Relativistic $\alpha$ - particles distributions and correlations for the projectile ($^{12}$C, $^{16}$O, $^{22}$Ne and $^{28}$Si) fragmentations at Dubna energies (4.1-4.5) A GeV/c

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Abstract:
The relativistic $\alpha$-particles distributions and correlations of the projectile fragments resulting from the peripheral interactions of (4.5 A GeV/c) $^{12}$C, $^{16}$O, $^{28}$Si, and (4.1 A GeV/c) $^{22}$Ne projectiles with emulsion have been analyzed and modeled. The distributions of $\alpha$-particles, the associated-mesons, and the range of the transverse momentum have been obtained. It has been found that, the $\alpha$-particles distributions obey the logarithmic function, while the associated- mesons distributions obey Gauss function, and the distributions of the range of the $\alpha$-particles transverse moment shows decaying functions. The correlations between the $\alpha$-particles numbers and the (min, max) transverse momentum $P_T$ of $\alpha$-particles are also calculated. From this study we could predict that, the dissociation into $\alpha$-particles is preferably a cascade process; especially; for heavy projectiles.

Keywords: alpha-particles, fragmentation, spectator, participant, synchrophasatron, Dubna, emulsion, Nuclear, transverse-momentum, heavy ion collisions, Transverse momentum distribution, clusterization, quantum bound state.

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 studying mesons production[1, 2]. The physics of high energy heavy ion collisions attract strong attention of the physics community as the existence of alpha particles cluster and the cascade dissociation processes had founded sufficient evidences. Utilizing high-energy nuclear collisions, it is possible to study nuclear matter under conditions of very high temperatures and densities. The most common form of nuclear matter, at least under terrestrial conditions, is found in the atomic nucleus, which consists of protons and neutrons bound together by the strong nuclear force. If nuclear matter is heated up to temperatures comparable to the rest mass of the pion, it becomes a mixture of nucleons, pions, and various other particles, collectively denoted hadrons. Under these circumstances, nuclear matter is referred to as hadronic matter.

The distribution of the transverse-momentum $P_T$ of all $\alpha$ -fragments were shown to have a tail at large transverse momentum and a single Maxwell-Boltzmann (M-B) model is not sufficient to describe this behavior, but a superimposition of two M-B models with different mean $P_T$, and temperatures $kT$ are adequate . That is there may be a two systems of energetic $\alpha$ –fragments [3]. El-Naghy, et al. [4] had studied the distributions of the
range of transverse momentum of relativistic α -fragments resulting from the interactions in nuclear emulsion of four projectiles; $^{12}$C, $^{16}$O, $^{22}$Ne, and $^{28}$Si with emulsion at (4.1-4.5) A GeV/c. It has been found that the behavior of $P_T$ -distribution of the emitted α–fragments is independent of the types of projectiles and also independent of the energy of the projectile. The dissociation of $^{12}$C $\rightarrow$ 3α and $^{16}$O $\rightarrow$ 4α are verified in S. S. Abdel-Aziz 1999 [5]. The cascade process has a predominate role in the dissociation process and it is necessary to assume a cascade process of the dissociation $^{12}$C $\rightarrow$ 8Be $+$α and then $^8$Be $\rightarrow$ 2α ,also $^{16}$O $\rightarrow$ 2($^8$Be ) $\rightarrow$ 4α. S.S.Abdel aziz [6] studied, particle correlations for the multiparticle emitted in the interactions of $^{12}$C, $^{16}$O, $^{28}$Si (4.5 A GeV/c), and $^{22}$Ne (4.1 A GeV/c) projectiles with emulsion have been investigated in both of the pseudo rapidity interval and the azimuthal interval. The results are showed formation of hadronic or baryonic cluster which may reflect the sideward flow of nuclear matter.

In the present work The relativistic α-particles distributions and correlations of the projectile fragments resulting from the peripheral interactions of (4.5 A GeV/c) $^{12}$C, $^{16}$O, $^{28}$Si, and (4.1 A GeV/c) $^{22}$Ne projectiles with emulsion (Em) have been analyzed and modeled. The distributions of α-particles, the associated-mesons, and the range of the transverse momentum have been obtained. It has been found that, the α-particles distributions obey the logarithmic function, while the associated- mesons distributions obey Gauss function, and the distributions of the range of the α -particles transverse moment shows decaying functions. The correlations between the -particles numbers and (min, max) $P_T$ of α-particles are also calculated.

