MECHANISMS OF α-PARTICLE PRODUCTION IN THE ^{16}Op COLLISIONS AT 3.25A GeV/s

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New experimental data on the kinematic characteristics of α-particles produced in the interactions of relativistic oxygen nuclei with protons are presented. It is shown that the statistical model of Goldhaber is not able to describe the momentum characteristics of light fragments and that the role of the evaporation mechanism can be neglected. The indication is obtained that a certain part of excited systems can execute a full 2π rotation before fragmentation.

Introduction

The nuclear fragmentation process has been discussed for a long time [1—3]. However, detailed studies have begun relatively recently when the heavy ion accelerators were put into operation in 1970s. Interesting results on the production of various types of fragments were obtained from the so-called "O-experiments" dedicated to the study of peculiarities of disintegration of colliding nuclei. In particular, it was found that, in a wide range of the masses and energies of colliding nuclei, the fragments production cross-section can be presented with a good accuracy in the form $\sigma_{pt}^f = \gamma_p^f \gamma_t$, where γ_p^f and γ_t are factors depending on the projectile and target characteristics, respectively [4].

An overall description of these experiments has been obtained within various versions of the statistical model of fragmentation [6—8]. However, further studies carried out in a 4π-geometry have shown that electron experiments in which the detection of secondary particles was limited by a narrow solid angle do not allow one to obtain sufficiently detailed information on fragmentation process [9—11].

The results obtained in the last years show that nuclear disintegration is a rather complex process having a multistep character. It is found from experiment that the structure of the observed fragments is significantly influenced by the α-cluster structure of the fragmenting nucleus [12]; theoretical calculations based on the statistical mechanism of fragmentation were not able to describe qualitatively the bulk of data.

An effective way to study nuclear fragmentation requires the detection of all light fragments (p, d, t, ^{3}He, and ^{4}He) in a 4π geometry because the cross-section of the yield of light particles is comparable to the total cross-section of the reaction. Formation of light fragments is typical of the nuclei fragmentation process. Secondly, it is well established that the majority of these fragments is emitted within the first stage of interaction of the colliding nuclei providing direct information on the dynamics of the interaction, which is not clearly understood till now [13].

During the fragmentation of light nuclei, the twice charged fragments have the highest yield of all multicharged fragments. The majority of them consists of ^{4}He nuclei [12]. At present time, several possible mechanisms of α-particle formation are known. Some of them are: Fermi break-up (statistical) mechanism, decay of intermediate non-stable nuclei (^{5}He, ^{5}Li, ^{8}Be, ^{9}B and others), and mechanisms of fusion or nucleon association. However, this variety of mechanisms is not studied completely.

In this work, an attempt is made to obtain information on possibles mechanisms α-particle formation in the ^{16}Op collisions at 3.25A GeV/s. Experimental data are compared with the calculation results from the Cascade-Fragmentation Evaporation Model (CFEM) [14]. The data are also compared with the predictions of the statistical model of Goldhaber [7] and with the calculations from the coalescence model [15].

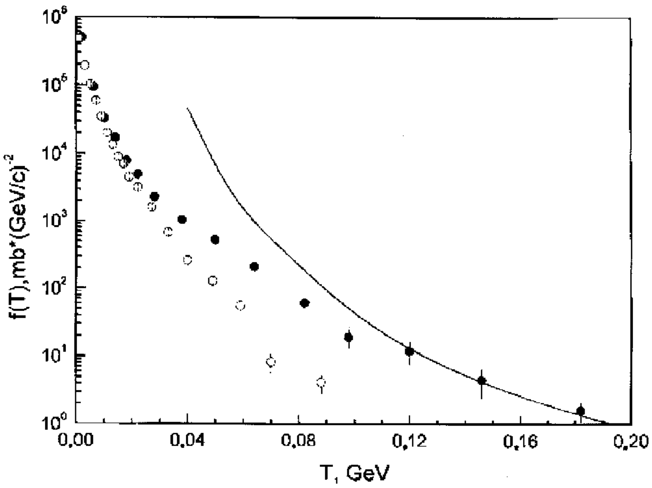

Fig. 1. The invariant differential cross-section of α-particles as a function of the kinetic energy T. Points: $\circ$ — CFEM, $\bullet$ — experiment, curve — calculations by the coalescence model [15]

