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Fragmentation in ^{16}O-emulsion interactions at 3.7 A GeV*

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The topology of ^{16}O fragmentation at 3.7 A GeV in reactions with emulsion nuclei is presented. The multiplicity distributions of projectile fragments, charged secondaries and their dependences on the projectile residues are discussed.

Keywords:relativistic heavy-ion collision, projectile fragmentation, nuclear emulsion
PACC: 2570N, 2587, 2940R

1. Introduction

In high energy nucleus–nucleus collisions the overlapping region of nuclear volumes is called the participant region where multiple production of new particles occurs and the nuclear matter breaks up into small pieces. The remaining parts of nuclei which do not participate in the disintegration process are called the spectator regions of the projectile and the target. In general, the constituents of spectator part of the projectile as well as those of the spectator part of the target can be well separated at energies like ours. Projectile fragments (PFs) have rapidity close to the beam rapidity and are concentrated in a narrow angular cone in the forward direction. However, the angular distribution of target fragments (TFs) is almost isotropic. The process where a part of the nucleus is suddenly liberated is called fragmentation[1] and if the second nucleus acts only as energy injector one refers to it as limiting fragmentation.[2]

Fragmentation of the nucleus is one of the fundamental questions in high energy nuclear physics.[2−4] A better understanding of the fragmentation mechanism is necessary for solving some problems in astrophysics and radiation physics.[5−8] The fragmentation process plays an important role in determining the composition of cosmic rays in proximity to the earth.

The first experimental information about fragmentation of nuclei was in fact obtained in experiments with cosmic-ray particles.[9] Acceleration of heavy ions up to relativistic energies at Berkeley and Dubna gave an opportunity for making more detailed studies of this phenomenon.[2,5,10−16] In the last 20 years, with the availability of mono-energetic beams of relativistic heavy ions at the Brookhaven National Laboratory (BNL) Alternating Gradient Synchroton (AGS), and CERN Super Proton Synchrotron (SPS) the fragmentation and multifragmentation of projectile spectator have been studied extensively not only in experiment[17−22] but also in theory such as the bond-percolation prescription.[23,24]

In this paper we discuss the topology for ^{16}O fragmentation at 3.7 A GeV and compare with the result at 60 A GeV.[20]

2. Experimental details

NIKFI BR-2 stacks of nuclear emulsions, 10cm× 10cm×2cm in volume, were exposed horizontally to the 3.7 A GeV ^{16}O beam at Synchrophasotron of the JINR, Dubna. The flux intensity was 10^3 particles/cm^2. Emulsion plates, 600μm in thickness, were scanned by the along-the-track method using XSJ-1 and XSJ-2 microscopes under 100× oil objectives and 16× eyepieces. Details about scanning, measurements and track classification have been given elsewhere.[25−27] A total of 2960 interactions of oxygen with the nuclei of the emulsion were observed by following a primary track length of 35768.9cm, which led to a mean free path $\lambda = (12.08 \pm 0.22)$cm. Among these interactions, 152 events were found to be pro-

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duced by electromagnetic interactions and 149 events were due to elastic interactions. Of these 2960 interactions, 2196 interactions(2044 for inelastic events, 152 for electromagnetic dissociation(ED) of projectile) were picked up, without any bias, for the final analysis. Interactions which were within 30μm from the top or bottom surface of the emulsion were not taken into consideration for the final analysis. For each detected interaction, the following features were recorded: $N_{\rm s}$, the number of minimum ionizing shower tracks with kinetic energies $E > 400$ MeV and a very high speed $\beta = v/c \geq 0.7$(most $N_{\rm s}$ tracks are for π-mesons); $N_{\rm g}$, the number of grey tracks (recoil protons with $40 < E < 400$ MeV, $0.3 < \beta < 0.7$ and range $R > 3$mm) and $N_{\rm b}$, the number of black tracks due to evaporated target fragments with $E < 40$ A MeV, $\beta \leq 0.3$, $R \leq 3$mm. $N_{\rm g} + N_{\rm b}$ is the sum of highly ionized charged particles, denoted by $N_{\rm h}$.

