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PAPER

Channels of projectile fragmentation of ^{16}O nucleus in nuclear emulsion

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Abstract

Experimental data are presented on the projectile fragments emitted from non-central collisions of 3.7 A GeV ^{16}O projectiles with nuclear emulsion. Charges of all projectile fragments are measured carefully and identified using δ-ray distributions. Each distribution is fitted by Gaussian shape and represented one of the possible charges of projectile fragments. Topology of ^{16}O fragmentation is reported and compared with that obtained at 60 A GeV. The multiplicity distributions for ^{16}O projectile fragments with charge $3 \leqslant Z \leqslant 7$ are studied and it classified according to the size of the target nucleus. In this range of energy, the mechanism responsible for projectile fragmentation is independent on its energy. Experimental observations proved that there is high probability for production α-clusters than all other nuclear fragments. The production rate of α-clusters fragments due to ^{16}O fragmentations is studied at range of energies 2–200 A GeV. The dependence of α-clusters on target components (CNO and AgBr) is formulated. Experimental data indicates that α-cluster represents the main unit of the structure of atomic nucleus.

1. Introduction

Five decades ago, a new field of nuclear research started at Berkeley [1, 2] is interested by nuclear fragmentations. Different experimental and theoretical efforts are directed to describe the reaction mechanism that is responsible for nuclear fragmentations [3–5]. Nowadays, it is still a subject of great interest [6]. Observations of the fragmentation of light relativistic nuclei make new opportunities to explore highly excited multi-particle decay threshold [7]. Such states have loosely bound systems with significantly exceedingly spatial spread the fragment sizes. In particular, population of 2α, 3α and 4α particle states is possible in decays of light radioactive nuclei. The advantage of this work provides a base for α-spectrometry thus investigate daughter states resulting from their decay rather than the implemented nuclei themselves. Such investigations provide a basis for possibilities of observing and studying decays of isotopes and light exotic nuclei with both neutron and proton excess. Nuclear fragmentations provide different information about geometry of nucleus-nucleus collisions and it is an indication to the primary structure of the parent nuclei. The geometrical concept of nucleus-nucleus collision assumes that nuclear material is classified into three parts. The first is the projectile fragments PFs, which are the point of interest in this research. It represents the part of projectile nucleus that split with the same momentum and kinetic energy of projectile. Mass and charge of PFs are conserved to that for projectile nucleus. Experimentally, the PFs come within small angles θ_{PF} around the direction of incident projectile. This study gives much information about the structure of the projectile nucleus and possible mechanism that is responsible for nuclear fragmentations. The second part is the participant nucleons from both projectile and target nucleus. This part studies the production of different secondary particles, which are emitted in wide range of angles with respect to the direction of projectile. The third part is the nuclear material that is due to the residual target nucleus at frame of the target. It is characterized by slow and evaporated fragments emitted in isotropic angles independent on the direction of the incident projectile [8].

The subject of this paper is devoted to study fragmentation of ^{16}O nuclei at momentum of 4.5 A GeV/c corresponding to energy 3.7 A GeV and at energy 60 A GeV in nuclear emulsion. The charges and multiplicities of all possible channels of fragmentation are analyzed. The phenomenon of emission of α-clusters as a projectile fragments, is carefully investigated because it is an interesting attention for more than forty years [9]. Many important results of structure of ^{16}O-nucleus have been obtained by detecting such light nuclei.

2. Operational methods

This work was carried out by using nuclear emulsion technique, which is very suitable for identifying the charges of projectile fragments with $Z \geqslant 1$. In this experiment, emulsion stacks made up pellicles of type NIKFI-BR-2, which are approximately equivalent to ILford G-5 type, 600 μm thick and 20×10 cm^2 in size. The stacks were exposed to ^{16}O beam parallel to the surface of emulsion pellicles with momentum 4.5 GeV/c per nucleon in Dubna synchrophastron Russia. Other details concerning the experimental procedure have been described in [10]. Also, in the present experiments stacks of FUJI type coated in both sides of polystream film tangentially exposed to 60 A GeV ^{16}O beams at CERN SPS. More details have been described in [11].

