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2002 J. Phys. G: Nucl. Part. Phys. 28 1251

(http://iopscience.iop.org/0954-3899/28/6/308)

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS G: NUCLEAR AND PARTICLE PHYSICS

J. Phys. G: Nucl. Part. Phys. **28** (2002) 1251–1258 PII: S0954-3899(02)29485-2

Multiple fast helium fragments production from ^{28}Si–emulsion interaction at 14.6 A GeV

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Received 5 October 2001, in final form 20 February 2002
Published 18 April 2002
Online at stacks.iop.org/JPhysG/28/1251

Abstract

The measurements of partial production cross-sections of the multiple helium fragments emitted at 14.6 A GeV ^{28}Si–emulsion interactions are reported. The production rate of helium fragments due to fragmentation of ^{28}Si ions is studied and compared with that obtained from different projectiles at various energies. The dependence of $\langle N_\alpha \rangle$ on the mass number of the incident beams is formulated. The multiplicity distributions of the helium fragments produced in 14.6 A GeV and 3.7 A GeV ^{28}Si aswell as 200 A GeV ^{32}S exhibit KNO scaling. The characteristics of He-multiplicity events associated with and without projectile fragments of charge $Z \geqslant 3$ are investigated.

1. Introduction

Fragmentation in finite nuclei is a fascinating research subject which has attracted continued attention for more than twenty years [1–8] or so. Many experimental and phenomenological efforts have been devoted to the investigation of projectile fragmentation in relativistic heavy-ion collisions. Many different aspects of the fragmentation process have been investigated, for example the various stages of interactions [9, 10] from initial impact through to the final formation of clusters in the nuclear fragmentation of heavy nuclei.

In recent papers [11, 12] we have studied the nuclear fragmentations and multi-fragmentation of ^{28}Si (14.6 A GeV) and ^{32}S (3.7 A GeV) through which the charge and multiplicity distributions of projectile fragments (PFs) with charge $Z \geqslant 3$ were discussed and studied. Recently, data features of the central events [13] using the above-mentioned beams with heavy emulsion target were investigated. This paper is an extension of a previous investigation. The goal of this paper is to study the characteristics of inelastic events

[5] Deceased.

having one or multiple fast helium fragments produced in ^{28}Si nuclear interactions with photo-emulsion at 14.6 A GeV.

2. Experimental details

Photo-emulsion chambers consisting of 600 μm thick 16 × 10 cm^2 stack of FUJI emulsions were used. The stacks were irradiated by a beam of ^{28}Si ions at an energy of 14.6 A GeV at Brookhaven National Laboratory (BNL) alternating gradient synchrotron (AGS). Each of the emulsion pellicles was doubly scanned along the tracks, fast in the forward direction and slowly in the backward one. The scanning of the emulsion pellicles was carried out using a 850056 STEINDORFF microscope. It has a stage of 18 × 16 cm^2 with an opening of 7 × 2.5 cm^2; stage adjustment in the x-direction is possible over a total length of 7.8 cm with a reading accuracy of the order of 0.1 mm. An oil immersion objective lens with magnification 100× was used for scanning the emulsion plates. Each primary Si track was picked up at the penetrating edge of the pellicle and was carefully observed until the Si ion either interacted or escaped from the pellicle.

Out of 962 inelastic interactions we selected 439, each of which has at least one helium projectile fragment. For each interaction, the number of shower particles (n_s) corresponding to singly charged relativistic secondaries with velocity ($\beta \geqslant 0.7$) and ionization less than 1.4 times the plateau ionization for singly charged minimum ionizing particles) has been determined. These particles mainly consist of produced π-meson and singly charged fragments. The number of slow-moving ($\beta \leqslant 0.7$) heavily ionizing particles N_h is also determined. N_h are subdivided into (i) grey tracks N_g ($0.3 \leqslant \beta \leqslant 0.7$ and range in emulsion $R > 3$ mm) which consist of recoil protons with kinetic energy E_k from 40 to 400 MeV and (ii) low-energy fragments emitted from the excited target nucleus known as black tracks N_b. They are single- and multi-charged fragments with $E_k < 40$ A MeV, $\beta < 0.3$ and range $R < 3$ mm. The heavy track multiplicity $N_h = N_g + N_b$.

