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Fragmentation of ^{16}O nuclei in nuclear emulsion*

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We present the topology of ^{16}O fragmentation at 60 A GeV in reactions with emulsion nuclei. We discuss the multiplicity distributions of projectile fragments, charged secondaries and their dependence on the target residues.

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

1. Introduction

Relativistic heavy-ion collisions have been regarded as promising for giving information about the underlying production processes. The number of participant nucleons in these collisions is very important for the study of meson production[1,2] and resonance matter. It also serves as an experimentally accessible substitute for the impact parameter. The expression 'participant nucleons' stems from the participant–spectator model in which nucleons residing in the geometrical overlap between projectile and target are considered participants of the heavy-ion collisions, whereas the nucleons not residing in the overlap are termed spectators.

In high-energy nucleus–nucleus collisions, fragments from the projectile and the target can be well separated. The process where a part of the nucleus is suddenly liberated is called fragmentation[3] and if the second nucleus acts only as energy injector, we call it limiting fragmentation.[4] A theoretical description of nuclear multifragmentation generally starts from the assumption of two stages, phases, of the interaction. In the first stage, the incident nucleons scatter on the target nucleons, ejecting some of them and leaving a certain amount of energy to the spectator part, which forms rather excited residues. In the second stage, after the escape of participant nucleons, the residues decay through evaporation of neutrons and light nuclei (p,d,^{3}He and ^{4}He) for low excitation energy. At higher excitation energies, the residues disintegrate into fragments of intermediate mass (IMF).

Nuclear emulsion has the highest spatial resolution (4π) compared with any other detector. Moreover, in emulsion not only the projectile fragments (PFs) but also all the target fragments (TFs) can be detected, which helps in the analysis of events.

This was first discussed by the EMU01 Collaboration[5] for the fragmentation of ^{28}Si at 3.7 A and 14.6 A GeV, and ^{32}S at 200 A GeV. El-Nadi *et al.*[6,7] discussed the fragmentation of ^{28}Si at 14.6 A GeV and ^{32}S at 3.7 A GeV. In this paper, we focus on the multiplicity distribution of fragments, charged secondaries, and their dependence on the projectile residues. The topological structure of the projectile fragmentation of ^{16}O nuclei at 60 A GeV is studied.

2. Experimental details

NIKFI BR-2 stacks of nuclear emulsions, $10\times10\times2\text{cm}^3$ in volume, was exposed horizontally to the 60 A GeV ^{16}O beam at the CERN Super Proton Synchrotron (SPS). The flux intensity was 10^3particles cm^{-2}. Emulsion plates, 600 μm thick, were scanned by the along-the-track method under 100× oil objectives. Details about scanning and measurements have been given elsewhere.[8–10]

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 reaction percentage of the ^{16}O induced reaction. The number N_h (which denotes the number of charged target fragments defined by range

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or energy loss in the emulsion) 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 $N_h = 0, 1$. The interactions having $N_h \geq 8$ almost definitely belong to AgBr collisions, while events with $2 \leq N_h \leq 7$ are due to interactions with CNO and peripheral AgBr.

At high incident energy nearly all the PFs with charge $Z \geq 2$ have small emission angles and can be well separated from the produced particles and TFs. All the PFs with charge $Z \geq 2$ are emitted within the fragmentation core defined by a critical angle $\theta_c = 3.3$mrad at 60 A GeV. This value corresponds to a spectator proton with a transverse momentum of 200MeV/c.

The charges of PFs are determined by δ-ray counting. Using the proportionality of the number of δ-ray per mm (N_δ) with Z^2 of fragments, i.e. $\frac{N_\delta \text{ for } ^{16}\text{O}}{N_\delta \text{ for } ^{4}\text{He}} = \frac{Z_{\text{O}}^2}{Z_{\text{He}}^2}$, we can obtain the linear relation expressed by $N_\delta = \text{A} + \text{BZ}^2$. The values of A and B should be determined for each emulsion plate. For lighter PFs with a charge Z=2 or 3, a complementary grain counting has been performed.

3. Results

With the above-mentioned criteria for separation and identification of the PF, we obtain the topology given in Table 1. 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 the H fragments, so that the total charge in each channel should be 8.

