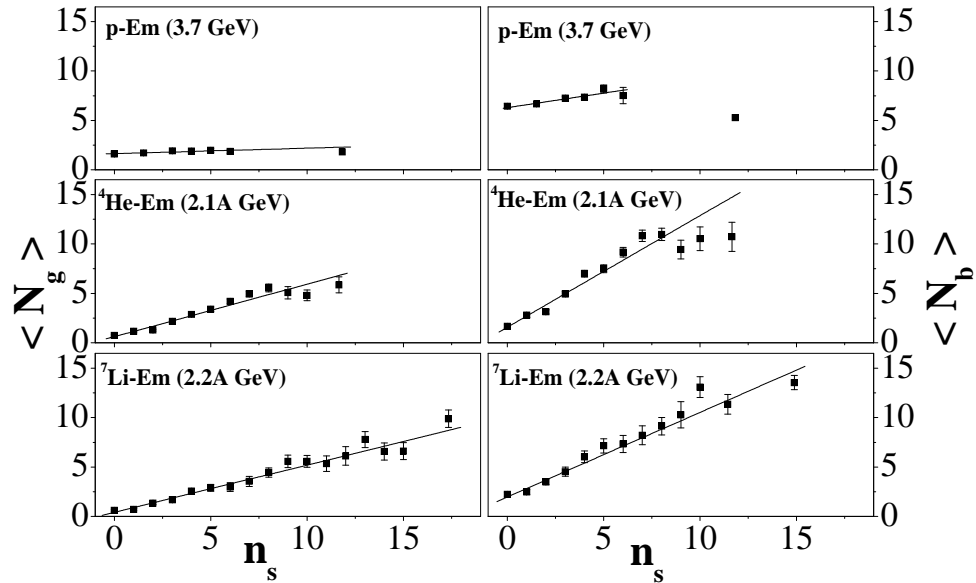


Figure 2. The dependence of $\langle N_g \rangle$ and $\langle N_b \rangle$ on n_s for the interactions of p (3.7 GeV), ^4He (2.1A GeV), and ^7Li (2.2A GeV) with emulsion, together with the linear fitting of the data (lines).

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 (3).

Table 3. The fitting parameters characterizing the correlations between $\langle N_{g,b} \rangle$ 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.

Projectile	$\langle N_g \rangle$ versus n_s		$\langle N_b \rangle$ versus n_s	
	α_g	β_g	α_b	β_b
p	1.64 ± 0.07	0.06 ± 0.02	6.30 ± 0.13	0.29 ± 0.05
${}^4\text{He}$	0.61 ± 0.10	0.53 ± 0.04	1.57 ± 0.25	1.13 ± 0.08
${}^7\text{Li}$	0.42 ± 0.07	0.48 ± 0.02	2.00 ± 0.18	0.86 ± 0.05

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 ${}^4\text{He}$ and ${}^7\text{Li}$.

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

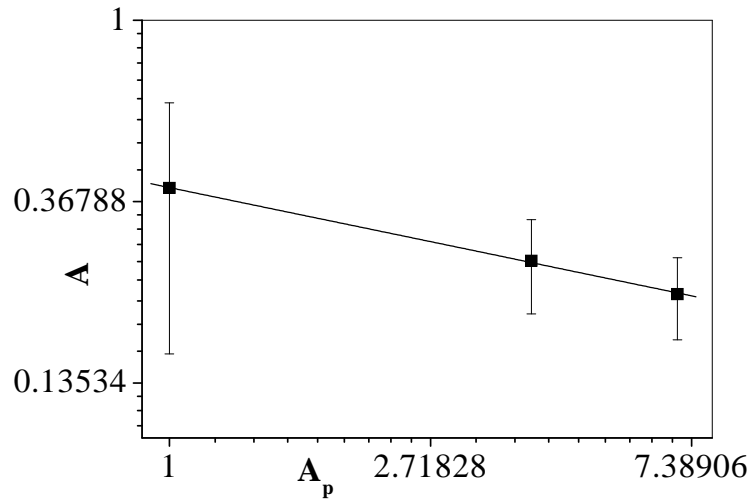


Figure 3. The change of the asymmetry parameter A with the projectile mass number A_p , for the interactions of p (3.7 GeV), ${}^4\text{He}$ (2.1A GeV), and ${}^7\text{Li}$ (2.2A GeV) with emulsion, together with the linear fitting of the data (line).