In nucleus–nucleus collisions, there is an additional group of particles. It consists of fragments from the incident nucleus, called PFs, with charge $Z = 1$, $Z = 2$ and $Z \geqslant 3$. The PFs having $Z \geqslant 2$ were identified by counting grain density and/or gap density, and by δ-ray counting for tracks having no change in ionization along a length of at least 1 cm from the interaction vertex, as discussed in [17]. Further details of the events classification can be found in [15]. A total of 762 He tracks were selected in 439 peripheral inelastic events. The polar angles of the PFs with $Z \geqslant 2$ are $\leqslant$13 mrad from the incident beam.

3. Partial production cross-section

Table 1 shows the partial cross-sections for central (σ_c), peripheral (σ_p) and multiple helium ($\sigma_{n\alpha}$) events. For comparison, the corresponding values for 3.7 A GeV ^{28}Si [16], 200 A GeV ^{32}S [17] aswell as those for a similar experiment [17] (parentheses) are given in this table. In other words, the results of the production cross-sections for Si-induced reactions measured at Dubna and Brookhaven (AGS) are compared with those produced in ^{32}S-induced reactions at CERNS SPS energy. The values of σ_{He} can be given using the relation

$$\sigma_{He} = \sigma_r \frac{\text{No of events having number of He} - \text{PFs}}{\text{Total no of interactions}}$$

where σ_r is the total experimental reaction cross-section of the present beam which is found to be 1002 ± 40 mb.

Table 1. The reaction cross-sections for central, peripheral and for different multiplicities of α-particles are given. The values in parentheses are the corresponding values taken from [17].

Cross-section (mb)	^{28}Si at 14.6 A GeV	^{28}Si at 3.7 A GeV [9]	^{32}S at 200 A GeV [17]
σ_c	183 ± 16 (209 ± 15)	215 ± 12	233 ± 15
σ_p	819 ± 34 (814 ± 30)	1000 ± 25	917 ± 30
$\sigma_{0\alpha}$	214 ± 17 (227 ± 16)	320 ± 14	281 ± 17
$\sigma_{N\alpha}$	605 ± 29 (587 ± 26)	680 ± 20	636 ± 25
$\sigma_{1\alpha}$	325 ± 21 (300 ± 18)	341 ± 15	345 ± 19
$\sigma_{2\alpha}$	171 ± 16 (171 ± 14)	199 ± 11	171 ± 17
$\sigma_{3\alpha}$	70 ± 10 (69 ± 9)	98 ± 8	81 ± 9
$\sigma_{4\alpha}$	21 ± 5 (44 ± 7)	30 ± 4	28 ± 5
$\sigma_{5\alpha}$	14 ± 5 (3 ± 2)	9 ± 2	8 ± 3
$\sigma_{6\alpha}$	1 ± 1 (1 ± 1)	4 ± 2	4 ± 2

It is noted that the partial production cross-sections for all reaction channels of ^{28}Si at 3.7 and 14.6 A GeV and ^{32}S at 200 A GeV are close to each other. Also, the production cross-sections for α channels, which are approximately the same within experimental errors, confirm the fact that the interaction cross-section does not depend on the projectile incident energy in the nucleus–nucleus interaction. This conclusion confirms the limiting fragmentation hypothesis.

Table 2 gives the percentage of α-particles multiplicity production for α-particles emitted as a PF for ^{12}C, ^{16}O, ^{22}Ne, ^{24}Mg, ^{28}Si and ^{32}S at various energies. It should be noted that the percentage of α multiplicities seems to be constant and independent of the incident beam and energy. The percentage producing 1α is about two times that of 2α and three times that of 3α. For heavier beams the production of 4αs, 5αs and 6αs constitutes about 6–9% of the total number of events having α-fragments.