Section 2-Experimental Work:

Nuclear Emulsion has the highest (4π) spatial resolution compared with any other detector. Using the Emulsion technique not only the projectile fragments (PF) can be detected but also all the target fragments, which help in the analysis of the events [9]. Four stacks of NIKFI-Br-2 nuclear emulsion pellicles of dimensions 10 cm ×20 cm × 0.06 cm were exposed to $^{12}$C, $^{16}$O, $^{22}$Ne, and $^{28}$Si ion beams at an energy range (4.1-4.5) A GeV/c at the Synchrophasatron Dubna, USSR. The nucleus-nucleus (A-A) interactions have been widely studied using the emulsion technique. The nuclear emulsion, as a 4π detector is a convenient tool for detecting all the charged particles emitted in the whole space [10]. The emulsion presents the advantage of having a very high spatial resolution up to a fraction of microns corresponding to a fraction of almost 10-16 seconds. But, it has the disadvantage of being tedious and time consuming. The developed emulsions showed a sensitivity of 28 grains /100 microns for relativistic electrons and a shrinkage factor of about 2.1. Doubly charged projectile fragments were identified by using the gap density method. These fragments can be identified as a non –interacting charged particles with a velocity b 0.97 c and can be classified according to the grain density g = 4 with no change of ionization. These fragments appear as gray tracks producing particles emitted within 3o with respect to the direction of the incident forward cone and going at least two centimeters, without energy losses. The kinetic energy (T in MeV) of the doubly charged particles is in the energy range of (105< T <1600). Doubly charged projectile fragments (which consists of about 75% $^4$He and 25% $^3$He) were considered as being emitted with the same momentum per nucleon as that of their incident projectiles. The emission of about 90% of Z=2 projectile fragments at space angle ≤ 3o supports their momentum to
be equal to the incident value \( \sim (4.1-4.5) \text{ GeV/c/n} \) [11]. In nucleus-nucleus collisions, there is an additional group of particles, consists of fragments from the incident nucleus, called projectile fragments (PFs), with charge \( Z = 1, Z = 2 \) and \( Z > 3 \). The PFs having \( Z > 3 \) were identified by counting grain density and/or gap density, and by \( \delta \)-ray counting for tracks having no change in ionization along a length of at least 1 cm from the interaction vertex, as discussed in [7,8].

3 – Data Analysis:

3-1 Transverse momentum calculations:

In the present analysis, the momentum per nucleon of the incident Proton is \( P_L = 4500 \text{ MeV/c} \). Assuming that the momentum per nucleon of a projectile fragment after collision is \( P_o \), then the transverse momentum per nucleon of the \( i^{th} \) fragment \( P_i = P_o \tan \theta_i \) where \( \theta_i \) is the emission angle of the \( i^{th} \) fragment. The direction of the vector \( P_i \) is the azimuthal direction of this fragment. The reaction plane is the plane, which contains the directions of the incidence and the vector \( R_\mu \), which is given by the formula [12,13].

\[
R_\mu = \sum_{i=1}^{N_f} w_i M_i P_i, \quad \mu = 1, 2, 3, \ldots, N_f
\]

Where, \( w_i = \begin{cases} 0 & P_i > 240 \text{MeV/c} \\ 1 & P_i \leq 240 \text{MeV/c} \end{cases} \)

The coefficients \( w_i \) are introduced to exclude fragments of very large transverse momentum. The quantity \( M_i \) is given by \( M_i = \sum_k W_{i,k} A_{i,k} \), where \( A_{i,k} \) is the mass number of the \( k^{th} \) isotope and the \( i^{th} \) fragment and \( W_{i,k} \) is the corresponding fractional abundance of the isotope [12]. The projection of the transverse momentum \( (P_\mu) \) on the vector \( R_\mu \) is \( (P_\mu^*) \), and is given by:

\[
P_\mu^* = \bar{P}_\mu \cdot \bar{R}_\mu / |\bar{R}_\mu|, \quad \mu = 1, 2, \ldots, n_f
\]

The mean transverse momentum per nucleon projected onto the reaction plane \( <P^*_\mu> \), is obtained by averaging \( P^*_\mu \) over all fragments and over all the selected interactions (hadronic or baryonic).