The nuclear emulsion used here contains hydrogen (10.58%), carbon (15.95%), nitrogen (4.72%), oxygen (12.22%), sulfur (0.16%), bromine (26.03%), silver (29.98%) and iodine (0.35%). The percentage given for each element is the percentage of ^{16}O induced reaction. The number $N_{\rm h}$ emitted in an interaction is an important parameter and greatly helps in separating events due to target types, i.e. all events due to H interactions have $N_{\rm h} = 0, 1$. The interactions having $N_{\rm h} \geq 8$ almost definitely belong to AgBr collisions, while events with $2 \leq N_{\rm h} \leq 7$ are due to interactions with CNO and peripheral AgBr. It was found that the events due to H, CNO and AgBr were estimated at 345(16.9%), 776(38.0%) and 923(45.5%), respectively.

At high incident energies nearly all PFs with charges $Z \geq 2$ have small emission angles and can be well separated from the produced particles and TFs. All PFs with charges $Z \geq 2$ are emitted within the fragmentation core defined by a critical angle $\theta_{\rm c}$=45mrad at 3.7 A GeV. These values correspond to a spectator proton with a transverse momentum of 200MeV/c.

In each event, the charges $Z \geq 2$ of individual PFs were determined by the combination of several methods that include grain, δ-ray densities. More details of the charge determination of PFs are given in Ref.[20]. PFs essentially travel with the same speed as that of the parent beam nucleus, so the energy of the produced PFs is high enough to distinguish them easily from the target fragments.

3. Experimental results

In table 1 we present the topology for all nuclear events of the minimum biased sample obtained from this work in comparison with the corresponding ones for 60 A GeV.[20] The topology seen in table 1 represents all minimum biased events in which each channel includes the participants and spectators of the ^{16}O beam.The participant part is represented by some or all H-fragments, so that the total charge in each channel should be 8.

Table 1. Topology of the ^{16}O fragmentation at 3.7 A GeV and 60 A GeV (minimum bias).

channel	3.7 A GeV				60 A GeV[20]			
	$N_{\rm h} = 0, 1$	$2 \leq N_{\rm h} \leq 7$	$N_{\rm h} \geq 8$	$N_{\rm h} \geq 0$	$N_{\rm h} = 0, 1$	$2 \leq N_{\rm h} \leq 7$	$N_{\rm h} \geq 8$	$N_{\rm h} \geq 0$
O	0	16	4	20	0	34	6	40
N+p	26	55	24	105	19	18	0	37
C+He	22	11	2	35	15	7	1	23
C+2H	36	63	19	118	84	73	30	187
B+Li	1	0	0	1	0	0	0	0
B+He+H	13	16	2	31	2	2	0	4
B+3H	22	35	16	73	15	11	4	30
Be+Be	1	1	1	3	0	0	0	0
Be+2He	5	1	1	7	1	1	1	3
Be+He+2H	14	17	6	37	16	19	5	40
Be+4H	14	28	18	60	14	26	13	53
Li+Li+He	1	0	0	1	0	0	0	0
Li+Li+2H	0	1	1	2	0	0	0	0
Li+2He+H	4	4	0	8	1	8	0	9
Li+He+3H	12	18	15	45	19	9	5	33
Li+5H	7	15	17	39	10	21	13	44
4He	8	5	1	14	4	2	0	6
3He+2H	50	68	22	140	44	47	12	103
2He+4H	61	121	82	264	75	103	64	242
He+6H	28	142	186	356	64	140	118	322
8H	20	159	506	685	30	114	385	529
All	345	776	923	2044	413	635	657	1705

Table 2 gives the event statistics for the samples obtained from this work and the corresponding ones at 60 A GeV.[20] For the comparison the results from ^{28}Si- and ^{32}S-Em interactions[17] are also included. This table also shows the number of events with total projectile destruction (TD). TD events are defined as those events where only PFs with charges $Z \leq 2$ remain. The ratio between the number of collisions having $2 \leq N_{\rm h} \leq 7$ (CNO and peripheral AgBr) and number of collisions having $N_{\rm h} \geq 8$(only AgBr) seems independent of the beam energy and projectile type(for ^{16}O and nearly same projectile ^{28}Si and ^{32}S).