4. Scaling of the multiplicity distributions of helium fragments

It is reported in recent papers [17, 20] that the validity of the Koba, Nielsen and Olesen (KNO) [18] scaling holds for the projectile helium fragments produced in heavy-ion interactions at Dubna, Bevatron, CERN and AGS energies. Here, we discuss the multiplicity distribution of the helium fragments produced in the ^{28}Si-induced reaction at 14.6 A GeV. According to KNO, the multiplicity distribution $P(N)$ in high-energy collisions obeys the scaling law

$$\psi(Z) = \langle N_\alpha \rangle P(N_\alpha) = \langle N_\alpha \rangle \sigma_{N\alpha}/\sigma_{\text{inel}}. \quad (1)$$

The quantity $\psi(z)$ should be an energy-independent function of the scaled variable $Z = N_\alpha/\langle N_\alpha \rangle$, where N_α represents the number of α-particles produced in an event and

Table 2. The percentage of He-multiplicity for different projectiles at various energies is represented.

	^{12}C	^{16}O				^{22}Ne	^{24}Mg	^{28}Si		^{32}S
Energy (A GeV)	3.7	3.7	14.6	60	200	3.7	3.7	3.7	14.6	200
Percentage										
1α	61.1[d]	51.0[f]	48.7[b]	48.7[b]	48.6[b]	60.0[d]	52.8[e]	50.0[a] 47.5[d]	53.6 52.6[a] 51.0[c]	50.3[a] 54.5[c]
2α	28.9[d]	29.8[f]	33.8[b]	31.2[b]	34.6[b]	24.3[d]	26.1[e]	29.3[a] 30.6[d]	28.2 27.0[a] 29.1[c]	29.2[a] 26.7[c]
3α	10.1[d]	17.9[f]	16.9	18.1[b]	16.0[b]	11.6[d]	13.4[e]	14.4[a] 14.1[d]	11.6 12.9[a] 11.6[c]	11.4[a] 12.6[c]
4α	–	1.4[f]	0.5[b]	1.5[b]	0.9[b]	3.5[d]	7.0[e]	4.1[a] –	3.9 4.3[a] 7.4[c]	6.1[a] 4.3[c]
4, 5, 6αs	–	–	–	–	–	3.7[d]	7.7[e]	6.2[a] 7.8[d]	6.4 7.4[a] 8.2[c]	9.2[a] 6.1[c]

[a] [9], [b] [16], [c] [17], [d] [20], [e] [21], [f] [22].

$\langle N_\alpha \rangle$ is the average He-multiplicity of the whole data sample. σ_{inel} refers to the total inelastic cross-section and $\sigma_{N\alpha}$ is the partial cross-section for the reaction channel with multiplicity N_α.

The multiplicity of the produced helium fragments from the events of different projectiles over a wide range of energies can be represented by a universal function of the following form:

$$\psi(Z) = AZ\exp(-BZ) \tag{2}$$

where A and B are constants.

In figure 1 we plot $\langle N_\alpha \rangle P(N_\alpha)$ as a function of the scaled $N_\alpha / \langle N_\alpha \rangle$ for helium fragments produced in ^{28}Si interactions at 14.6 A GeV compared with those for ^{28}Si at 3.7 A GeV and ^{32}S at 200 A GeV. It is noteworthy that for energies 3.7–200 A GeV all the data points for ^{28}Si and ^{32}S lie on a simple universal curve represented by equation (2) suggesting a scaling behaviour for the multiplicity distributions of the helium fragments. This experiment provides the values of the constants of equation (2) which are determined through the fit to be $A = 5.6 \pm 0.9$ and $B = 2.2 \pm 0.4$.