1. Experimental Data

The experimental data were obtained using stereograms taken from a one-meter Hydrogen Bubble Chamber (HBC) HEL JINR irradiated at the synchrophasotron by ^{16}O nuclei with a momentum of 3.25A GeV/s. 11089 ^{16}Op events were analyzed. The conditions of experiment allow us to identify visually the precise charge of every secondary particle and fragment. At the track length of a light fragment in the working volume of the camera of $L \geq 35$ cm long, the average relative error in the momentum measurement was no more than 3.5%. This allowed us to perform mass separation for light fragments with the charge $Z \leq 4$. The twice charged fragments with momenta of $10.8 < P < 15.5$ GeV/s were related to α-particles. The analysis of the momentum distribution of fragments with $Z \geq 5$ made it possible to determine the yields of some isotopes.

Mass separation of fragments was carried out using the measured values of momentum and charge [12]. We have selected the tracks with length $L \geq 35$ cm, which is required for better mass separation and reliable analysis of kinematic characteristics of fragments.

In the following analysis, the energy and angular distributions of α-particles are translated into the anti-laboratory system, i.e. to the rest system of oxygen.

2. Experimental Results and their Analysis

2.1. Invariant Structure Function

In Fig.1, we present the invariant structure function $f(T) = E\frac{d^3\sigma}{dp^3}$ as a function of the kinetic energy T of α-particles. Experimental data, CFEM calculations from code [14] and coalescence model calculations based on [15] are shown by closed circles, open circles, and solid line, respectively.

The contribution of evaporative processes to the fragment formation cross-section in CFEM is negligibly small because ^{16}O is a light nucleus. Therefore, when simulating the ^{16}Op collisions (in our case), the contribution of the evaporation mechanism is not taken into account. Fermi break-up is considered as the basic mechanism for the formation of fragment. In the model, the secondary break-up of non-stable nuclei by the channels ^{5}He $\to$ α+n, ^{5}Li $\to$ α+p , ^{8}Be $\to$ 2α, and ^{9}Be $\to$ 2α+p is also taken into account. Although the CFEM can well describe the multiplicities of the twice charged fragments, it is not capable of reproducing their isotope composition [12]; the average number of α-particles $\langle n_\alpha \rangle$ occurred to be 0.50 ± 0.01 in experiment and 0.36 ± 0.01 in the CFEM model. Therefore, for the quantitative comparison of the studied properties of α-particles in the experiment and model, the CFEM spectra have been normalized by the experimental spectra.

As one can see from Fig.1, experimental spectrum sharply decreases with energy up to $T \approx 10$ MeV. Then its slope reduces and, starting from $T \approx 80$ MeV, the T-distribution attains an exponential form. The CFEM calculations in the region of $T < 15$ MeV reproduce the experimental spectrum within statistical errors. As was shown in [12], the model significantly overestimates the yield of protons in this region. This occurs because the CFEM does not take into account the contribution of the evaporation mechanism of light fragments formation. From the agreement observed in our case, we conclude that the contribution of the evaporation mechanism to α-particle production is negligibly small. In the region of $T > 15$ MeV, the deviation between calculations and experiment increases with the kinetic energy of α-particles. Theoretical spectrum ends at $T \approx 100$ MeV, whereas the experimental distribution spreads to $T \approx 200$ MeV. Such a sharp difference between experiment and CFEM calculations is, apparently, related to the fact that CFEM does not take into account the α-cluster structure of light nuclei, as well as the pick-up and coalescence mechanisms.

According to the coalescence model, the cross section of fragments with mass number A is given in terms of the protons yield cross-section as follows:

$$E_A\frac{d^3\sigma_A}{dp_A^3}=C_A\Big(\frac{d^3\sigma_A}{dp_A^3}\Big)^A, \quad (1)$$

where the difference between proton and neutron spectra is neglected. Here, $p_A = Ap_p$, C_A is the coalescence probability weakly depending on the target mass and not depending on the energy of a projectile and emission angle of a fragment [16].