3-2 The events selection criteria:

The relativistic \( \alpha \)-particles are identified within fragmentation events with characteristic criteria consistent with the physics of peripheral collision, and the projectile dissociation. The collision is peripheral if there is no heavy target fragments (\( ZZ = N_{bf} + N_{gf} = 0 \)), and the relativistic heavy ions exist (\( N_{gf} > 0 \)) with, at least, two projectile heavy ions fragments must coexist (\( N_{pf} = N_{gf} + N_{bf} > 1 \)). The fragments within the forward cone are due to projectile fragmentation (\( \theta < 3^\circ \)). The charge of the selected fragments is two (\( Z = 2 \)). The mesons are counted as the shower fragments with the azimuthal angles greater than the
cut angle $\theta_{cut} = 3^\circ$. The transverse momentum technique is used to investigate cascade fragmentation. The minimum and the maximum values of $P_T$ for $\alpha$-particles in each event are obtained and the range $\Delta P_T = \max(P_T) - \min(P_T)$ is calculated per event. The numbers of $\alpha$-fragments $N_\alpha$, shower particles $N_S$, mesons $N_{meson}$ and gray fragments $N_{GF}$ per event are registered. The $\Delta P_T$-distribution for each projectile $\alpha$-fragments is obtained with 25 GeV, and 100 GeV bins. The modeling of the two distributions are carried out for each projectile and found to be related. The periodicity investigation for bin-width = 25 GeV is executed by fast Fourier transform FFT. The distributions of $\min(P_T)$, $N_S$, $N_{meson}$, $N_{GF}$, $N_\alpha$ are calculated and modeled. The correlations between these quantities are investigated and the most significant are plotted.

4 – The Model:
Peripheral heavy ion collisions follow through three main stages. The first stage is the formation of one participant and two spectators. The second stage is the dissociation of the cluster and sub clusters systems, which are stable or excited. The excited spectators may be formed and subsequently decayed into more stable fragments, in the third stage. The bions, the Kaons and other mesons are essentially coming from the participant. The long-lived quantum bound-states of $\alpha$-particles predominate the other types of bound-states fragments, because the $\alpha$-particles are the most stable fragments [14, 15], and the subsequent decays of the pre-excited quantum states in the projectile participant is the main source of relativistic $\alpha$-particles.

5 – Results and Discussions:
The investigation of shower particle distributions reveals the Gaussian nature [16]. Fig. 1 shows the distributions of shower particles and the included mesons for the selected events concerning each of the four projectiles (4.5 A GeV/c) $^{12}$C, $^{16}$O, $^{28}$Si, and (4.1 A GeV/c) $^{22}$Ne. The distributions are modeled by a gauss-functions. The central-averages of mesons per event cover from 2.4 up to 5.8 mesons/event, while for the shower particles the covering is from 1.5 to 3.1 shower-particles/event with a wider peaks for mesons-distributions. That is the source of mesons must be very hot, and unstable [3].

Fig. 2 presents the distributions of $\alpha$-particles and the gray-fragments. The two distributions are similar for light and intermediate projectiles, and the exception is observed for heavy nuclei $^{28}$Si. These reveal the common source of the gray-fragments and $\alpha$-particles, which is mainly the projectile spectator for light and intermediate nuclei. The logarithmic distribution function as well as the power-laws distributions are signatures of decays of quantum bound states [9, 13].