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

channel	N_h			
	$N_h = 0, 1$	$2 \leq N_h \leq 7$	$N_h \geq 8$	$N_h \geq 0$
O	26	34	6	66
N+p	19	18	–	37
C+He	15	7	1	33
C+2H	84	73	30	187
B+He+H	2	2	–	4
B+3H	15	11	4	30
Be+2He	1	1	1	3
Be+He+2H	16	19	5	40
Be+4H	14	26	13	53
Li+2He+H	1	8	–	9
Li+He+3H	19	9	5	33
Li+5H	10	21	13	44
4He	4	2	–	6
3He+2H	44	47	12	103
2He+4H	75	103	64	242
He+6H	64	140	118	322
8H	30	114	385	529
All	439	635	657	1731

Table 2 gives the event statistics for the two samples given by the EMU-01 Collaboration[5] and that obtained from this work. This table also shows the number of events with total projectile destruction (TD). TD events are defined as those events where only PFs with charge $Z \leq 2$ remain. The ratio between the number of collisions having $2 \leq N_h \leq 7$ (CNO and peripheral AgBr) and the number of collisions having $N_h \geq 8$ (only AgBr) is independent of the beam energy (in the case of nearly the same projectiles ^{28}Si, ^{32}S).

Table 2. The statistics of events for 60 A GeV ^{16}O interactions with emulsions for different N_h groups.

	This work	3.7 A GeV ^{28}Si[5]	14.6 A GeV ^{28}Si[5]	200 A GeV ^{32}S[5]
Total number of collisions	1731	1986	995	775
$N_h = 0, 1$	439	443	265	283
$2 \leq N_h \leq 7$	635	734	328	234
$N_h \geq 8$	657	809	362	258
$N(2 \leq N_h \leq 7)/N(N_h \geq 8)$	0.97 ± 0.08	0.91 ± 0.07	0.91 ± 0.08	0.91 ± 0.12
TD events				
$N_h = 0, 1$	217(94)	75	58	50
$2 \leq N_h \leq 7$	406(254)	265	135	80
$N_h \geq 8$	579(503)	557	237	166
$N(2 \leq N_h \leq 7)/N(N_h \geq 8)$	0.70 ± 0.06	0.48 ± 0.05	0.49 ± 0.07	0.48 ± 0.09

It has been shown in Ref.[11] that the cross section of TD events should follow a geometrical formula like that suggested by Bradt and Peter[12] for relativistic (inelastic) nucleus–nucleus interactions

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

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 a geometrical formula suggested by Westfall *et al.*[13] Events with $N_h = 0, 1$ are predominantly 'quasi-nucleon' interactions, i.e. interactions with an H nucleus or with only one bound nucleon in a CNO or AgBr nucleus. The $N_h = 2-7$ group is dominated by CNO collisions and peripheral AgBr collisions, whereas the $N_h \geq 8$ group consists 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*[5] the calculated TD fraction of TD events gives an underestimation of experimental values, especially for the $N_h = 0, 1$ group. The reason may be that the criteria of selecting TD suggested by Ref.[5] cannot be well applied to a lighter projectile nucleus like the oxygen nucleus. Up to now, it seems that no paper has discussed the fragmentation of a projectile with charge $Z \leq 14$, so the validity of the criteria for choosing the TD for this kind of projectile suggested by Admovich *et al*[5] needs to be tested for smaller projectiles. If we define the TD of an oxygen nucleus as those events where only one He projectile fragment or proton remains, the TD event statistics in Table 2 is that in parentheses. The ratio between the number of collisions having $2 \leq N_h \leq 7$ (CNO and peripheral AgBr) and the number of collisions having $N_h \geq 8$ (only AgBr) is 0.50 ± 0.03, seems to be independent of the beam energy and the projectile. According to our new TD criteria, the fraction of TD events in minimum bias collisions with various degrees of target break-up is given in the parentheses in Table 3, which is better than that based on the criteria suggested by Admovich *et al.*[5]

Table 3. Fraction of TD events in minimum bias collisions with various degree of target break-up. The calculations are based on equation (1).

N_h range	Experimental Results	Calculated Results
$N_h = 0, 1$	$49 \pm 6 (21 \pm 2)$	13
$N_h = 2-7$	$64 \pm 6 (40 \pm 3)$	56
$N_h \geq 8$	$88 \pm 7 (77 \pm 3)$	78

