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FRAGMENTATION OF ^{32}S NUCLEI IN PHOTOEMULSION AT 3.7 AGeV

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ABSTRACT

Data on fragmentation of ^{32}S nuclei in emulsion at 3.7 AGeV are presented. The fragmentations are studied in terms of the impact parameter of collisions of the ^{32}S projectiles with the different target nuclei. The fragmentation cross sections and the multiplicities of the different fragments are nearly independent of the sulfur incident energy. The fragmentation of ^{32}S nuclei into alpha isotopes are extensively studied. The transverse momentum spectra of the emitted fragments are fitted by two Maxwell-Boltzmann distributions of different average transverse momenta. The characteristics (multiplicities and P_t-distributions) of the He-fragments produced in the central collisions are different from those emitted in the peripheral collisions.

KEYWORDS

Nuclear reaction; ^{32}S - Emulsion → projectile fragments; E = 3.7AGeV; Transverse momentum distribution of He-fragments.

INTRODUCTION

One of the component parts of the complex process of the inelastic interaction of relativistic nuclei is the fragmentation of the incident nucleus. The first experimental information (Greiner *et al.*, 1975; Chernov *et al.*, 1984) on the momentum distribution of the fragmentation products of relativistic nuclei revealed a Gaussian shape in the rest system of the fragmenting nucleus, with a parabolic dependence of the dispersion of this distribution (consequently the nuclear temperature) on the mass of the fragment.

Study of relativistic alpha particles which are the products of the projectile fragmentation process (Baumgardt, Friedlander and Schopper,1981 and Bhalla, Chaudhry and Lokanathan, 1981) can provide information about the fragmentation mechanism and thus help to give solutions to a number of problems of astrophysics, cosmic ray physics and radiation physics. The choice of alpha particles is due to the ease and reliability of their identification in the emulsion plates in addition to their high production cross section .

It was found that the momentum distribution of the emitted alpha particles can be represented by two Maxwell-Boltzmann distributions with two different temperatures (Baumgardt, Friedlander and Schopper, 1981 and Ganssauge *et al.*, 1985). Abdurazakova *et al.* (1988) stated that the alpha particles with large transverse momenta cannot be treated as the direct product of decay of the residual fragmenting nucleus.

In the present paper, we study the fragmentation of ^{32}S nuclei in emulsion at 3.7 AGeV. Multiplicities and momentum characteristics for fragments of different charges are obtained with special attention to helium fragments. Events are divided into different reaction channels, depending upon the interaction impact parameter. Different fragmentation characteristics are studied in each group.

EXPERIMENTAL PROCEDURE

This experiment has been performed in a stack of NIK-FI-Br-2 emulsion exposed at Dubna to a beam of ^{32}S nuclei with kinetic energy of 3.7 AGeV. A total of 769 inelastic interactions of ^{32}S nuclei were picked up by along the tracks double scanning, fastly in the forward direction and slowly in the backward one. The scanned primary beam tracks were further examined by measuring the delta electron density on each of them to exclude the tracks having a charge less than the incident nucleus charge. The general characteristics and other details on our experiments have been published before (El-Nadi *et al*. 1995a and El-Nadi *et al*. 1996). Charged secondaries of the obtained events were classified into the following types:

"black" particles (b-particles) with a range in emulsion $L \le 3$mm ($E_{proton} \le 26$ MeV), "gray" particles (g-particles) with $L > 3$mm ($26 < E_{proton} < 400$MeV) - for b- and g-particles together one uses the term "heavy" tracks (h-particles) ($\beta = v/c = 0.7$) - and "shower" particles (s-particles) which are singly charged particles with $\beta > 0.7$. The tracks of the last type having an emission angle mrad were further subjected to accurate multiple scattering measurement for momentum determination and consequently the produced pions can be separated from the single charged projectile fragments. The projectile fragments (PF's) of charge $Z=1$ were not included in the following analysis of s-particles. All projectile fragments are emitted within the fragmentation cone defined by a critical angle $\Theta_c = 44$ mrad. This value corresponds to a spectator proton with a transverse momentum of 200 MeV/c. Selection of PF's in nuclear emulsion can easily be performed since these tracks are characterized by high ionization which, in contrast to b- and g-particles, does not change over large distances (several cm). Furthermore they do not reveal noticeable multiple scattering.