The scanning of the emulsion pellicles was carried out by using 850 056 STEINDORFF microscope. It has a stage of 18×16 cm^2 with an opening of 7×2.5 cm^2. The 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. A total 1540 events were recorded where the respective mean free path is 12.7 ± 0.35 cm corresponding to inelastic reaction cross-section with emulsion nuclei of 988.3 ± 27 mb. The sample of the events, which are obtained for the projectile, is bias free and can be considered to as minimum bias events. The minimum ionizing shower tracks include spectator protons from the projectile; they have $\approx$35 grains per 100 μm. The used experimental definitions of the particle groups are as follows [12–14]:

- N_s: the number of shower particles. These are assumed to be mostly produced pions having $\beta = v/c > 0.7$.
- N_g: the number of grey particles with velocity $0.3 \leqslant \beta \leqslant 0.7$. They are often assumed to be protons with kinetic energy $26 < E_k \leqslant 400$ MeV.
- N_b: the number of black particles having velocity $\beta < 0.3$. These are the fragments from the target nucleus to be protons with kinetic energy $E_k < 26$ MeV.
- N_h : the heavily ionizing particles. It is equal $N_g + N_b$ and has $\beta \leqslant 0.7$.

The observed interactions were carefully looked for the PFs. They were checked and rechecked by scanning the track up and downstream from its production point. PFs refer to the spectator nucleons of the projectile with velocity $\approx$0.97c emitted within a fragmentation forward cone (θ_c) [15]. In this study they are singly-charged fragments with $Z = 1$ or multiply charged fragments with $Z \geqslant 2$. The singly-charged fragments [16] are visually separated and identified according to their number of grains per 100 micron when followed up to a distance of $\approx$1 cm from the interaction point without changing its ionization. The PFs of charge $Z \geqslant 2$ were determined and identified by measuring the grain density, gap density and by δ-rays counting. The methods of counting have been described in [15]. A charged particle while passing through a material medium interacts with it as atomic interactions. As result of which, some electrons are knocked out. In sensitive nuclear emulsion, these electrons produce short thin tracks projecting from the trajectory of the parent particles. These ejected electrons from the atoms, which have the ability to ionize other atoms, are known as δ-rays. The production of these rays depends on the charge and velocity of the particle. In this work, the measurements of projectile fragments were greatly simplified by the persistence of relativistic beam velocity. The grain criterion i.e. counting δ-ray with a different numbers of grains was employed and we counted δ-ray over a track segment of 10 mm from the center of the interactions. These measurements were confined to a depth between 30 μm and 220 μm from the surface of the emulsion, and a distance of at least 3 mm from the edges. Under these conditions the corrections due to the variation of the degree of development of the plates can be neglected. In each event the total charge of non-interacting nucleons $Q = \sum Z_{PFs}$ was estimated. The events associated with PFs emitted in the fragmentation cone with charge $Z \geqslant 2$ represent peripheral collisions at large impact parameters b [16]. The following measurements are the used δ-ray method to identify the possible charge of PFs.

A calibration line is done by using six primary beams which are available in our laboratory ^{4}He, ^{12}C, ^{16}O, ^{22}Ne, ^{24}Mg, and ^{32}S at 3.7 A GeV from Dubna sychrophastron. The relationship between the average number of δ-rays per mm for a sample of 40 tracks from each beam and corresponding charge is shown

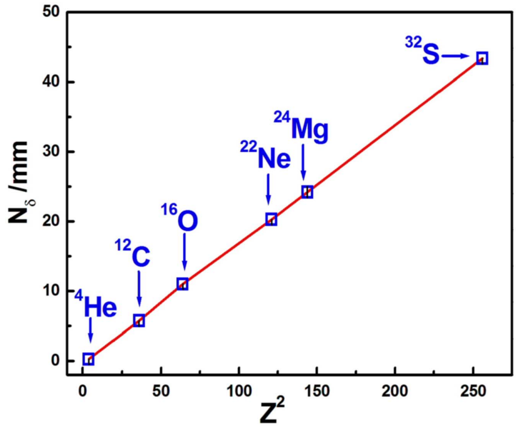

Figure 1. The calibration curve, showing the linear relation between the number of δ-rays per mm on the track length and the square of the projectile charges Z^2.