Table 2. The statistics of events for 3.7 A GeV and 60 A GeV ^{16}O interactions with emulsions for different $N_{\rm h}$ groups.

	3.7 A GeV ^{16}O	60 A GeV ^{16}O[20]	3.7 A GeV ^{28}Si[17]	14.6 A GeV ^{28}Si[17]	200 A GeV ^{32}S[17]
Total number of collisions	2044	1705	1986	995	775
$N_{\rm h} = 0, 1$	345	413	443	265	283
$2 \leq N_{\rm h} \leq 7$	776	635	734	328	234
$N_{\rm h} \geq 8$	923	657	809	362	258
$N(2 \leq N_{\rm h} \leq 7)/N(N_{\rm h} \geq 8)$	0.84 ± 0.06	0.97 ± 0.08	0.91 ± 0.07	0.91 ± 0.08	0.91 ± 0.12
TD events	1459(1041)	1202(851)	897	430	296
$N_{\rm h} = 0, 1$	167(48)	217(94)	75	58	50
$2 \leq N_{\rm h} \leq 7$	495(301)	406(254)	265	135	80
$N_{\rm h} \geq 8$	797(692)	579(503)	557	237	166
$N(2 \leq N_{\rm h} \leq 7)/N(N_{\rm h} \geq 8)$	0.62 ± 0.05	0.70 ± 0.06	0.48 ± 0.05	0.49 ± 0.07	0.48 ± 0.09

It has been shown in Ref.[28] that the cross-section of TD events should follow a geometrical formula like the one suggested by Bradt and Peter[29] for relativistic (inelastic) nucleus–nucleus interactions:

$$\sigma_{\rm TD} = (1.58A_1^{0.026})^2(A_1^{1/3} + A_2^{1/3} - 0.85A_1^{0.38})^2 {\rm fm}^2, \quad (1)$$

where A_1 and A_2 denote the mass numbers of the projectile and target, respectively. Table 3 gives a comparison between the experimental and calculated values. The cross-section of inelastic relativistic nucleus–nucleus interactions was calculated according to geometrical formula suggested by Westfall *et al.*[30] Events with $N_{\rm h} = 0, 1$ are predominantly "quasi-nucleon" interactions, i.e. interactions with an H nucleus or with only one bound nucleon in CNO or AgBr nuclei. The $N_{\rm h} = 2 - 7$ groups are dominated by CNO collisions and peripheral AgBr collisions whereas the $N_{\rm h} \geq 8$ groups consist of AgBr interactions with a substantial degree of disintegration. This table shows that according to the criteria of selecting TD suggested by Admovich *et al*[17] the calculated TD fraction of TD events gives a underestimation of experimental values especially for the $N_{\rm h} = 0, 1$ groups. The reason may be that the criteria of selecting TD suggested by Ref.[17] can not well apply to a lighter projectile nucleus like oxygen nucleus. Using the new definition discussed in our previous paper[20] that the TD of an oxygen nucleus is the event where only one He projectile fragment or proton remains, the TD event statistics in Table 2 is indicated in parentheses. The ratios between the number of collisions having $2 \leq N_{\rm h} \leq 7$ and the number of collisions having $N_{\rm h} \geq 8$ for TD events are 0.43 ± 0.04 and 0.50 ± 0.05 for 3.7 A GeV and 60 A GeV ^{16}O-Em interactions, respectively. Within experimental errors, this ratio is independent of the beam energy and the projectile for TD events at such high incident energies. According to our new TD criteria, the fractions of TD events in minimum biased nuclear collisions with various degrees of target break-up are given in the parentheses in Table 3, which are better than those based on the criteria suggested by Admovich *et al.*[17]

Table 3. Fractions of TD events in minimum bias collisions with different degrees of target breakup. The calculations are based on Eq.(1).