The charge of the projectile fragments with $Z = 2$ was determined by the integral gap length method. The multicharged projectile fragments of $Z \ge 3$ were accurately identified by counting the δ-electrons on a track length of more than 1 cm. The calibration measurements of the average number of δ-electrons per mm (N_δ) were done in Fig. 1, for different primary projectiles incident on the same type of emulsion plates (Br-2) at Dubna energy (Mettwalli and Kellany, 1994) and for the present ^{32}S beam . The data are best fitted by the following relation:

$$N_\delta = 0.17\,Z^2 - 0.17 \quad (1)$$

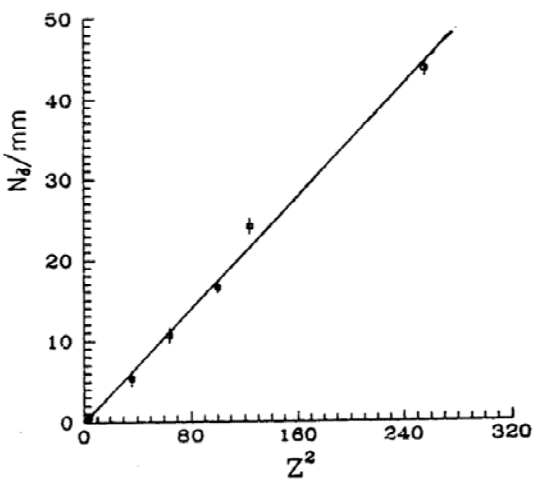

Fig. 1. The calibration curve showing the proportionality of the number of δ-electrons per mm (N_δ) on the square of the projectile fragment charge (Z^2)

The transverse momentum per nucleon (P_t) of a projectile fragment was calculated on the basis of its emission angle Θ,

$$P_t = P_0 \sin \Theta , \tag{2}$$

in the present experiment P_0 = 4.5 GeV/c.

RESULTS AND DISCUSSION

Multiplicities of secondaries from target and projectile fragmentation

The average multiplicities of s-. g- and b-particles from projectile fragmentation in 3.7 AGeV ^{32}S - Em interactions for different channels, depending upon N_h [$N_h \le 1$, 2-7, 8-15, 16-27 and ≥ 28] are presented in Table 1. The average of the total projectile spectator charges <Q>, (where $Q = \Sigma N_i Z_i$, N_i is the number of PF's having charge Z_i) and the mean number $<N_\alpha>$ of He fragments are also presented in the table . The last reaction group ($N_h \ge 28$) is characterized by the smallest value of <Q> (<Q> = 2.54 ± 0.41) and the highest value of $< n_s >$ ($< n_s >$ = 31.45 ± 1.48). This reaction group may be due to the central interaction of ^{32}S ions with heavy emulsion nuclei (Heckman *et al.*, 1978 and Tolstov, 1981). As can be seen from the data in Table 1, $< N_\alpha >$ is very weakly dependent on the impact parameter of the interactions. For the sake of comparison, the percentages of interaction events with various degrees of target break up for the present exposure and for 3.7 AGeV ^{28}Si-Em and 200 AGeV ^{32}S-Em interactions (Adamovich, *et al.*, 1995) are presented in Table 2.

Table 1. Mean number of: s-, g-, b-particles, He-fragments and the total projectile spectator charges Q, for different groups of events in 3.7 AGeV ^{32}S Em interactions

Reaction group	Multiplicity				
	$< N_S >$	$< N_g >$	$< N_b >$	$< Q >$	$< N_\alpha >$
$N_h \ge 0$	13.06 ± 0.45	3.43 ± 0.15	6.71 ± 0.25	9.51 ± 0.20	1.79 ± 0.08
N_h (0,l)	4.03 ± 0.37	0.22 ± 0.03	0.22 ± 0.03	14.00 ± 0.23	1.70 ± 0.18
N_h (2-7)	8.76 ± 0.46	1.43 ± 0.08	2.82 ± 0.09	11.27 ± 0.25	1.83 ± 0.11
N_h (8-15)	10.81 ± 0.88	3.39 ± 0.22	7.78 ± 0.29	9.93 ± 0.45	1.95 ± 0.25
N_h (16-27)	23.71 ± 0.95	6.89 ± 0.22	14.40 ± 0.25	4.43 ± 0.34	1.57 ± 0.19
$N_h \ge 28$	31.45 ± 1.48	11.82 ± 0.52	19.69 ± 0.43	2.54 ± 0.41	1.51 ± 0.20

The ratio between the number of collisions with $2 \le N_h \le 7$ (CNO + peripheral AgBr) and the number of collisions with $N_h \ge 8$ (only AgBr) is independent of the beam energy. The same result was observed before by EMUOl-collab. (Adamovich *et al.*, l995). This conclusion confirms the fact that the interaction cross section does not depend on the projectile's incident energy in the nucleus-Emulsion interactions .