The solid line in Fig.1 was calculated according to Eq. (1) using the experimental proton spectrum. The coefficient C_A is obtained in the region of $T \geq 120$ MeV by approximation by the least square method. The nucleon momenta corresponding to this region of T are higher than 235 MeV/s. One can see that the α-spectrum in this region is in a good agreement with the coalescence model predictions. This provides an evidence for that the nucleon evaporation processes do not contribute to the formation of relatively fast α-particles.

2.2. Transverse Momentum

The α-particle distributions over the transverse momentum are presented in Fig.2. Closed circles represent experimental data, open circles show the CFEM prediction, and the solid line shows the fitting of experimental data by the expression

$$F(p_T)=Ap_T\exp(-bp_T^2). \quad (2)$$

where $A = 27.81\pm1.19$, $b = 31.02\pm1.37$ and $\chi^2/f.d.n. = 17.56$. This expression can be derived from the statistical fragmentation model of Goldhaber [7]. From Fig.2, one can see that the experimental distribution has a wide maximum at $p_T \approx 0.12$GeV/s, which can be fitted by Eq.(2) up to $p_T \approx 0.3$GeV/s. Starting from $p_T \approx 0.5$GeV/s, the experimental distribution acquires an exponential form (shown in Fig.2 as a straight line) with a slope parameter of (5.5 ± 0.5) (GeV/s)$^{-1}$. This form of the p_T distribution is caused by non-statistical character of the corresponding formation of fragments. The average value of the transverse momentum of α-particles obtained in our experiment is (192 ± 2) MeV/s. Within statistical errors, the CFEM calculation gives the same value. In spite of this, as seen from Fig.2, CFEM can only qualitatively describe experimental data: at $p_T < 150$ MeV/s and $p_T > 550$ MeV/s, the model underestimates experimental data, whereas, in the region of $p_T = 150 \div 500$ MeV/s, it overestimates the experimental data. It is also seen from Fig.2 that the

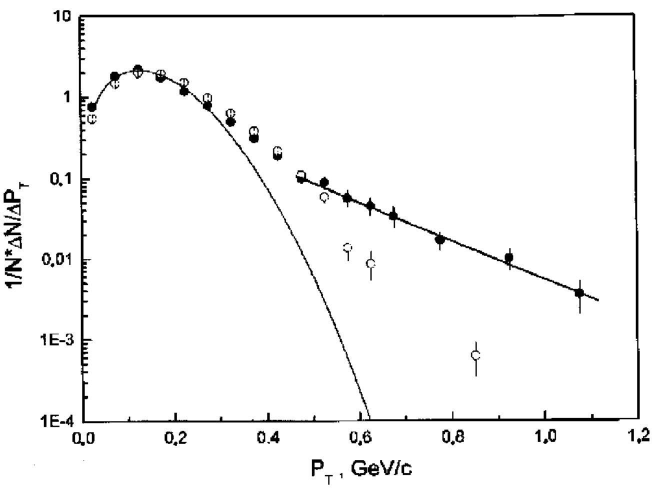

Fig. 2. α-particle distribution over the transverse momentum p_T. Points: $\circ$ — CFEM, $\bullet$ — experiment, curve — calculations by the Goldhaber model [7], solid line — exponential fit in the region of $p_T > 0.5$ GeV/s

Goldhaber model reasonably describes the p_T distribution at $p_T < 0.3$ GeV/s only, and that it significantly deviates from the experimental points at higher values of p_T.

As shown in [17], the longitudinal momentum distribution for fragments with charges $Z = 2 \div 7$ produced in the OBe collisions at the energy of 2.1 GeV/nucleon is well described by Eq.(2) introduced in [7]. Apparently, this agreement is related to a limited range of emission angles ($\theta < 12.5$ mrad), covering mainly the formed fragments of statistical origin. Deviations of the Goldhaber model [7] predictions from our experimental data indicate that a contribution of non-statistical mechanisms to the α-particle formation at $p_T > 0.3$ GeV/s is important. These fragments can be formed, as mentioned above, in the decays of various non-stable intermediate nuclei, having different excitation energies and being produced with different cross sections. Besides, as was shown before, the coalescence mechanism [15] can contribute to the cross section of relatively fast α-particles with $T > 120$ MeV.