N_h range	Experimental Results		Calculated Results
	3.7 A GeV	60 A GeV[20]	
$N_h = 0, 1$	$49 \pm 6(21 \pm 2)$	$48 \pm 6(14 \pm 3)$	13
$N_h = 2 - 7$	$64 \pm 6(40 \pm 3)$	$64 \pm 5(39 \pm 4)$	56
$N_h \geq 8$	$88 \pm 7(77 \pm 3)$	$86 \pm 6(75 \pm 5)$	78

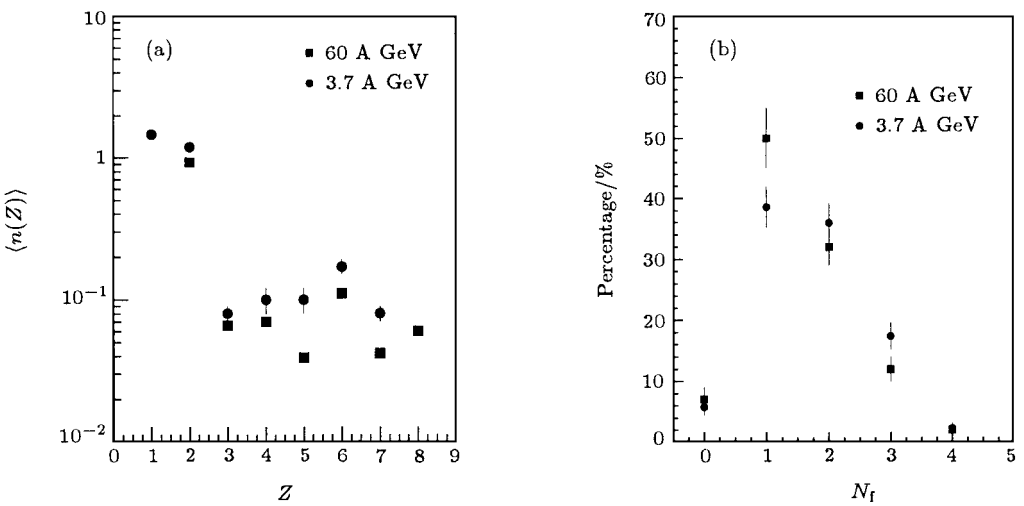


Fig.1. (a) Charge distributions (left) and (b) multiplicity distributions of PFs(right).

Figure 1 represents (a) the average charge distributions of $Z \geq 1$ PFs in interactions of quasi-nucleon type, and (b) the multiplicity distributions of $Z \geq 2$ fragments in interactions of type $N_h = 0, 1$ at 3.7 A GeV and 60 A GeV.

It is interesting to perform the analysis of the multiplicity dependence on the quantity Q per event which measures the total charge of non-interacting PFs for inelastic interactions, i.e. $Q = \sum_i n_i Z_i$, where n_i is the number of PFs with charges $Z_i \geq 1$ in an event. The value of Q characterizes the volume of the non-overlapping part of the projectile nucleus. Thus, this quantity enables us to estimate the average number of interacting nucleons per event, i.e. $N_{int} = (Z_p - Q)A_p/Z_p$ where Z_p and A_p are the atomic and mass numbers of the projectile nucleus.

The effects of impact parameter (as indicated by the value of N_h) on the total charge of the PF are displayed in Fig.2 for $N_h = 0, 1$, $N_h = 2 - 7$, $N_h \geq 8$ and $N_h \geq 0$. It can be noticed that the major contribution for quasi-nucleon events is toward the high values of Q (Fig.2(b)). In Fig.2(c) the yield increases with the net charge of the spectators Q, which is connected with the gentle low-temperature processes, while in Fig.2(d) the yield decreases with Q, which characterizes the violent high-temperature processes.