Table 2 also shows the percentages of interaction events having total projectile destruction (TD). In general the percentage of TD events is approximately the same, within the errors, at the three compared exposures for both N_h=2-7 and $N_h \ge 8$ groups. Some difference is observed for events with N_h=0,1. This group of events belongs to the interactions of the incident projectile with free hydrogen nucleus or with only one bound nucleon in CNO or AgBr emulsion nuclei. From Table 2, it is interesting to notice that the ratio between the number of TD events with $2 \le N_h < 7/ N_h \ge 8$ is reduced to about one half of its corresponding value for the total sample of interactions.

• Events with total destruction (TD), as defined by EMUO1-Collab. (Adamovich *et al.,1995)*, are those events where only projectile fragments with charge $Z \le 2$ remain.

Table 2. Percentages of events for 3.7 AGeV ^{32}S, 3.7 AGeV ^{28}Si and 200 AGeV ^{32}S interactions with emulsion for different ranges of N_h

Projectile energy	^{28}Si (3.7 AGeV)	^{32}S (3.7 AGeV)	^{32}S (200 AGeV)
Total no. of collisions	1986	762	775
The percentage of events with			
N_h (0, 1)	22.31 ± 1.17	20.73 ± 1.81	36.52 ± 2.54
N_h (2-7)	37.00 ± 1.60	38.98 ± 2.67	30.19 ± 2.25
$N_h \geq 8$	40.74 ± 1.70	41.21 ± 2.76	33.29 ± 2.39
N_h ($2 \leq N_h \leq 7$) / N ($N_h \geq 28$)	0.91 ± 0.07	0.95 ± 0.08	0.91 ± 0.12
The percentage of events with total destruction (TD) of the projectile nucleus having			
$N_h \geq 0$			
N_h (0, 1)	45.17± 1.82	42.78 ± 2.83	38.19 ± 2.61
N_h (2-7)	8.36 ± 1.00	3.99 ± 1.13	16.89 ± 2.58
$N_h \geq 8$	29.54 ± 2.07	27.30 ± 3.26	27.02 ± 3.40
N_h ($2 \leq N_h \leq 7$) / N ($N_h \geq 28$)	62.10 ±. 3.35	68.71 ± 5.96	56.08 ±. 5.44
	0.48 ± 0.05	0.40 ± 0.05	0.48 ± 0.09

Charge distribution of projectile fragments

Figure 2, shows the charge yield distribution, represented by the percentage of the projectile fragmentation cross section relative to the inelastic cross section σ_z / σ_{inel}, of $Z \geq 1$ emitted PF's for 3.7 AGeV ^{32}S projectile. The distribution has a characteristic shaped form, where it has a minimum at Z=4 followed by a broad maximum (i.e., the distribution is nearly saturated) in the region $7 \leq Z \leq 16$. More details for the projectile fragments charge distribution were discussed in our previous publication (El-Nadi *et al.*, 1995a).

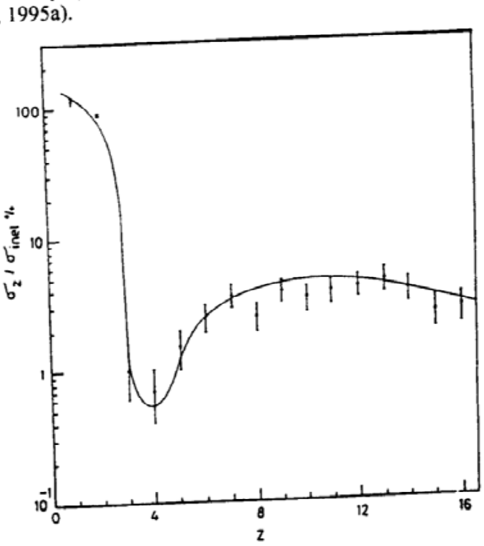

Fig. 2. The yield distribution of the emitted projectile fragments with charge $Z \geq 1$

The probability distribution of Z =2 PF's for the present data together with those for 200 AGeV ^{32}S-Em (Adamovich *et al.*, 1995) and for 3.7 AGeV ^{24}Mg - Em (El-Nadi *et al.* 1995b) are plotted in Fig. 3.