in figure 1. The data are fitted by the linear relation $N_\delta = aZ^2 + b$ where $a = 0.171 \pm 0.004$ and $b = -0.420 \pm 0.089$. On the other hand, at each interaction point, the PF with $Z = 1$ can be well separated by visual inspection of tracks whose ionizations are similar to those of shower ($\approx$30 grains per 100 micron). Identification of charge $Z = 2$ (mainly alpha particle) produced from parent stars of heavily ion beams is unique and easily compared to those of $Z = 3, 4$ by a visual comparison of the track diameter which enables the observer to determine the non equality of the charge of the PFs [17]. In addition, the magnitude of the charge is easily identified in all laboratories by different methods, which include the grain density (gap density) or δ-ray counting [18].

3. Experimental results and discussions

The charges of all possible PFs are determined by using the gap density method for tracks of single and double charges but the tracks with higher diameter are identified by using the δ-ray density, which are compared with the calibration line shown in figure 1. Figure 2 shows the experimental results obtained for δ-rays frequency distribution (histograms) of the projectile fragments having charge $Z = 3$–8 emitted from ^{16}O projectile at 3.7 A GeV. Gaussian distribution (smooth curved line) can fit it with a peak corresponding to a certain value of Z. The frequency distribution of δ-rays shows regular form around maximum value of production that is used as a fine indication to the magnitude of the charge of the fragment producing this track. There is no overlap between δ-rays measurements of the two successive charges, which assures that the δ-ray measurements is good experimental indicator to the magnitude of charge passing through emulsion and also its magnitudes give a limited error within fraction of unit charge. From these measurements, new calibration line is obtained as previously illustrated. The results are given in figure 3. Unknown charge of possible PFs can be easily identified from δ-rays measurements.

According to the criteria of the separation and the identification of PFs, table 1 gives topology for all minimum biased events in which each channel includes the participants and the spectators of the oxygen beam obtained from energy 3.7 A GeV in comparison with corresponding ones, at energy 60 A GeV. The similarity of the two distributions obviously indicates that the beam energy is of little importance for the nuclear fragmentation process. Evidence to a limited fragmentation hypothesis is shown which implies that both projectile and target may be fragmented irrespective of each other, and this fragmentation is independent of the beam energy. In addition, alpha projectile fragments α-PFs are the more probable fragment than any other possible charge to collaborate heavy fragments. It may indicate that ^{16}O-nucleus is a collection of α-clusters. The possible experimental evidence will be explained in the following text.

Figure 4 represents the topological diagram for the interactions of two oxygen beams with all emulsion components, which are characterized by events with $N_h \geqslant 0$. The numbers below represent the magnitude of the charges which are identified from $Z = 2$ up to 8. The two's number which accompany some of the fragments represent the α-PFs which appear as a special mode of fragmentations for most modes of all possible fragmented nuclei of $Z \geqslant 3$. The fraction of each channel of ^{16}O-nucleus fragmentations is similar at the two projectile energies. It proves that the mechanism that is responsible for projectile fragmentations into all possible fragment nuclei is independent of the projectile energy but these modes depend only of the essential properties of the nucleus of the projectile. A similar observation was concluded for ^{28}Si in [10].