The transverse momentum technique is used to investigate the distributions of the ranges of $P_T$, and $\min(P_T)$ as well as the correlation between $\min(P_T)$ and $\max(P_T)$. The distributions and their modeling are given in figs. 3,4.
Fig. 1: The shower-particles and meson distributions for the selected events for each of the projectiles $^{12}$C, $^{16}$O, $^{22}$Ne, and $^{28}$Si.
Fig. 2: The α- and gray- particles distributions of the selected events for the projectiles $^{12}$C, $^{16}$O, $^{22}$Ne, and $^{28}$Si.
Fig. 3: The $\Delta P_T$ distributions for each projectile. The first column is bind with bin width of 25 GeV/c, and the second column is of bin-width = 100 GeV/c. The FFT algorithm is applied on the 25 GeV/c histograms.
Fig. 4: The distribution of $\Delta P_{T,\alpha}$ and the correlation between min($P_{T,\alpha}$) and max($P_{T,\alpha}$), for the projectiles $^{12}$C, $^{16}$O, $^{22}$Ne, and $^{28}$Si.
Fig. 3 is the modeling of $\Delta P_T - \alpha$ histograms of two binning system with bin-width =25 GeV/c in the right column, and 100 GeV/c in the left column of the figure. The model is investigated for 100 GeV/c bin-width, and then used for the 25 GeV/c with added periodic functions to estimate the period of fluctuations. The periods in units of GeV/c are deduced by the application of fast Fourier transform FFT numeric algorithm to $\Delta P_T - \alpha$ histograms at bin-width = 25 GeV/c. Except for $^{12}\text{C}$ –projectile $\alpha$-fragments - where the statistics is insufficient, and zero bins are presented – this method predicts a quasi periods with periods and their error ranges appear in the figure. The quasi periods are signature of cascade productions of $\alpha$-particles. This argument is confirmed by comparison between $\Delta P_T - \alpha$ and number of $\alpha$-particles in each event as shown in fig. 5.

The distribution of min($P_T - \alpha$) in fig. 4 is found to be Gaussian with widths parameter $w$ of 240 GeV/c for light projectiles $^{12}\text{C}$, $^{16}\text{O}$, and $w$ of 104.2, 129.7 GeV/c for intermediate and heavy projectiles. The $\alpha$-particles coming from the decays of quantum bound-states show more uncertainty in positions of their bound-state source inside the excited projectile participant for heavy nuclei. This is known as a multi-source production of $\alpha$-fragmentation [17]. The subsequent decays in cascade processes have unpredictable angels with respect to the transverse plane. This randomness results in Gaussian form of the distribution of min($P_T - \alpha$). The correlation between min($P_T - \alpha$), max($P_T - \alpha$) is weak in general, but the diagonal-line represents the events which posses only one $\alpha$-fragment increases the correlation factors. The most events are concentrated for low values of min($P_T - \alpha$), max($P_T - \alpha$). This is another confirmation that is, most events having relativistic $\alpha$-fragments due to decays of bounded quantum states.

Fig. 5: The scattering-plot illustrate the relation between $N_\alpha$ and $\Delta P_T - \alpha$, for the projectiles $^{12}\text{C}$, $^{16}\text{O}$, $^{22}\text{Ne}$, and $^{28}\text{Si}$.

The classification of $\Delta P_T - \alpha$ by the $N_\alpha$ is illustrated in the scattering-plot fig. 5. The small number appearing over the sticks are the frequency of occurring of a specified number of $\alpha$-particles over all the collision events. It has been found that the dissociation of two $\alpha$-particles is the most frequent and probable. The gaps in $\Delta P_T - \alpha$ are forbidden values of the resultant $P_T$ of $\alpha$-particles coming from decays of bound quantum states.
living in the projectile participant. The horizontal addition of sticks will result in $\Delta P_{T\alpha}$-distributions in fig. 3.

Fig. 6: The scattering-plot illustrate the relation between $N_\alpha$ and $N_{\text{meson}}$, for the projectiles $^{12}\text{C}$, $^{16}\text{O}$, $^{22}\text{Ne}$, and $^{28}\text{Si}$.

Fig. 6. Represents the classification of $N_{\text{meson}}$ by the numbers $N_\alpha$. The decrease in the number of mesons with the increasing of $\alpha$-particles per event is due to the increase of the impact-parameters and the expected smaller size of participant. The gaps in the classes of $N_{\text{meson}}$, if are not due to insufficient statistics, it should be reasoned to the absorption of mesons by bound quantum-states included in the participants.

6– Conclusion:
The observed periodicity in $\Delta P_{T\alpha}$ is a result of cascade decays of existence of $\alpha$-clusters in spectators of the projectile nuclei. The $\alpha$-clusterization is a self-organizing process in the spectators. The $\alpha$-clusters are bound-quantum states living and may be excited by meson absorption inside the spectator.

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