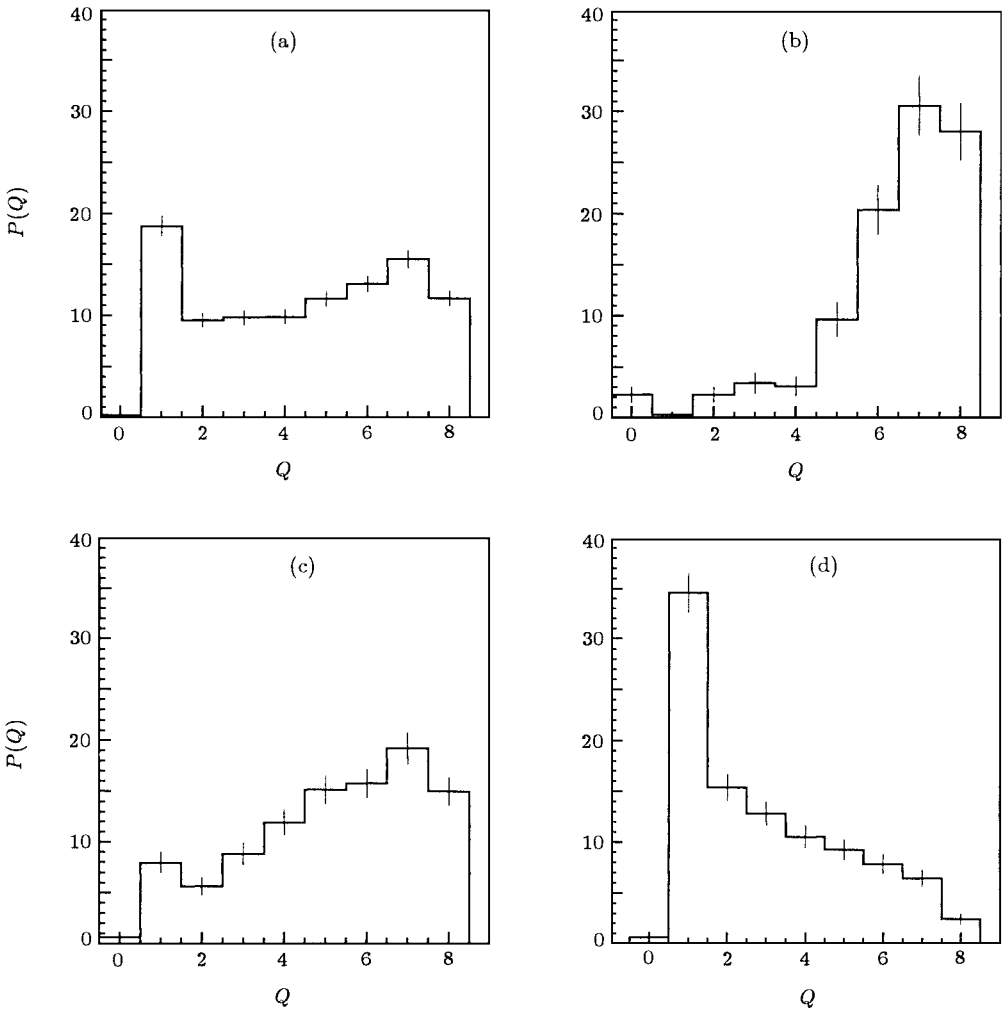


Fig.2. The distributions of events with a given value of Q: (a) for $N_h \geq 0$, (b) for $N_h = 0, 1$, (c) for $2 \leq N_h \leq 7$ and (d) for $N_h \geq 8$.