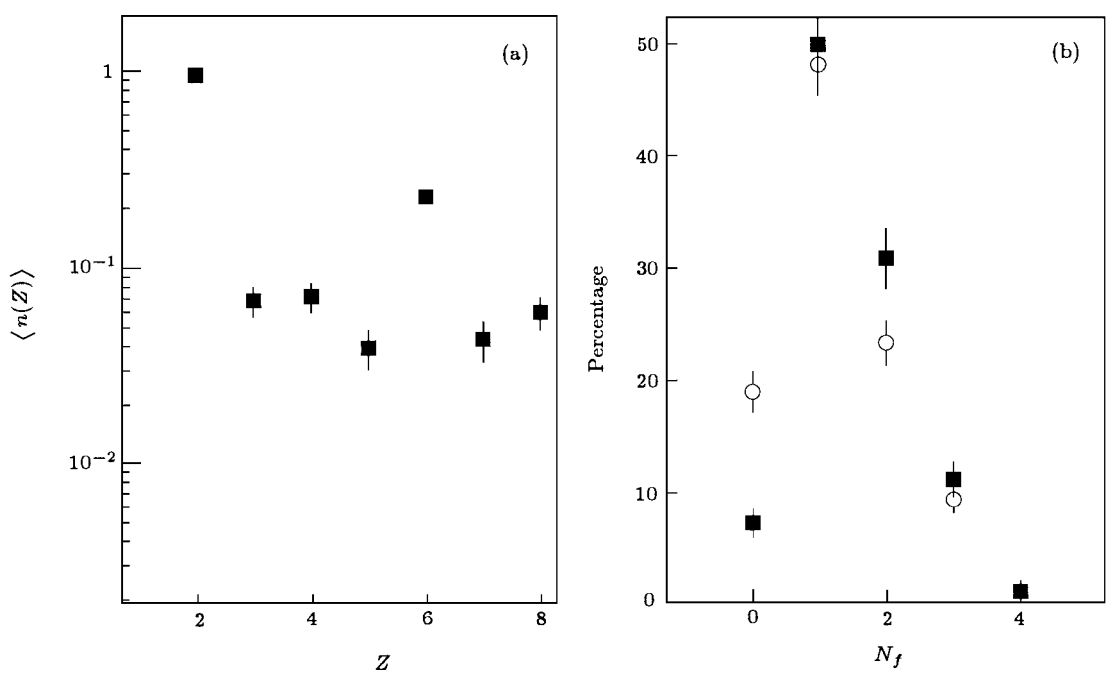


Fig.1. (a) Charge distribution and (b) multiplicity distribution of PFs.

Figure 1 presents (a) the average charge distribution of $Z \geq 2$ PFs in interactions of quasi-nucleon type, and (b) the multiplicity distributions of $Z \geq 2$ fragments in interactions of type $N_h = 0, 1$ (filled square) and type $2 \leq N_h \leq 7$ (open circle).

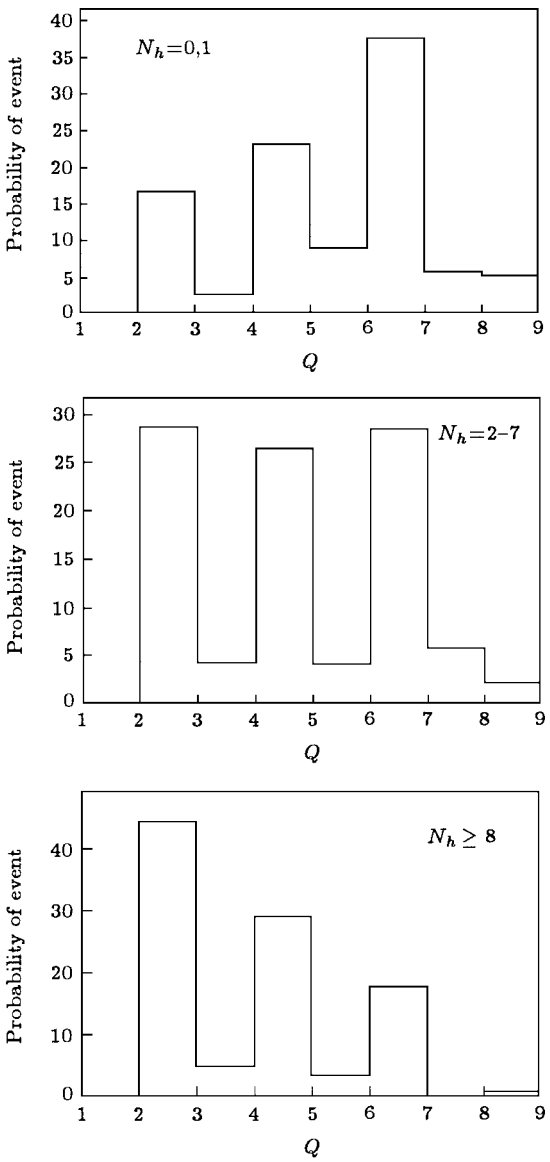


Fig.2. The distribution of events with a given Q.