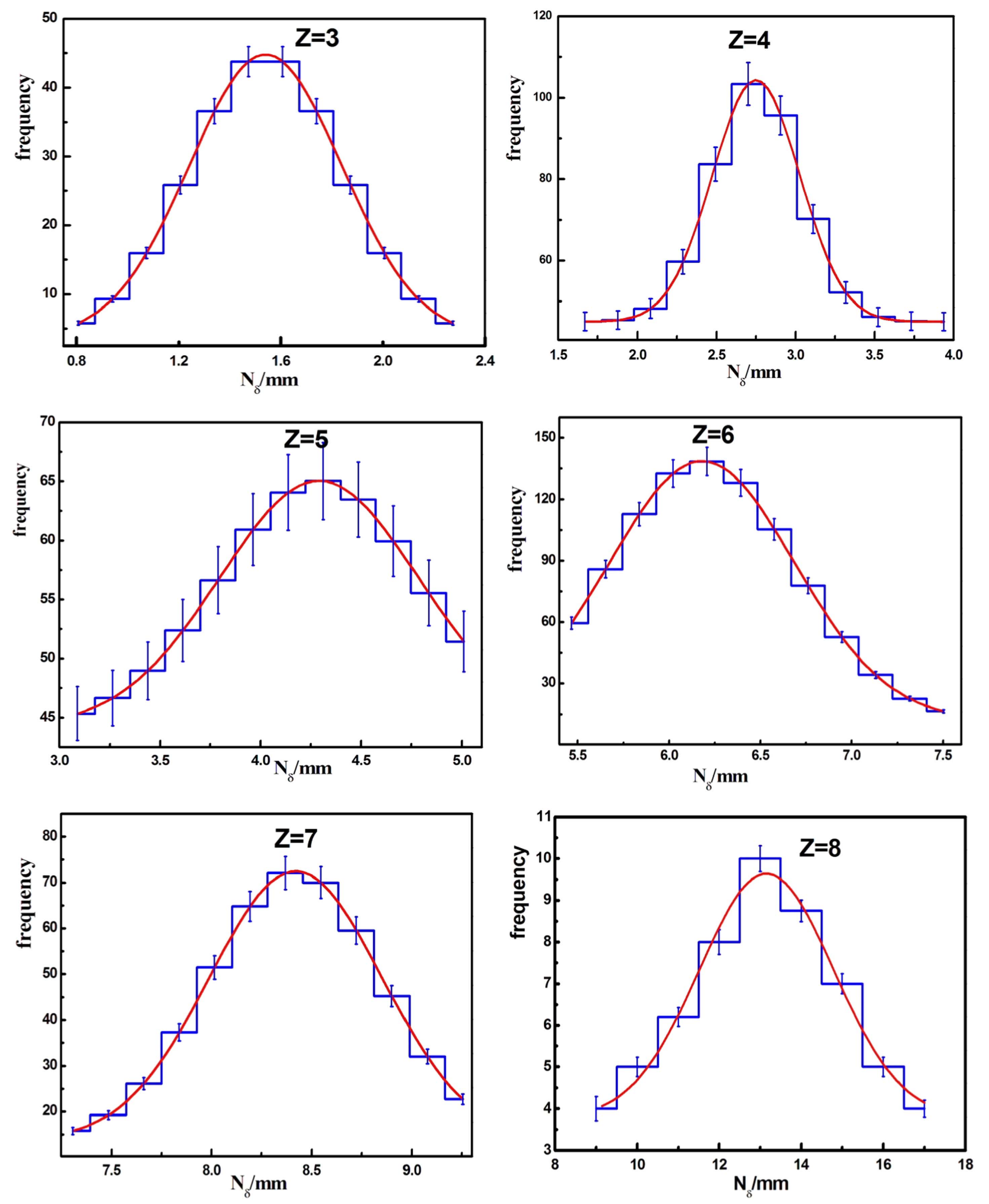

Figure 2. The charge distributions of δ–rays density (number of δ–rays/mm) for secondary projectile fragments due to ^{16}O interactions with emulsion at 3.7 A GeV (histograms) is fitted by typical Gaussian (smooth curves).