Another consequence of the multiplicity scaling implies the energy independence of the moments given by

$$C_q = \left\langle N_\alpha^q \right\rangle / \langle N_\alpha \rangle^q$$

for $q = 2$, 3, 4 and 5 of the helium fragments produced in the interactions of C, Ne, O, Mg, Si and S ions in emulsion at various incident energies. Table 3 shows the moments C_2–C_5 for these beams. It includes the second Muller moment [19]

$$F_2 = (C_2 - 1)\langle N_\alpha \rangle^2 - \langle N_\alpha \rangle$$

which is given in table 3 for all given projectiles at different energies. It is obvious from this table that the values of C_2 and C_3 moments do not seem to depend upon the energy or mass number (A) within the experimental errors. On the other hand, the values of higher

Table 3. The mean value of α-particle production, C_q moments, the ratio $\langle N_\alpha \rangle / D$ and the second Muller moment F_2 for different beams and various energies. See text for definitions and details.

	^{12}C	^{16}O			^{22}Ne	^{24}Mg	^{28}Si		^{32}S
Energy (A GeV)	3.7	14.6	60	200	3.7	3.7	3.7	14.6	200
$\langle N_\alpha \rangle$	$1.5 \pm 0.1^{\rm d}$	$1.7 \pm 0.1^{\rm b}$	$1.7 \pm 0.1^{\rm b}$ $1.6 \pm 0.1^{\rm c}$	$1.7 \pm 0.1^{\rm b}$ $1.6 \pm 0.2^{\rm c}$	$1.6 \pm 0.1^{\rm d}$	$1.8 \pm 0.1^{\rm e}$	$1.8 \pm 0.1^{\rm a}$ $1.9 \pm 0.1^{\rm d}$	1.7 ± 0.1 $1.8 \pm 0.1^{\rm a}$ $1.9 \pm 0.1^{\rm c}$	$1.8 \pm 0.1^{\rm a}$ $1.7 \pm 0.1^{\rm c}$
C_2	$1.2 \pm 0.1^{\rm d}$	$1.2 \pm 0.1^{\rm b}$	$1.2 \pm 0.1^{\rm b}$ $1.2 \pm 0.1^{\rm c}$	$1.2 \pm 0.1^{\rm b}$ $1.2 \pm .1^{\rm c}$	$1.3 \pm 0.1^{\rm d}$	$1.3 \pm 0.1^{\rm e}$	$1.3 \pm 0.1^{\rm a}$ $1.3 \pm 0.1^{\rm d}$	1.3 ± 0.1 $1.3 \pm 0.1^{\rm a}$ $1.3 \pm 0.1^{\rm c}$	$1.3 \pm 0.1^{\rm a}$ $1.3 \pm 0.1^{\rm c}$
C_3	$1.7 \pm 0.2^{\rm d}$	$1.7 \pm 0.1^{\rm b}$	$1.7 \pm 0.1^{\rm b}$ $1.8 \pm 0.1^{\rm c}$	$1.7 \pm 0.1^{\rm b}$ $1.7 \pm 0.1^{\rm c}$	$2.1 \pm 0.1^{\rm d}$	$2.1 \pm 0.1^{\rm e}$	$2.1 \pm 0.1^{\rm a}$ $2.2 \pm 0.1^{\rm d}$	2.3 ± 0.1 $2.1 \pm 0.1^{\rm a}$ $2.3 \pm 0.1^{\rm c}$	2.4 ± 0.1 $2.3 \pm 0.1^{\rm c}$
C_4	$2.7 \pm 0.2^{\rm d}$	$2.6 \pm 0.2^{\rm b}$	$2.8 \pm 0.1^{\rm b}$ $2.9 \pm 0.2^{\rm c}$	$2.6 \pm 0.1^{\rm b}$ $2.8 \pm 0.5^{\rm c}$	$4.0 \pm 0.1^{\rm d}$	$3.9 \pm 0.2^{\rm e}$	$4.2 \pm 0.1^{\rm a}$ $4.4 \pm 0.2^{\rm d}$	4.6 ± 0.2 $4.7 \pm 0.2^{\rm a}$ $4.0 \pm 0.2^{\rm c}$	$5.0 \pm 0.3^{\rm a}$ $4.7 \pm 0.2^{\rm c}$