Figure 3 shows the average multiplicities of shower, grey, black and heavily ionized track particles as a function of the total charge Q of non-interacting PF for the ^{16}O at 3.7 A GeV. It is interesting to notice that the mean number of shower particles $\langle N_s \rangle$ increases with the decrease of Q, and its maximum value at Q=0 (when oxygen constituents completely participate in the collision and a large amount of energy is transferred to the target nucleus, $\langle N_s \rangle$ reaches its maximum value). The variations of $\langle N_g \rangle$, $\langle N_b \rangle$ and $\langle N_h \rangle$(target fragments) as a function of the spectator projectile charge Q are shown in Figs.3(b), (c) and (d), respectively. The average multiplicities of target fragments decrease with the increase of total charge Q of non-interacting PFs of ^{16}O. The multiplicities of N_g fragments increase rapidly with the increase of centrality (i.e. with lower Q). This dependence is weaker in the case of black particles, which consist only of slow target fragments.

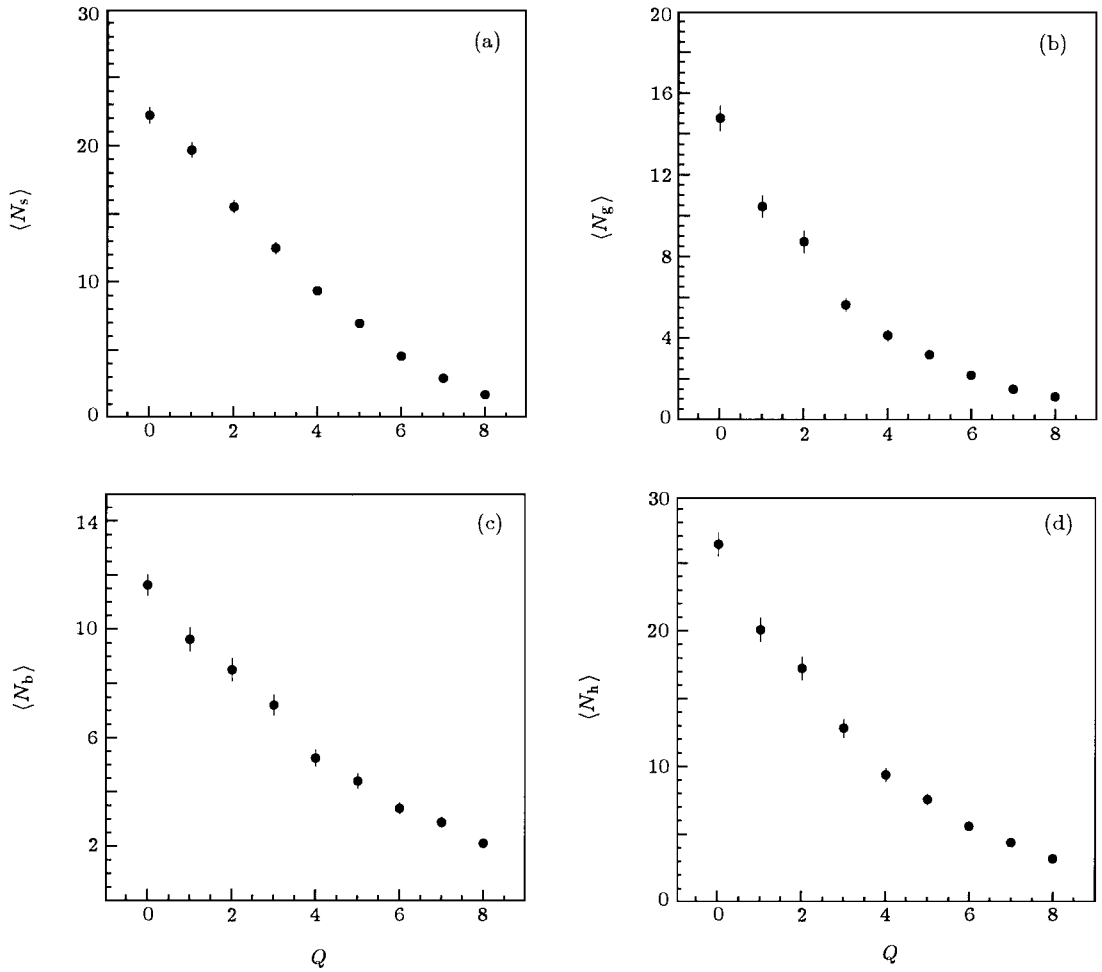


Fig.3. The average multiplicity of (a) shower, (b) grey, (c) black and (d) heavily ionized track particles as a function of Q for ^{16}O at 3.7 A GeV.