Clustering is a generic phenomenon, which can appear in the homogeneous matter when the density decreases. The importance of the phenomenon of α-clusters was very early [19] because it may be apply for low-density nuclear matter [20], and light nuclei [21]. It was considered as the atomic nucleus as a collection of α-clusters and both theoretical and experimental efforts were directed to study the clustering phenomena in nuclei [21–24]. Light alpha conjugate nuclei like those that for ^{12}C is considered as an example of nuclear collection of α-clusters. It represents a building block of nuclear matter rather than individual protons [22–27]. This concept based on magnitude of binding energy of the nuclear system, which increases for some nuclei with alpha conjugate such as ^{12}C and ^{16}O. This takes a special character of the alpha particle as the most bound nuclear system, whose first excited state lies above 20 MeV [26].

Now we investigate and search for experimental evidence of α-particle clustering from excited nuclear matter. In this section, we analyze in further detail, the possible experimental signatures of presence of the α-clusters in ^{16}O nucleus, which have direct significance for analysis of its ultra-relativistic collisions with emulsion

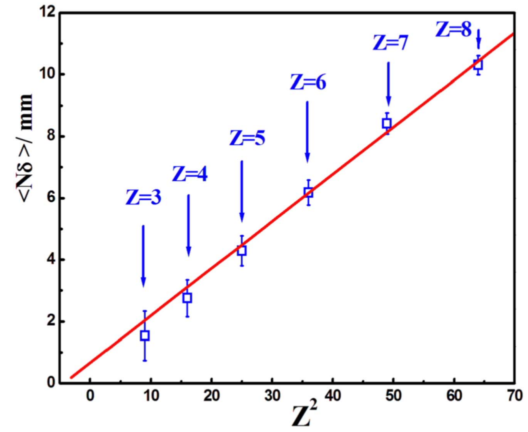

Figure 3. The experimental points of $\langle N_\delta \rangle$/mm for all of the square charges Z^2 of projectile fragments of ($Z = 3$–8) emitted from 3.7 A GeV ^{16}O-Em interactions. The straight line $\langle N_\delta \rangle = aZ^2 + b$ where $a = 0.665\,17 \pm 0.283$, $b = 0.152\,58 \pm 0.006$ represents the fit to experimental points.

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

N_h	0–1		2–7		⩾8		⩾0		Fraction of event	Fraction of event
Energy A GeV	3.7	60	3.7	60	3.7	60	3.7	60	3.7	60
Channel										
O	0	4	8	0	0	0	8	4	0.0053	0.0042
N + H	10	6	33	7	44	13	87	26	0.0564	0.0275
C + He	4	37	89	60	86	56	179	122	0.1162	0.1292
C + 2H	17	29	86	42	166	49	269	120	0.1746	0.1271
B + He + H	1	18	69	19	56	17	126	54	0.0818	0.0572
B + 3H	11	7	26	15	43	15	80	37	0.0519	0.0391
Be + 2He	5	16	85	39	85	40	175	95	0.1136	0.1006
Be + He + 2H	0	1	24	7	18	4	42	12	0.0272	0.0127
Be + 4H	1	1	12	3	6	6	19	10	0.0123	0.0105
Li + 2He + H	1	0	23	1	4	3	28	4	0.0181	0.0042
Li + He + 3H	0	1	4	0	2	3	6	4	0.0038	0.0042
Li + 5H	0	0	0	0	0	0	0	0	0	0
He + Be + 2H	0	0	2	0	0	0	2	0	0.0012	0
He + 3He	7	16	70	21	16	15	93	52	0.0603	0.0550
He + 2He + 2H	1	1	8	2	0	1	9	4	0.0058	0.0042
He + C	0	0	15	4	11	4	26	8	0.0168	0.0084
H + 3He + H	0	0	5	1	3	0	8	1	0.0051	0.0010
H + 2He + 3H	0	0	0	0	0	0	0	0	0	0
H + He + 5H	0	0	0	0	0	0	0	0	0	0
Q = 0	1	1	123	130	259	229	383	391	0.2487	0.4141
All	59	138	682	351	799	455	1540	944	1	1

nuclei. Figure 5 represents the multiplicity distribution of α-PFs from the inelastic interactions of ^{16}O with emulsion nuclei at 3.7 A GeV (this work), compared with the corresponding distributions at 2 A GeV [28], 60 A GeV and 200 A GeV [17]. This figure shows that the percentage for 1α, 2α, 3α and 4α is about 50%, 32%, 15%, and 0.7% for 2, 3.7, 60 and 200 A GeV ^{16}O-Em interactions, respectively.