C_5	$4.7 \pm 0.4^{\rm d}$	$4.3 \pm 0.1^{\rm b}$	$4.7 \pm 0.2^{\rm b}$ $4.9 \pm 0.3^{\rm c}$	$4.3 \pm 0.2^{\rm b}$ $4.6 \pm 0.4^{\rm c}$	$8.5 \pm 0.2^{\rm d}$	$7.9 \pm 0.5^{\rm e}$	$9.3 \pm 0.3^{\rm a}$ $8.9 \pm 0.3^{\rm d}$	10.6 ± 0.5 $10.6 \pm 0.5^{\rm a}$ $8.2 \pm 0.4^{\rm c}$	$11.9 \pm 0.6^{\rm a}$ $11.0 \pm 0.4^{\rm c}$
D	$0.7 \pm 0.1^{\rm d}$	$0.8 \pm 0.1^{\rm b}$	$0.8 \pm 0.1^{\rm b}$ $0.9 \pm 0.1^{\rm c}$	$0.8 \pm 0.1^{\rm b}$ $0.9 \pm .1^{\rm c}$	$0.9 \pm 0.1^{\rm d}$	$1.1 \pm 0.1^{\rm e}$	$1.0 \pm 0.1^{\rm a}$ $1.0 \pm 0.1^{\rm d}$	1.0 ± 0.1 $1.0 \pm 0.1^{\rm a}$ $1.0 \pm 0.1^{\rm c}$	$1.1 \pm 0.1^{\rm a}$ $1.0 \pm 0.1^{\rm c}$
$\langle N_\alpha \rangle / D$	$2.2 \pm 0.2^{\rm d}$	$2.2 \pm 0.2^{\rm b}$	$2.1 \pm 0.2^{\rm b}$ $1.8 \pm 0.1^{\rm c}$	$2.2 \pm 0.1^{\rm b}$ $1.8 \pm 0.2^{\rm c}$	$1.9 \pm 0.1^{\rm d}$	$1.7 \pm 0.2^{\rm e}$	$1.8 \pm 0.1^{\rm a}$ $1.8 \pm 0.1^{\rm d}$	1.8 ± 0.1 $1.7 \pm 0.1^{\rm a}$ $1.8 \pm 0.1^{\rm c}$	$1.7 \pm 0.1^{\rm a}$ $1.8 \pm 0.1^{\rm c}$
F_2	$1.0 \pm 0.1^{\rm d}$	$1.1 \pm 0.1^{\rm b}$	$1.1 \pm 0.1^{\rm b}$ $1.0 \pm 0.1^{\rm c}$	$1.1 \pm 0.1^{\rm b}$ $1.0 \pm 0.1^{\rm c}$	$0.9 \pm 0.1^{\rm d}$	$0.8 \pm 0.1^{\rm e}$	$0.8 \pm 0.1^{\rm a}$ $0.8 \pm 0.1^{\rm d}$	0.8 ± 0.1 $0.8 \pm 0.1^{\rm a}$ $0.8 \pm 0.1^{\rm c}$	$0.7 \pm 0.1^{\rm a}$ $0.7 \pm 0.1^{\rm c}$

[a] [9], [b] [16], [c] [17], [d] [20], [e] [21].

moments (C_3, C_4, C_5) show a slow increase with increase of mass number. The second Muller moments are nonzero. This shows a strong correlation among the produced helium fragments. An interesting observation of this experiment is the dependence of the mean values of α-particle production on the projectile mass number A_p. This dependence can be represented by the power law of the following:

$$\langle N_\alpha \rangle = a {A_p}^b \tag{3}$$

where a and b are constants fitted to be equal to $a = 1.1078 \pm 0.36942$ and $b = 0.14566 \pm 0.11629$ with correlation coefficient $R = 0.586$ and standard deviation SD $= 0.06129$. These values are approximately close to those given in [20]. The mean per dispersion ratio $\langle N_\alpha \rangle / D$ $\left(D = \left\langle N^2{}_\alpha \right\rangle - \langle N_\alpha \rangle^2\right)$ yields a practically constant value close to 2 in keeping with asymptotic multiplicity scaling. This value is approximately equal to that observed in hadron–nucleus interaction [17]. These exhibit an almost identical behaviour, which leads to an energy and mass number independent effect mechanism on the break up of nuclei through α-particle.