It is also interesting to study the dependence of the average transverse momentum of α-particles on the excitation energy of the fragmenting nucleus. In our experiment, different topologic channels can be considered as the measure of excitation energy. Fig.3 represents the dependence of $\langle p_T\rangle$ on the α-particle production in different topologic channels: closed circles present experimental data, open circles are CFEM predictions. One can see that the maximal value of $\langle p_T\rangle$

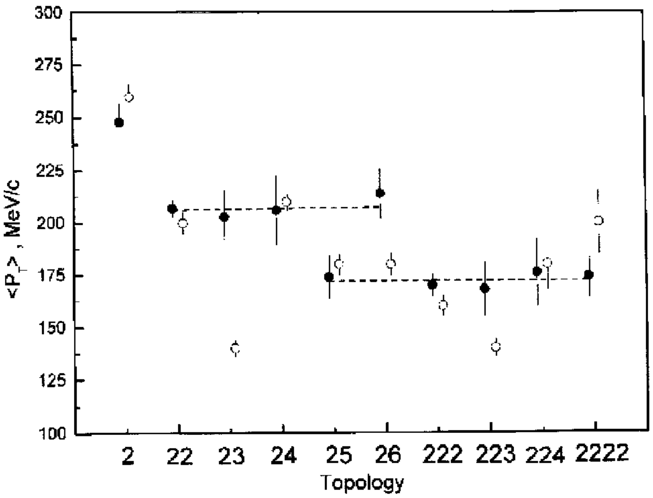

Fig. 3. Dependence of the average value of the transverse momentum of α-particles on the topology. Points: ∘ — CFEM, • — experiment

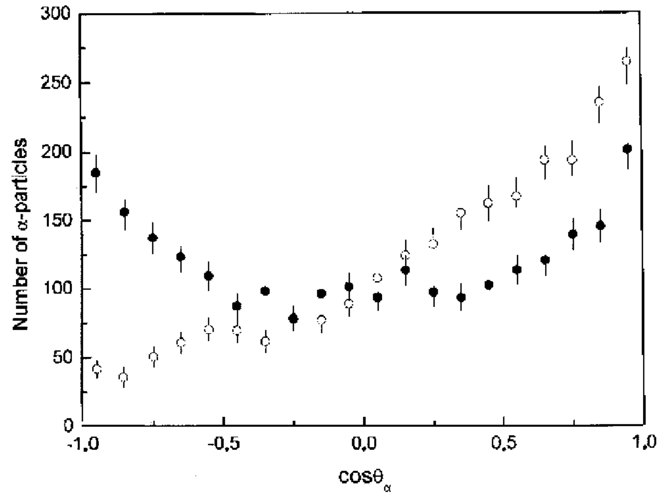

Fig.4. Distribution of α-particles with $T < 10$ MeV over the cosine of the emission angle. Points: ∘ — CFEM, • — experiment

is observed, both experimentally and in the model, in the topology channel with one α-particle production (2). In Fig.3, topology channels are divided into two groups by the average value of the transverse momentum within statistical deviations. The first group consists of (22), (23), (24), and (26) channels (the numbers in the brackets denote the charge composition of the fragment). The second group includes (25), (222), (223), (224), and (2222) channels. The dashed lines in Fig.3 represent the average values of the transverse momentum for each group separately. Although the topology (26) has a lower energy threshold than that in (22), (23) and (24) channels, the $\langle p_T \rangle$ values are the same in all four topologies. As the analysis in [12] showed, the break-up of the relativistic oxygen nuclei in channel (26) takes place mainly by quasi-elastic knock-out of α-particles by a proton of the target. A large discrepancy between the CFEM and our experiment is observed for lithium and carbon yields. The lowest values of $\langle p_T \rangle$ predicted by CFEM are observed in (23) and (223) channels.