This indicates that α-cluster is essential in the structure of oxygen and α-multiplicity distribution is independent of the beam energy. The probability or the multiplicity distribution of production of α-clusters decreases gradually with high multiple α-particles. The probability difference between 1α and 2α is nearly equal that between 2α and 3α and for 3 to 4α. The difference appears nearly fixed magnitude between the multiple α-productions. This can be explained by considering that the process of projectile fragmentation can take place as a quantization of emissions in the form of α-clusters. This quantization mode is independent on interaction energy because α-clusters are essential in the initial structure of the parent nucleus before undergoing the processes of fragmentations. In addition, the possibility of production of one α-cluster is easy and more frequent

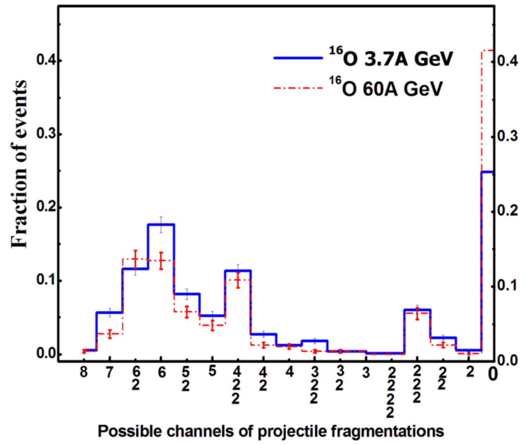

Figure 4. Topological diagram for $N_h \geqslant 0$ events. The numbers below the x-axis represent the charge distribution of the spectators with and without α-fragments.

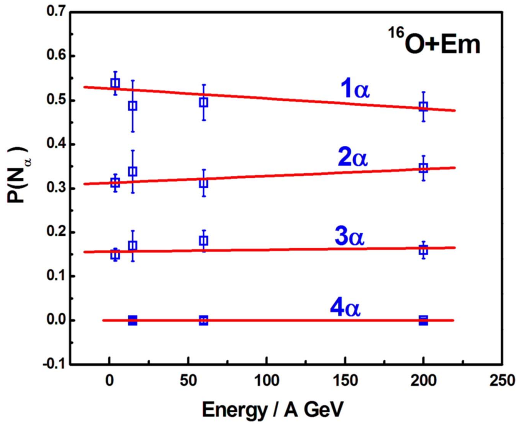

Figure 5. The multiplicity distribution of α-projectile fragments emitted from ^{16}O-Em interactions at different collision energies in the range 2–200 A GeV.

than that of two alphas and gradually decreases. This can be explained by considering that the fragmentation process is non-regular due to changes in the overlapping of projectile with target nucleons. The overlapping creates a crowded medium of mixed nucleons, which are sufficient for projectile to lose gradually the initial structure and the regularity of production of α-clusters.

A point of interest is the dependence of multiplicity of α-PFs on the target size. In this experiment, the target is compound nucleus and can be easily classified into three main groups of interactions. Experimentally, classification of these interactions is characterized by multiplicity of heavily ionizing secondary charged particle N_h. This particle is a pure target fragment and can be taken as an experimental parameter for target size, which describes the degree of overlapping of projectile and target nuclei. The first group with $N_h \leqslant 1$ is the interactions with hydrogen which are excluded from this consideration because they have low statistics. The second is the interactions with light emulsion components CNO, where $2 \leqslant N_h \leqslant 7$ and is considered as gentle interactions. The third group is the interactions of ^{16}O with heavy emulsion nuclei AgBr that is considered as hard interactions and characterized by $N_h \geqslant 8$.