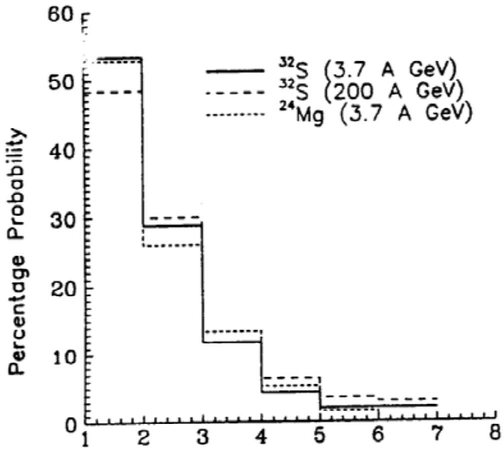

Fig. 3. The multiplicity distribution of He-fragments.

It is obvious that, as the number of the emitted doubly charged projectile fragments per event increases, the percentage probability decreases. It is seen, as has been previously noted (Kulberg *et al.*, 1977; Adamovich *et al.*, 1995 and El-Nadi *et al.*, 1995b) that this behavior does not depend either on the projectile mass number or projectile's energy.

Figure 4 shows the variation of $< N_\alpha >$ as a function of the projectile mass number A_{proj} . The following functional form was found to fit the data reported by Hussien (1994):

$$< N_\alpha > = a\, A^{b}_{proj} \quad (3)$$

where a = 0.534 ± 0.005 and b = 0.378 ± 0.003. These values are approximately equal to those given earlier (Singh, Ismail and Jain, 1991). The average He-PF's of the present data sample ($< N_\alpha > = 1.79 \pm 0.08$) verifies well (3).

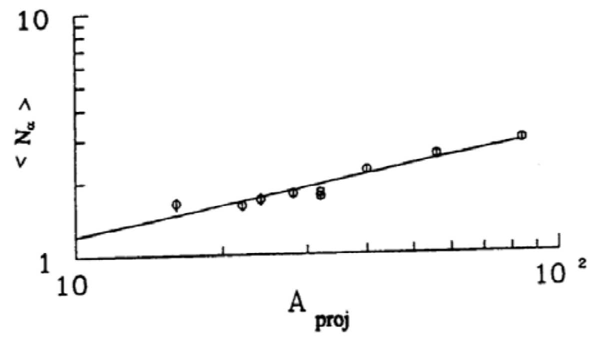

Fig. 4. A plot of average multiplicity $< N_\alpha >$ versus the mass number A_{proj} of the incident projectile.

Transverse momentum distribution

In Table 3 we present the experimentally obtained values of the average transverse momentum per nucleon, $< P_t >$. for projectile fragments having charge Z = 1,2 and ≥ 3 emitted in 3.7 AGeV ^{32}S-Em interactions. Also, in Table 3 are listed the values of $< P_t >$ of PF's in interactions at different impact parameters (all N_h, $N_h < 8$ and $N_h \geq 8$).

Table 3. Average transverse momentum and values of parameters of the doubly Rayleigh distribution in different ensembles of 3 7 AGeV ^{32}S- Em interactions

Ensemble	Experimental	Parameters of doubly Rayleigh distribution			
	$< P_t >$ MeV / c / n	$< P_t >_1$ MeV / c / n	$< P_t >_2$ MeV / c / n	(1-α) %	χ2 / DOF
Z=1 PF's ($N_h \geq 0$)	169 ± 7	119	225	41	1.06
Z=2 PF's ($N_h \geq 0$)	163 ± 8	130	250	31	0.21
Z=2 PF's ($N_h < 8$)	149 ± 9	113	310	29	1.93
Z=2 PF's ($N_h \geq 8$)	190 ± 17	155	250	40	0.21
Z≥ 3 PF's ($N_h \geq 0$)	138 ± 9	93	250	29	2.96
Z ≥ 1 PF's ($N_h \geq 0$)	161 ± 4	113	250	39	0.74
Z ≥ 1 PF's ($N_h < 8$)	185 ± 10	138	250	40	0.96
Z ≥ 1 PF's ($N_h \geq 8$)	152 ± 5	100	250	39	1.12

It can be seen from Table 3, that the experimental $< P_t >$ of PF's, measured in the laboratory system, decreases with increasing the charges of these PF's. Considering the alpha PF's, $< P_t >$ increases with the decrease of the impact parameter, i.e. going towards central collisions. This observation is not clear in the case of Z ≥ 1 PF's.