5. Characteristics of events having helium fragments

Table 4 presents the salient features of the primary peripheral events of ^{28}Si nuclei yielding different He-multiplicities. The characteristics of different charged secondaries obtained from

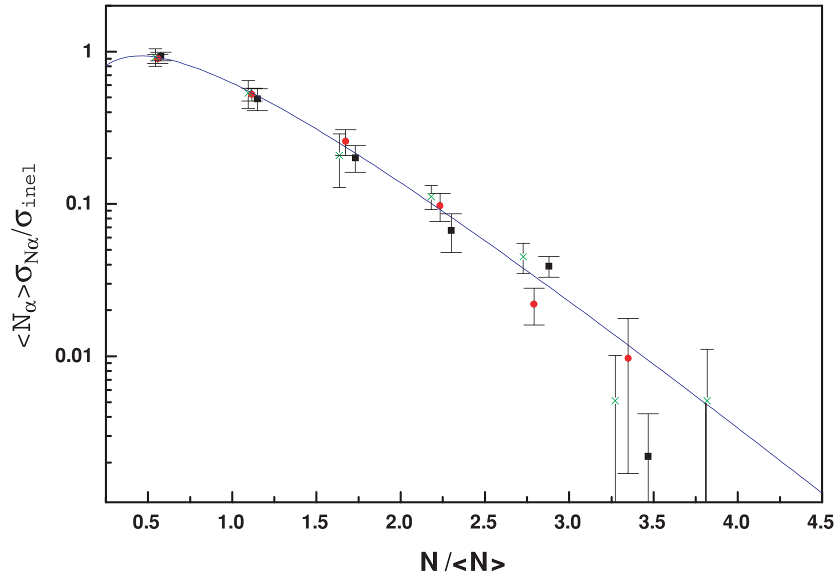

Figure 1. The scaling distribution of helium projectile fragments $\langle N_\alpha\rangle\, \sigma_{N\alpha}/\sigma_{\rm inel}$ as a function of the scaled variable $N_\alpha/\langle N_\alpha\rangle$ for ^{28}Si at 14.6 (●) and 3.7 (■) A GeV and ^{32}S (×) at 200 A GeV. The solid curve represents the theoretical fitting of the experimental points by a function given in equation (2).

Table 4. The mean values of secondary charged particles as a function of He-multiplicity associated with, without and all projectile fragments. The values in parentheses are the corresponding allowed values in [17].