Figure 6 shows the frequency distributions of α-PFs for interactions of ^{16}O with CNO and AgBr nuclei at collision energy 3.7 A GeV versus the multiplicity of N_h. In this figure, for each target the probability distribution of α-PF has a constant value in specific range of N_h and decreases gradually with high multiplicity of α-PF. This behavior is noticed for groups. It is a normal behavior for both mechanisms of projectile fragmentations regardless of their target size. For each multiplicity of α-PF, the probability distribution of the ^{16}O-AgBr is lower than the corresponding channel for ^{16}O-CNO interactions. This can be understood if we consider that, there is a fixed negative effect of target size on structure of projectile nucleus to save initial form of α-clusters. This negative effect is regular with high multiplicity of α-PFs. It could be explained by considering that the increase in the overlapping volume between the projectile and the target nuclei increases the number of interacting

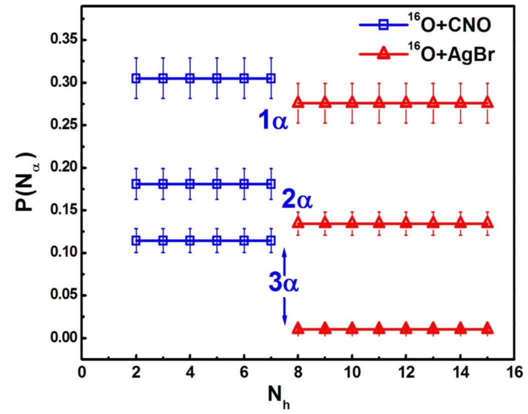

Figure 6. Probability distribution of α-cluster multiplicity with interaction of two emulsion components CNO and AgBr versus multiplicity of secondary heavily ionizing charged particles N_h.

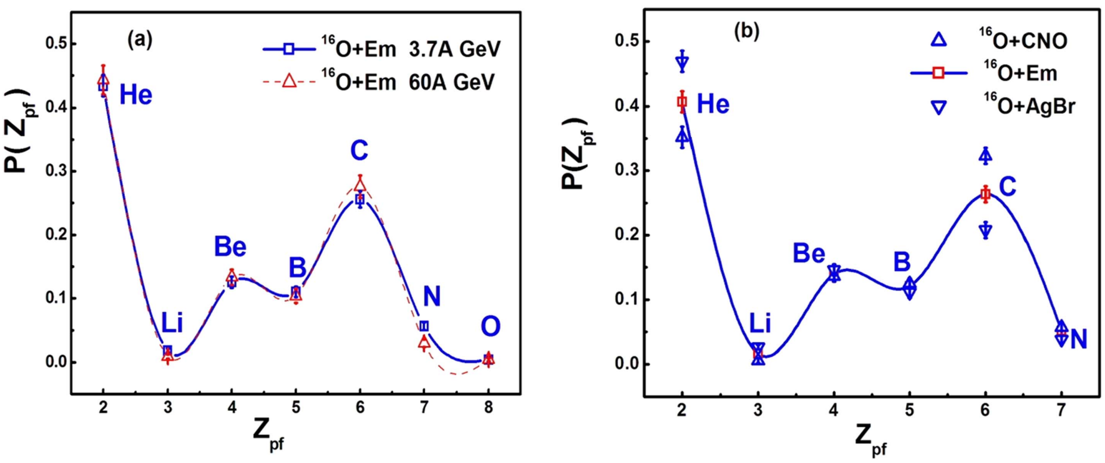

Figure 7. Charge multiplicity distribution for of all possible fragments emitted from interaction of 3.7 A GeV and 60 A GeV ^{16}O with emulsion are compared in (a). The corresponding distributions for interactions of ^{16}O with CNO and AgBr target components are compared in (b). The solid line represents the free hand behavior.

nucleons and hence the transfer energy. This lead to projectile nucleus loses the initial structure. This effect is observed for ^{16}O-AgBr interactions more than ^{16}O-CNO interactions. One can conclude that, the probability of the projectile to break up with the same initial structure of α-clusters decreases when volume or target participant nucleons increase. This means that the experimental observation supports the theory of cluster [29], which is based on the presence of clusters in the parent nucleus before it penetrates the nuclear barriers and reaches the sessions of configuration after running down the Coulomb barrier.