Following Abdurazakova *et al.* (1988), the P_t-distributions were approximated by a double Rayleigh distributions characterized by two different dispersions (temperatures). The double Rayleigh distribution has the form

$$dN/dP = \alpha \exp(-P_t^2 / 2\sigma_1^2) + (1-\alpha) \exp(-P_t^2 / 2\sigma_2^2) \qquad (4)$$

where $\sigma_{1,2} = \sqrt{2/\pi} < P_t >_{1,2}$.

In Table 3, we list for each distribution the corresponding parameters, the fraction (1-α) which represents the weight of the high temperature and the value of χ^2 / DOF.

The histogram, the solid curve and the dashed curves in the following Figs. 5-8 are the experimental data, the double Rayleigh distribution and the contributions of the two parts of the double Rayleigh, respectively.

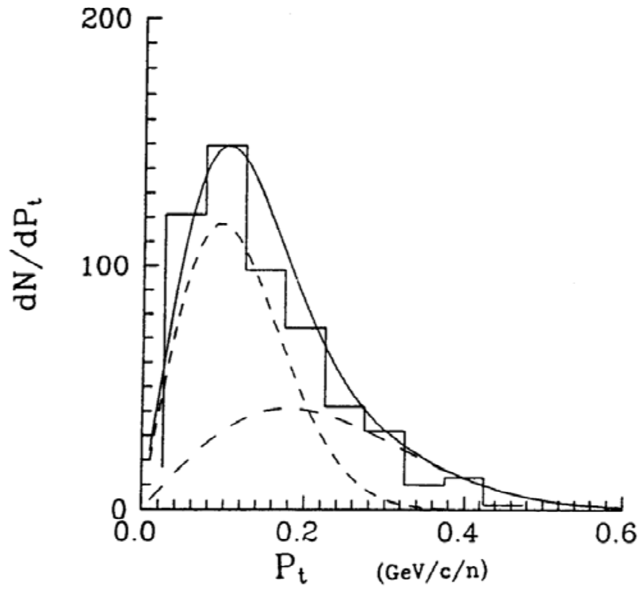

Fig. 5. The P_t -distribution of $Z = 1$ PF's in 3.7 AGeV ^{32}S-Em interactions having $N_h \geq 0$.

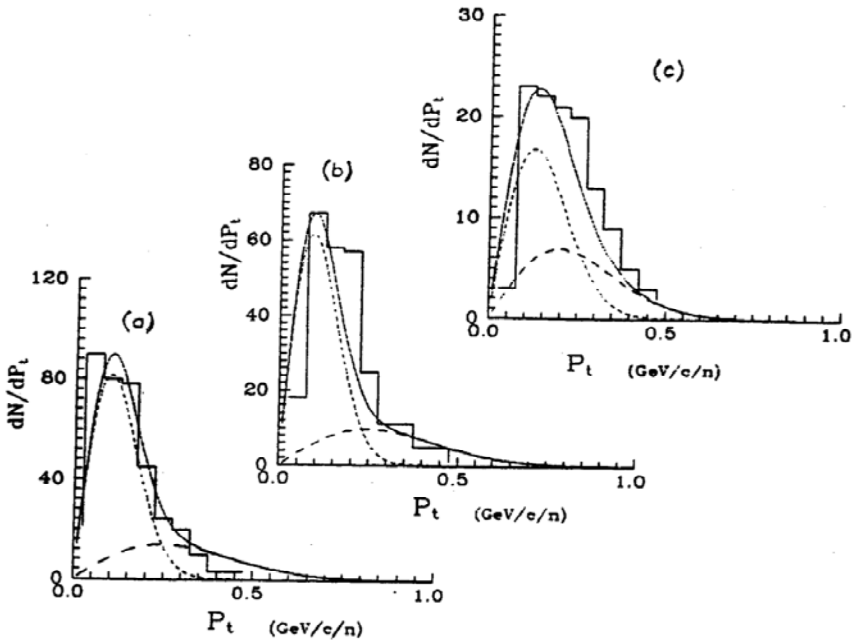

Fig. 6. The P_t -distributions of He - PF's in 3.7 AGeV ^{32}S-Em interactions having $N_h \geq 0$ (a), $N_h < 8$ (b) and $N_h \geq 8$ (c).