2.3. Angular Distribution of Slow α-particles ($T < 10$ MeV/s)

It is known that the angular distributions of fragments with energies less than 10 MeV per nucleon according to the statistical theory of fragmentation must be isotropic so that the corresponding cosine distributions are uniform.

In [12], the p, d, t and ^{3}He emission at $T < 10$ MeV/nucleon in the collisions of ^{16}O with proton at a momentum of $3.25A$ GeV/s is revealed to be symmetric with respect to 90° angular distributions with noticable maxima in the forward and backward directions. This observation was interpreted as the evidence for that the angular momentum of the excited fragmenting system may differ from zero. For a more convincing proof of this phenomenon, we present the angular distribution of α-particles at significantly smaller energies, namely at $T < 2.5$ MeV/nucleon, in Fig.4.

One can see from Fig.4 that the experimental data (closed circles) are symmetric with respect to $\theta = 90°$, whereas the CFEM angular distribution (open circles) shows a maximum in the forward direction; average values of $\cos\theta_\alpha$ are 0.01 ± 0.01 and 0.31 ± 0.01 in the experiment and CFEM, respectively. Although the average value of the experimental $\cos\theta_\alpha$ within statistical errors is zero, the distribution exhibits the peaks at $\cos\theta_\alpha = \pm 1$, which may be a sign that the system can gain non-zero angular momentum before the fragmentation stage. The effect increases with the transition from light to heavy fragments. For example, the fraction of protons and α-particles with $\cos\theta < -0.7$ and $T < 10$ MeV/nucleon was found to be equal to 0.14 ± 0.01 and 0.22 ± 0.01, respectively.

Conclusion

The analysis of the kinematic characteristics of α-particles produced in the ^{16}Op collisions at 3.25 A GeV/s was carried out. As was expected, the majority of α-particles is produced due to the Fermi break-up statistical mechanism, whereas the evaporation mechanism contribution is negligibly small. The role of the coalescence effects is well manifested in the region of large kinetic energies and transverse momenta. The observed α-particle angular distribution is symmetric with respect to 90° and exhibits the maxima in the forward and backward directions which at low energy would be interpreted as a sign for the formation of a rapidly rotating compound system. In our case of relativistic collision energies, these pecularities of angular distributions indicate that a system formed at the beginning of the fragmentation process may execute a full 2π-rotation; the angular anisotropy increases with the transition from light to heavy fragments, proving our earlier results on p, d, t and ^{3}He yields [12]. To shed more light on the production of fragmenting nuclei with non-zero angular momentum, it is necessary to carry out studies of various interaction characteristics in the azimuthal plane.

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Received 27.12.02

МЕХАНІЗМИ НАРОДЖЕННЯ α-ЧАСТИНКИ В (^{16}Op)-СПІВУДАРАХ ПРИ ІМПУЛЬСІ 3,25 A ГеВ/с

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Р е з ю м е

Наведено нові експериментальні дані з кінематичних характеристик α-частинок, утворених в результаті взаємодій релятивістських ядер кисню з протонами. Показано, що статистична модель Гольдхабера не може описати імпульсні характеристики легких фрагментів і що випарним механізмом можна знехтувати. Отримано дані про те, що певна частина збуджених систем може повертатися на кут 2π перед фрагментацією.

МЕХАНИЗМЫ РОЖДЕНИЯ α-ЧАСТИЦЫ В (^{16}Op)-СОУДАРЕНИЯХ ПРИ ИМПУЛЬСЕ 3,25 A ГэВ/с

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Р е з ю м е

Представлены новые экспериментальные данные по кинематическим характеристикам α-частиц, образованных в результате взаимодействий релятивистских ядер кислорода с протонами. Показано, что статистическая модель Гольдхабера не может описать импульсные характеристики легких фрагментов и что испарительным механизмом можно пренебречь. Получены данные свидетельствующие, что определенная часть возбужденных систем может поворачиваться на угол 2π перед фрагментацией.