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 interaction, i.e. $Q = \sum_i n_i Z_i$, where n_i is the number of PFs with charge $Z_i \geq 2$ in an event. The value of Q characterizes the volume of the non-overlapping part of the projectile nucleus. Here the definition of Q is different from that given by Nadi *et al.*[7] In their paper, n_i is the number of fragments with charge $Z_i \geq 1$ in an event.

The effects of the impact parameter (as indicated by the value of N_h) on the total charge of PF are displayed in Fig.2 for $N_h = 0, 1$, $N_h = 2 - 7$ and $N_h \geq 8$. It can be noticed that the major contribution for quasi-nucleon events is toward the high values of Q, but for the interactions of type $N_h \geq 8$ the situation is quite different.

Figure 3 shows the average multiplicity of TFs as a function of the total charge Q of non-interacting PF. It is interesting to notice that the mean number of TFs increases with decreasing Q, and its maximum value is at Q=2, i.e. when the nucleons of oxygen that participate in the collision increase, the energy transferred to the target nucleus increases.

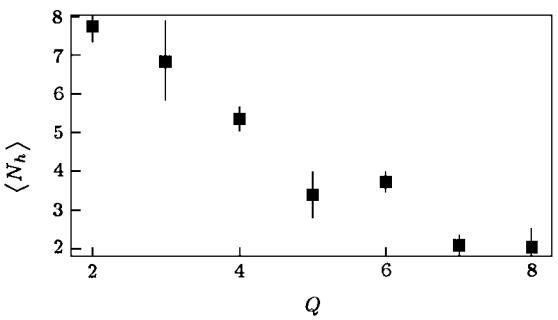


Fig.3. The average multiplicity of TFs as a function of Q.

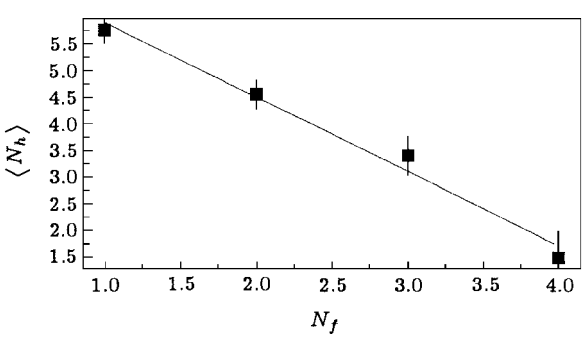


Fig.4. The mean multiplicity of TFs as a function of the number of PFs.

The mean multiplicity of TFs changes with the number of PFs, as shown in Fig.4. It can be noticed that the average multiplicity of TFs decreases linearly with the increase of the number of PFs. This result further confirms the result obtained in Fig.3. By using the least-χ^2 fit, we obtain the result $\langle N_h \rangle = 7.52 - 1.46 N_f$.

4. Concluding remarks

The results obtained from this study lead to the following conclusions:

(1) The yield of multiply-charged fragments is independent of the 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 TFs decreases with the increasing of the number of PFs and the values of Q.

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References

[1] El-Nagdy M S 1993 *Phys. Rev.* C **47** 346
[2] Hanris J W *et al* 1987 *Phys. Rev. Lett.* **58** 463
[3] Goldhaber A S 1974 *Phys. Lett.* B **47** 306
[4] Heckman H H, Greiner D E, Lindstrom P J and Bieser F S 1972 *Phys. Rev. Lett.* **28** 236
[5] Admovich M I *et al* (EMU-01 Collaboration) 1995 *Z. Phys.* A **351** 311
[6] El-Nadi M, El-Nagdy M S, Abdelsalam A *et al* 1998 *J. Phys. G: Nucl. Part. Phys.* **24** 2265
[7] El-Nadi M, El-Nagdy M S, Ali-Mossa N *et al* 1999 *J. Phys. G: nucl. Part. Phys.* **25** 1169
[8] Zhang D H, Sun H C and Gharibi G 2001 *Chin. Phys.* **10** 21
[9] Zhang D H and Sun H C 2001 *Acta Phys. Sin.* **49** 1938 (in Chinese)
[10] Zhang D H and Sun H C 2001 *High Energy Phys. Nucl. Phys.* **25** 651 (in chinese)
[11] Bogdanov V G *et al* 1988 *Yad. Fiz.* **47** 1814
[12] Bradt H L and Peters B 1950 *Phys. Rev.* **77** 54
[13] Westfall G D, Wilson L W, Lindstrom P J *et al* 1979 *Phys. Rev.* C **19** 1309