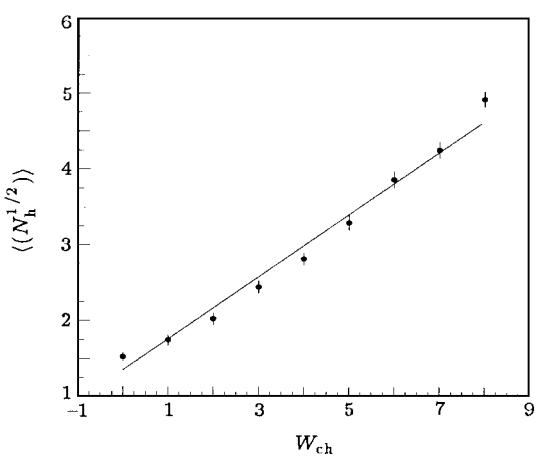


Fig.4. The quantity $\langle (N_h)^{1/2} \rangle$ as a function of W_{ch}.

In high energy nucleus–nucleus collisions the average number of interacting nucleons per event, N_{int}, is an important quantity which can help us describe the yield of reaction quantitatively, but it cannot be measured directly in experiments. N_{int} is dependent on the number of protons participating in the reaction, i.e. $W_{ch} = Z_p - Q$ linearly. Figure 4 shows the dependence of $\langle (N_h)^{1/2} \rangle$ on W_{ch}. This figure shows that $\langle (N_h)^{1/2} \rangle$ increases with the W_{ch} linearly. By using the least-χ^2 fit, we obtain the result $\langle (N_h)^{1/2} \rangle = 1.35 + 0.41 W_{ch}$.

The mean multiplicity of target fragments as a function of the number of PFs with charges $Z \geq 2$, is shown in Fig.5. It can be noticed that the average multiplicity of target fragments decreases linearly with the increase of number of PFs. This result is the same as the result at 60 A GeV where $\langle N_h \rangle = 7.52 - 1.46 N_f$. By using the least-$\chi^2$ fit, we obtain the result $\langle N_h \rangle = 9.77 - 1.97 N_f$ with a minimum $\chi^2 = 1.09$. One can see that all values of N_h are higher for interactions at 3.7 A GeV than those at the higher energy, 60 A GeV. This may be due to the possible emission of high-energy grey track particles in the exposure of 60 A GeV such that an overlap may occur

between the limits of the specific ionization characterizing the grey and shower tracks. This tendency observed in our experiments also exists in ^{28}Si–Em interactions at 3.7 A GeV and 14.6 A GeV.[19]

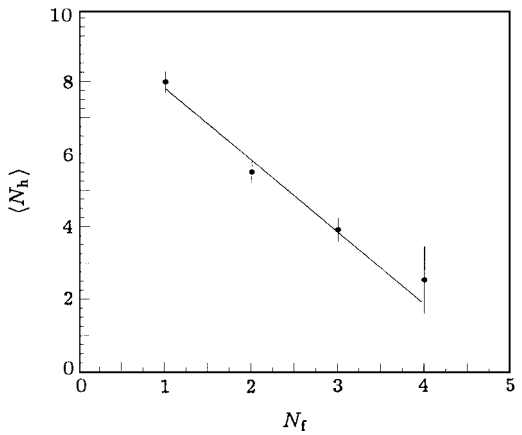


Fig.5. The mean multiplicity of target fragments as a function of the number of PFs.

4. Conclusions

We summarize the important conclusions in the following:

1. The yield of multiply-charged fragments is independent of projectile energy but dependent on projectile mass.

2. The major contribution for quasi-nucleon events is toward the high Q values but for the interactions of type $N_h \geq 8$ the major contribution is from small values of Q.