Events		1α	2α	3α	4α	All α's
Without	$\langle n_s\rangle$	36.4 ± 0.3	22.3 ± 2.6	18.0 ± 2.9	8.6 ± 1.9	26.8 ± 1.7
projectile	$\langle N_g\rangle$	3.8 ± 0.4	2.4 ± 0.3	2.2 ± 0.3	1.0 ± 0.3	2.8 ± 2.8
fragment	$\langle N_b\rangle$	7.2 ± 0.7	5.4 ± 0.9	5.1 ± 0.9	3.2 ± 0.8	5.9 ± 0.4
having $Z \geqslant 3$						
With	$\langle n_s\rangle$	11.5 ± 1.1	10.4 ± 1.6	7.8 ± 2.6	10.5 ± 5.5	11.0 ± 0.9
projectile	$\langle N_g\rangle$	1.0 ± 0.1	1.4 ± 0.3	1.2 ± 0.5	0.8 ± 0.6	1.1 ± 0.1
fragments	$\langle N\rangle$	3.2 ± 0.3	4.1 ± 0.7	2.3 ± 0.9	1.8 ± 1.1	3.4 ± 0.3
having $Z \geqslant 3$						
With all	$\langle n_s\rangle$	23.8 ± 1.6	17.6 ± 1.6	16.0 ± 2.3	8.9 ± 1.8	20.2 ± 1.0
projectile		(22.7 ± 1.4)	20.3 ± 1.6)	(17.1 ± 2.2)	(13.8 ± 2.2)	(20.6 ± 0.9)
fragments	$\langle N_g\rangle$	2.4 ± 0.2	2.0 ± 0.2	2.0 ± 0.3	1.0 ± 0.3	2.1 ± 0.1
	$\langle N_b\rangle$	5.2 ± 0.4	4.9 ± 0.5	4.6 ± 0.7	3.0 ± 0.7	4.9 ± 0.3
	$\langle N_h\rangle$	7.6 ± 0.5	6.9 ± 0.7	6.6 ± 1.0	4.0 ± 0.8	7.0 ± 0.4
		(8.0 ± 0.5)	(7.2 ± 0.6)	(7.9 ± 1.0)	(3.8 ± 1.1)	(7.4 ± 0.3)

439 events are shown in table 4. There are two types of events characterizing the emission of the helium fragments. In the first type the multiplicities of events having helium fragments with no associated heavy PFs of charge $Z > 2$ is given. In the second type the multiplicities of events associated with heavy PFs of $Z > 2$ is given. The last rows in table 4 represent the complete set of events including the first and second types of events.

One can observe from this table that $\langle n_s \rangle$ for events associated with He-multiplicities produced without fragments having $Z \geqslant 3$ increases rapidly as the He-multiplicity decreases; on the other hand $\langle n_s \rangle$ decreases as the events become more peripheral. Also, for these events $\langle N_g \rangle$, $\langle N_b \rangle$ and $\langle N_h \rangle$ decrease as the He-multiplicity increases but with a small rate. On the other hand, $\langle n_s \rangle$ for events associated with He-multiplicities produced with heavy fragments having $Z \geqslant 3$ seems to be constant as He-multiplicity increases, and exhibits independent behaviour of the He-multiplicity. This reflects that the energy transferred from projectile to target nucleus is nearly constant for all these events. This is also confirmed by observing $\langle N_g \rangle$ for these events, which seems to be constants through the He-multiplicities; this can also be concluded from the invariance of $\langle N_g \rangle$, knowing that N_g is believed to be composed mainly of recoil target protons as well as protons originating from low-energy nucleonic cascades initiated by recoil protons. Also, $\langle N_b \rangle$, which is related to evaporated slow particles from target, increases slowly with decreasing He-multiplicity. This may reflect the unsaturation of evaporated targets in this type of events. The values in parentheses shown in table 4 are obtained from a similar experiment [17]. These values agree with the observations of this experiment.

6. Conclusions

From this investigation we conclude the following:

1. The partial production cross-sections for α-particles emitted with different channels are independent of the projectile energy in the energy range 3.7–200 A GeV for the projectiles having almost the same mass.
2. The multiplicity distribution of the helium fragments produced in the ^{28}Si-induced emulsion reactions in the range of incident energy from 3.7 to 200 A GeV exhibits a KNO scaling. The second and third moments are found to be independent of the masses and energies of the incident beams. The dependence of $\langle N_\alpha \rangle$ on the mass number of the incident beam is fitted by $\langle N_\alpha \rangle = a\, A_p^b$.
3. The average values of the emitted particles $\langle n_s \rangle$, $\langle N_g \rangle$, $\langle N_b \rangle$ and $\langle N_h \rangle$ characterize the primary inelastic events, which are determined as a function of the He-multiplicity associated with and without the heavy PFs of charge $Z > 2$. These are discussed in the text.

Acknowledgment

We are thankful to Professor P L Jain, State University of New York at Buffalo, for supplying the irradiated emulsions.

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