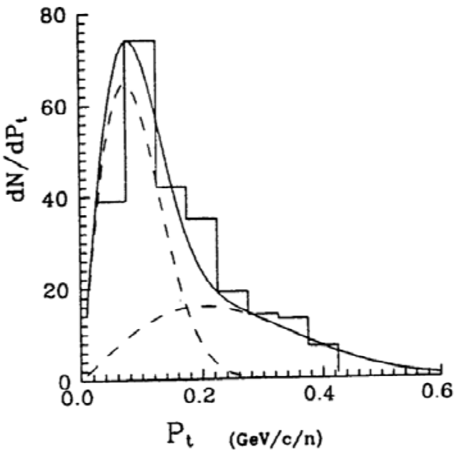

Fig. 7. The P_t -distribution of $Z \geq 3$ PF's in 3.7 AGeV ^{32}S-Em interactions having $N_h \geq 0$.

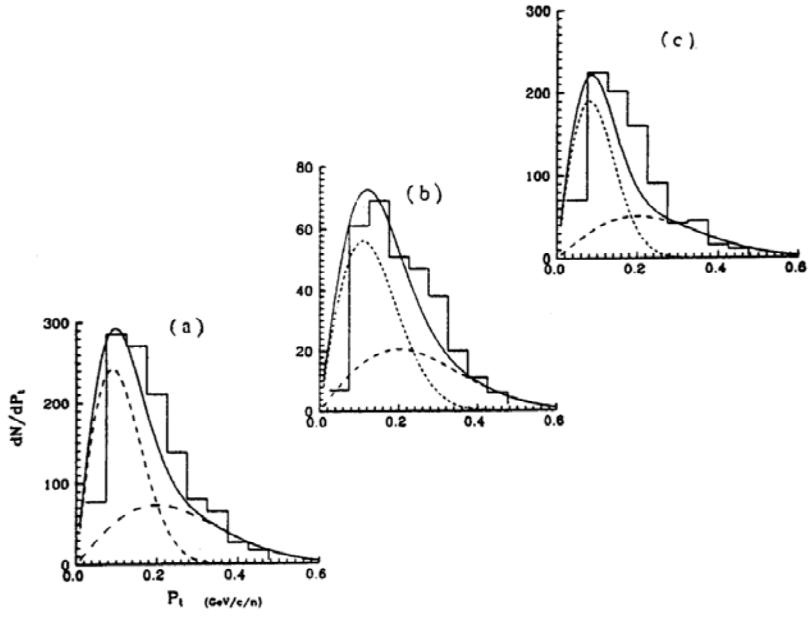

Fig. 8. The P_t -distribution of $Z \geq 1$ PF's in 3.7 AGeV ^{32}S-Em interactions having $N_h \geq 0$ (a),
$N_h < 8$ (b) and $N_h \geq 8$ (c).

From the above data in Figs. 5-8 and Table 3, it follows that:

1- Each experimental P_t-distribution can be fitted by a double Rayleigh distribution. The dispersions of the different distributions (consequently $< P_t >_1$ and $< P_t >_2$) seem to be independent of both the charge of the emitted PF's and the target size. The same conclusion was obtained before (Ganssauge *et al.,* 1985 and Abdurazakova *et al.,* 1988).

2-The contribution of the emitted He-PF's with high temperature increases with increasing target size, i.e. the emission of high temperature He-PF's is greater in violent interactions ($N_h \geq 8$) than in gentle ones ($N_h < 8$).

CONCLUSION

From the above data analysis, it can be concluded that:

1- Limiting fragmentation of the projectile into α-particles seems to be achieved at 3.7 AGeV.

2- The average multiplicity $<N\alpha>$ can be parametrized in terms of the projectile mass number A_{proj}.

3- The yield of the total projectile destruction of events (TD) is approximately the same at 3.7 AGeV and 200 AGeV.

4- The ratio for TD events between the number of collisions with $Z \leq N_h \leq 7$ and the number of collisions with $N_h \geq 8$ is reduced to about one half its corresponding value for the total sample interactions.

5- The P_t-distributions for events in different ensembles of different charges PF's can be fitted by double Rayleigh distributions having two different temperatures.

6- The dependence of $< P_t >_1$ and $< P_t >_2$ of all the double Rayleigh distributions on both the charge of the emitted PF's and the target size is not clear.

7- The number of emitted fragments with high temperature increases in violent interactions in comparison to the number of those emitted in gentle ones.

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