3. The average multiplicity of target fragments decreases with number of projectile fragments and value of Q increasing.

4. By using the new definition of total projectile destruction of ^{16}O nucleus the cross section of TD events follows a geometrical formula like the one suggested by Bradt and Peters for relativistic nucleus–nucleus collisions and the ratio between the number of collisions having $2 \leq N_h \leq 7$ and the number of collisions having $N_h \geq 8$ for TD events, and is independent of projectile type and energy at such high incident energies.

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References

[1] Goldhaber A S 1974 *Phys. Lett.* **B47** 306
[2] Heckman H H, Greiner D E, Lindstrom P J and Bieser F S 1972 *Phys. Rev. Lett.* **28** 926
[3] Schuttauf A, Kunze W D, Worner A *et al* 1996 *Nucl. Phys.* A **607** 457
[4] Cherry M L, Dabrowska A, Deines-Jones P *et al* 1997 *Z. Phys.* C **73** 449
[5] El-Naghy A 1981 *Z. Phys.* A **302** 261
[6] Bannik B P, El-Nadgy A, Krasnov S A *et al* 1988 *Z. Phys.* A **329** 341
[7] El-Naghy A, Krasnov S A, Tolstov K D *et al* 1988 *J. Phys.* G **14** 1125
[8] Abd Allah N N, 1993 *Nucl. Sci. J.* **30** 167
[9] Powell C F, Fowler P H and Perkins D H 1959 *Study of Elementary Particles by the Photographic Method* (London: Pergamon)
[10] Ahmad M S, Khan M Q R and Hasan R 1989 *Nucl. Phys.* A **499** 821
[11] Chernov G M, Gulamov K G, Gulyamov U G *et al* 1984 *Nucl. Phys.* A **412** 534
[12] Singh B K and Tuli S K 1999 *Nuovo Cimento* A **112** 1093
[13] El-Sharkawy S, Jilany M M, Abd Allah N N *et al* 1999 *Nuovo Cimento* A **112** 941
[14] Joseph R R, Ojha I D, Singh B K and Tuli S K 1992 *J. Phys.* G **18** 1817
[15] Abd-Allah N N and Mohery M 2001 *Czech. J. Phys.* **51** 1189
[16] Heckman H H, Greiner D E, Lindstrom P J and Shwe H 1978 *Phys. Rev.* C **17** 1735
[17] Admovich M I, Aggarwal M M, Alexandrov Y A *et al* (EMU-01 Collaboration) 1995 *Z. Phys.* A **351** 311
[18] El-Nadi M, El-Nagdy M S, Abdelsalam A *et al* 1998 *J. Phys.* G **24** 2265
[19] El-Nadi M, El-Nagdy M S, Ali-Mossa N *et al* 1999 *J. Phys.* G **25** 1169
[20] Zhang D H 2002 *Chin. Phys.* **11** 1254
[21] Holynski R 1994 *Nucl. Phys.* A **566** 191c
[22] Dabrowska A, Holynski R, Olszewski A *et al* 2001 *Nucl. Phys.* A **693** 777
[23] Bauer W, Post U, Dean D R and Mosel U 1986 *Nucl. Phys.* A **452** 699
[24] Campi X 1986 *J. Phys.* A **19** L917
[25] Wu F J, Zhang D H, Li J S and Li Z Y 2004 *Chin. Phys.* **13** 646
[26] Li J S, Zhang D H, Li Z Y and Wu F J 2004 *Chin. Phys.* **13** 836
[27] Zhang D H, Li Z Y, Li J S and Wu F J 2004 *Chin. Phys.* **13** 1239
[28] Bogdanov V G *et al* 1988 *Yad. Fiz.* **47** 1814
[29] Bradt H L and Poters B 1950 *Phys. Rev.* **77** 54
[30] Westfall G D, Wilson L W, Lindstrom P J *et al* 1979 *Phys. Rev.* C **19** 1309