It is also interesting to study the special behavior of ^{16}O projectile fragmentation to produce α-clusters more than other possible fragments. Figure 7(a) shows the charge multiplicity distribution of events with projectile fragments for all possible charges emitted due to interactions of ^{16}O with emulsion at energies 3.7 A GeV and 60 A GeV . The main observation is that, for the two values of the projectile energies the distributions for all possible charges of fragments are fixed due to a unique fragmentation mechanism. It indicates that, the mechanism of projectile fragments production is independent of projectile energy not only for α-cluster but also for all possible charges of fragments. In addition, figure 7(b) shows a comparison of the same distributions for interactions with the main components of the target emulsion nuclei, (light component CNO and heavy components AgBr). It is noticed that the effect of the target size on the mechanism of the projectile fragmentation is approximately similar for all possible charges of fragments. Another observation is the high probability of α-cluster production more than all other charges of fragments. This is for both the two groups of target nuclei. The second probability for preferred charge is for ^{12}C that is considered as a combination of three of α-clusters. The following probabilities of the projectile fragmentations are observed for ^{4}Be and ^{5}B. The lower values of frequencies of projectile fragmentations are for ^{7}N and ^{3}Li that are characterized by odd number of protons and far from α-cluster formations. This concludes that ^{16}O-nucleus is composed of cohesive α-clusters.

Experimentally, projectile fragmentations prove that α-cluster may be the building block of the atomic nuclei in the ground state and it is the most probable unit in channels of fragmentations. Many theoretical works [30–33] predicted that α-clusters could be present in the ground state of the basic structure of atomic nuclei. This prediction is supported the present experimental results in this study. Convincing arguments for existence of such structures were provided by the present experimental observations on the clear and special mode for the production of α-cluster from the fragmentation of ^{16}O-nuclei. In addition, there is a clear systematic of the binding energies of the even–even nuclei with equal number of protons and neutrons [34] as well as the systematic of the binding energy of the additional neutron in nuclei like ^{9}B, ^{13}C and ^{17}O. The latter systematic could be explained by assuming that the valence neutron moves in a multi-center potential with centers identified with alpha particles.

4. Conclusions

The possible charges due to the fragmentation of ^{16}O nucleus with emulsion are well identified using δ-ray distribution of possible fragments. The topology of projectile fragmentation and the possible channels at energies 3.7 and 60 A GeV are similar which conclude that the fragmentation process is energy independent. This study investigates the experimental evidence that depends on the presence of α-clusters as the main unite of the structure of the normal state of the nuclear materials. This evidence depends on the nature and the experimental properties of the projectile fragmentations. Our studies can conclude the following

1. Mechanism of the production of α-PFs in projectile fragmentations is independent of the collision energy in the range 2 up to 200 A GeV.
2. The probability of α-clusters production decreases by a certain value with high multiplicity, which is independent of both projectile energy and target size. Increasing in the target mass number shows negative effect on the α-clusters production. This is due to increasing in the participant nucleons and hence the transfer energy. This effect leads to the projectile loses initial structure of alpha clusters.
3. Energy independence is observed for charge distributions not only for production of projectile α-clusters but also for all possible fragments of ^{16}O projectile fragmentations.
4. The frequency distributions of all charges produced as projectile fragmentations are maximum for α-clusters and followed by Carbon, Beryllium, and Boron distributions as even–even nuclei. The minimum frequency is observed for Lithium and Nitrogen as odd nuclei. This behavior is considered as the experimental evidence for formation of α-clusters as the building block of construction of light atomic nuclei in its normal or ground state.

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