The values of A decrease with A_p in the following power relation, $A = \mu A_p^\nu$, where, $\mu = 0.40 \pm 0.00$, $\nu = -0.30 \pm 0.01$. Since, the asymmetry is not constant, thus there may be a tendency of symmetry trend between the system emitting grey particles and that emitting black particles. However, such systematic change over the projectile size

indicates a limiting behavior in the fragmentation system by light nuclei at Dubna energy.

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

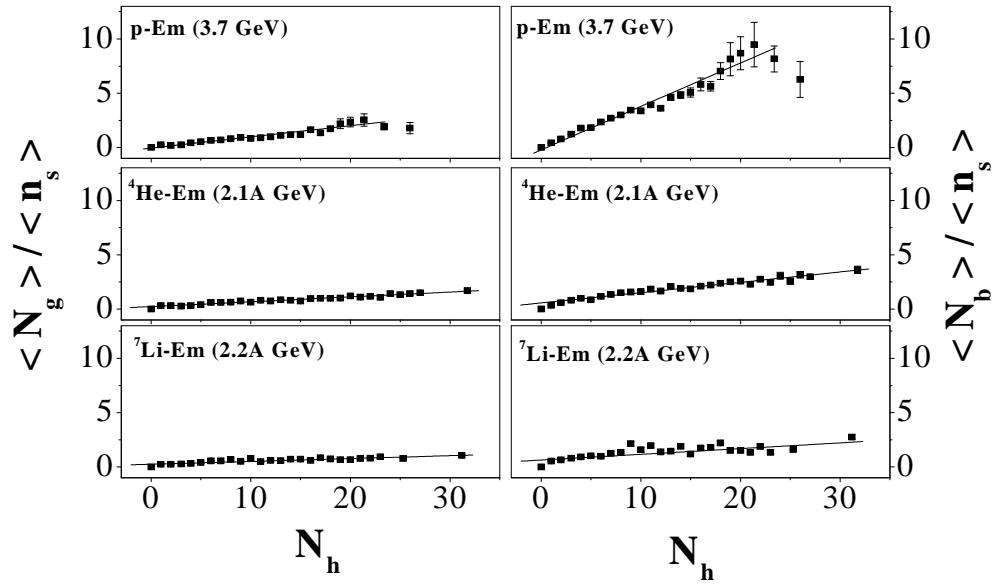


Figure 4. The dependences of $\langle N_g \rangle / \langle n_s \rangle$ and $\langle N_b \rangle / \langle n_s \rangle$ ratios on N_h for the interactions of p (3.7 GeV), ^4He (2.1A GeV), and ^7Li (2.2A GeV) with emulsion, together with the linear fitting of the data (lines).

It is clear from Fig. (4) that, the data are fitted linearly well, using the relation of the form, $\frac{\langle N_{g,b} \rangle}{\langle n_s \rangle} = cN_h + d$. The fitting parameters are shown in Table (4).

Table 4. The fitting parameters characterizing the dependences of $\langle N_g \rangle / \langle n_s \rangle$ and $\langle N_b \rangle / \langle n_s \rangle$ ratios on N_h for the interactions of p (3.7 GeV), ^4He (2.1A GeV), and ^7Li (2.2A GeV) with emulsion.

Projectile	$\langle N_g \rangle / \langle n_s \rangle$ versus N_h		$\langle N_b \rangle / \langle n_s \rangle$ versus N_h	
	c_g	d_g	c_b	d_b
P	0.10 ± 0.01	-0.05 ± 0.08	0.40 ± 0.02	-0.21 ± 0.23
^4He	0.04 ± 0.00	0.22 ± 0.03	0.09 ± 0.00	0.56 ± 0.07
^7Li	0.03 ± 0.00	0.25 ± 0.02	0.05 ± 0.01	0.64 ± 0.06

From Fig. (4) and Table (4), 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 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).

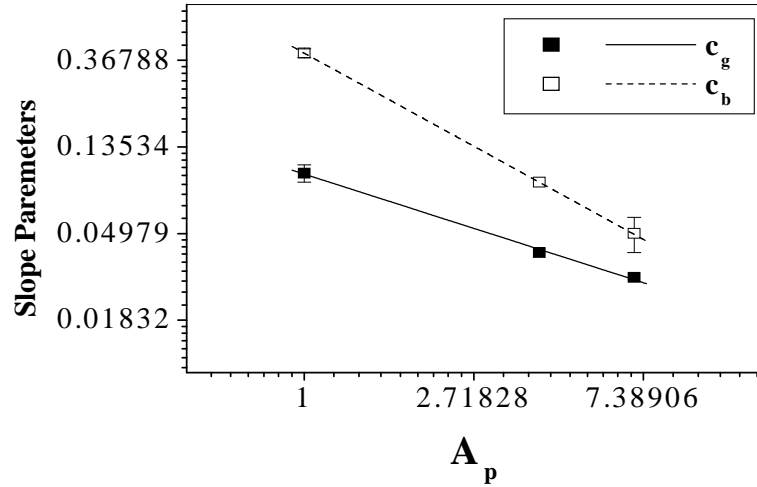


Figure 5. The change of the slope parameters c_g and c_b as a function of the projectile mass in the interactions of p (3.7 GeV), ^4He (2.1A GeV), and ^7Li (2.2A GeV) with emulsion, together with the fitting (lines).

As seen in Fig. (5), the slope parameters decrease with the projectile mass number A_p in the shape of 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, Figs. (6, a and b) present the normalized N_h multiplicity distributions in the interactions of p (2.2 GeV) [17], p (3.7

GeV), d (3.7A GeV) [18 – 21], ^4He (2.1A GeV), and ^7Li (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 target fragmentations criteria).

In Figs. (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, regarding the tail of N_h at the total sample.

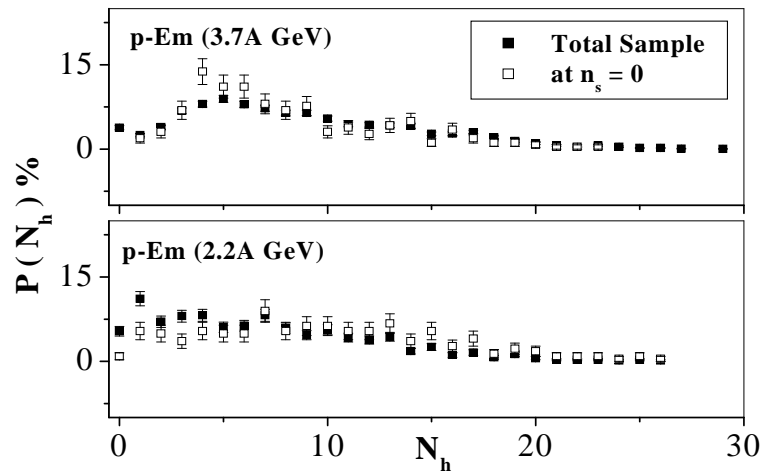


Figure 6a. N_h – multiplicity distributions for the interactions of proton at 2.2 GeV [17] and 3.7 GeV with emulsion.

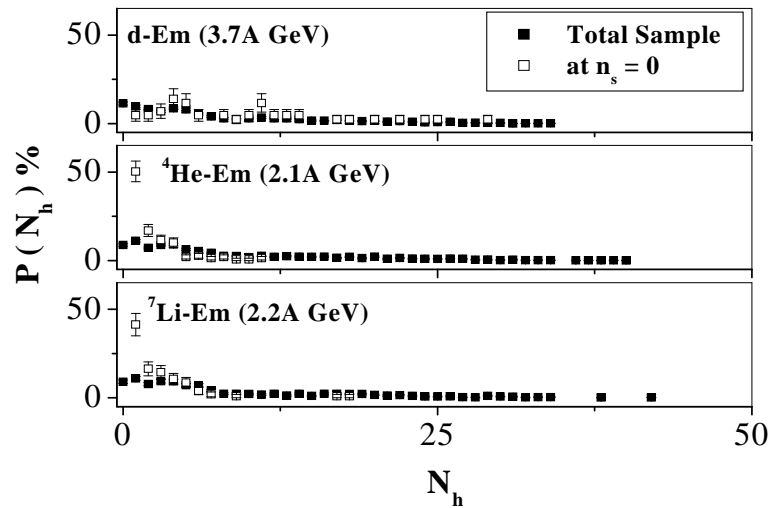


Figure 6b. N_h – multiplicity distributions for the interactions of d (3.7A GeV) [18 – 21], ^4He (2.1A GeV), and ^7Li (2.2A GeV) with emulsion.

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

Currently, the demonstrations in Fig. (7 and 8) are 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.

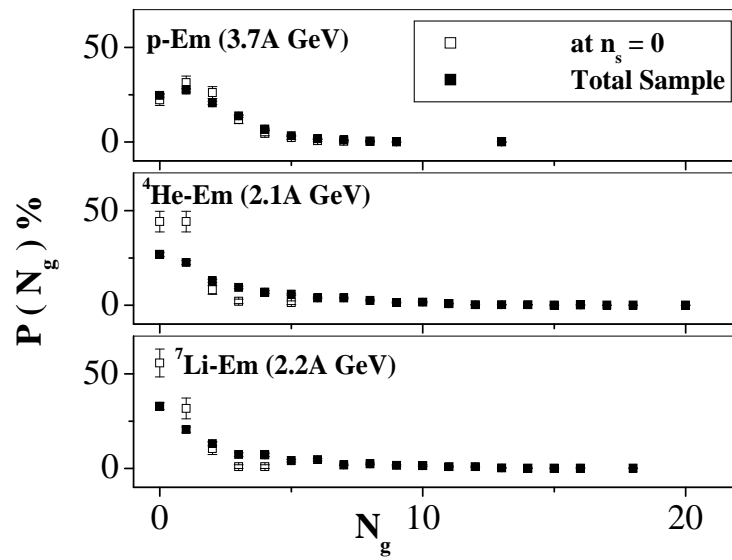


Figure 7. N_g – multiplicity distributions for the interactions of different projectiles with emulsion.

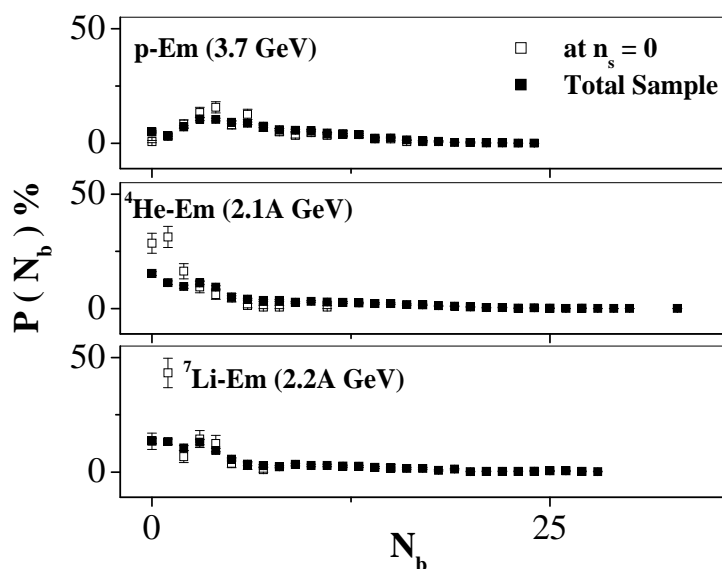


Figure 8. N_b – multiplicity distributions for the interactions of different projectiles with emulsion.

CONCLUSION

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

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 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 $\langle n_s \rangle$ and N_h in the case of p – emulsion interactions, while the correlations for nucleus – nucleus interactions are positive and moderate. The shower particles multiplicity depends significantly on the size of the target in nucleus – nucleus interactions, while the dependence for nucleon – nucleus interactions is inappreciable. 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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عن تشظي أنوية الهدف في المستحلب النووي عند الطاقات النسبوية

عبد الله عبد السلام¹ و بدوي محمد بدوي²

¹ قسم الفيزياء، كلية العلوم، جامعة القاهرة، مصر.

² قسم طبعة المفاعلات، مركز البحوث النووية، هيئة الطاقة الذرية، مصر.

لقد أوضح تفاعل البروتون مع أنوية المستحلب النووي عند 3.7 جيجا إلكترون فولت صورة لتصادم الهادرون مع النواة، أما تصادم النواة مع النواة فقد مثل من خلال تفاعلات أنوية هيليوم 4 و ليثيوم 7 مع المستحلب النووي عند حوالي 2 جيجا إلكترون فولت لكل نوكلليون (نفس الطاقة تقريبا).

ومن ناحية أخرى فإنه باعتبار نطاق الطاقات النسبوية هو ابتداء تطبيق التشظي النووي المحدد فإنه قد تم اختيار عينة من النفاذات غير المرنة و التي لاقت حدوث تشظي لأنوية الهدف لدراسة تلك الظاهرة، و قد كان معيار الإختيار لتلك العينة هو التفاعلات التي لم ينتج عنها أية هادرونات نسبوية.

و قد درست المميزات العددية لشظايا أنوية الهدف الناتجة من التفاعلات، و كذا مدى اعتماد تلك الشظايا على نواة القذيفة. ولوحظ حدوث إنهدام كامل لأنوية الفضة الثقيلة في المستحلب النووي من خلال تفاعلات النواة مع النواة و ذلك عند معيار محدد لشظايا نواة الهدف.

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