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The study of light nuclei production in different interactions at 4.2 AGeV/c

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Abstract

Average multiplicity of light nuclei, produced in different interactions at 4.2A GeV/c is studied as a function of centrality. A change in multiplicity is observed with increase in the mass of projectile. In ^{12}CC -interactions an unexpected increase in the multiplicity is seen in the most central events. These measurements are compared with the predictions of Cascade and Fritiof models, which fail to account for the experimentally observed effects. In case of ^{12}CC , it is suggested that the inclusion of nuclear coalescence effect can be an explanatory reason for the deviation of experimental measurements from the models' predictions.

Keywords: Collisions, Centrality, Coalescence, Interactions, Fragments

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Introduction

In heavy ion collisions, light nuclei are produced mainly from the disintegration of projectile and target nuclei. However, nuclei are believed to be formed in final state interactions between nucleons as a result of coalescence, when they are in same phase space [1]. Considering the momentum space, the probability density of nuclei formation of mass number (A) is proportional to the A^{th} power of proton density [2-4]. A quantitative description of this process is typically based on the proportionality parameter B_A known as coalescence parameter, which depends upon the transverse mass of cluster and does not depend upon the centrality of the collisions [5]. The fragments of the projectile and target decrease with the centrality of the collisions [6]. In the

most central events the production of Deuterons and Tritons from target spectator area is suppressed [7]. At maximum centrality, the nuclei from either mechanism (fragmentation or coalescence) decrease exponentially with the mass number (A) of producing nuclei [8]. So the study of the centrality dependent properties of light nuclei production can give essential information about the initial and final states of collisions and the production mechanisms. In this paper the average multiplicity of light nuclei produced in Proton-Carbon (pC), Deuteron-Carbon (dC), Helium-Carbon (HeC) and Carbon-Carbon (^{12}CC)-interactions at 4.2 A GeV/c is studied as a function of centrality. The centrality is defined by the number of identifying protons (N_p) in an event [9-11]. This study provides significant information about the behavior and production mechanisms of light nuclei.

Experiment and Method

The data were recorded with the 2m Propane Bubble Chamber [13], installed at the Laboratory of High Energy of the Joint Institute for Nuclear Research (JINR), Dubna, Russia. The chamber was placed in a 1.5 T magnetic field, and irradiated with the beams of relativistic Protons (p), Deuteron (d), Helium (He) and Carbon nuclei (^{12}C) with Propane (C_3H_8) as target. Almost all charged particles emitted at 4π , provided they exceed the threshold value of the energy required for visible track formation were detected well in the chamber.

In total, we analyzed 12757 (twelve thousands seven hundred and fifty-seven) events of pC_3H_8 , 9016 (nine thousands and sixteen) of $d C_3H_8$, 22975 (twenty-two thousands nine hundred and seventy-five) of HeC_3H_8 and 39543 (thirty-nine thousands five hundred and forty-three) of $^{12}C C_3H_8$. The interactions with Carbon nuclei were selected from all interactions of beams with Propane (C_3H_8), using criteria based on the determination of total charge of secondaries, presence of slow Protons (with momentum $P < 0.75$ GeV/c), Protons in backward hemisphere and negatively charged particles etc. as described in Refs. [14,15]. This criterion is not used for pC interaction because light nuclei cannot be produced in pp (Proton-Hydrogen) interaction.

Particles were identified by their tracks, which they left in the chamber and their momentum was calculated by the curvature of these tracks and the magnetic field of the chamber. The uncertainty in the measurement of momentum was about 11% and in measurement of emission angle θ , was about 0.8% [16,17].

Every particle required a least amount of momentum to produce a visible track particular to its mass. The average momentum for Pion registration was set to about 70 MeV/c, below this momentum Pion cannot produce visible tracks. All negative particles, except for those identified as electron were considered as π^- mesons. The contamination from the misidentified electrons and negative strange particles were about 5% and 1% respectively. The π^+ mesons were identified and differentiated well from Protons by the ionization produced in the chamber in momentum region less than 0.5 GeV/c. Above this momentum π^+ mesons were mixed with Protons except a few which were recognized as π^+ mesons. The lowest momentum required for the track formation of Proton, singly charged nuclei and multi charged nuclei was about 0.15 GeV/c, 0.75 GeV/c and 0.185 GeV/c respectively. The corrections to account for losses of particles were introduced by the weights defined by the Collaboration of 2m propane bubble chamber [13] for each particle. The protons were identified finely within the momentum interval 0.15-0.5 GeV/c beyond this momentum Protons were contaminated with π^+ mesons. The nuclei were detected in two groups singly charged and multi-charged nuclei. The singly charged nuclei Deuteron (d) and Triton (t) were identified as a mixture and differentiated well from other singly charged positive particles in the momentum interval 1-3 GeV/c, for the momentum greater than this value and emission angle θ less than 4° Deuteron and Triton could not be separated from stripping Protons. The multi-charged nuclei with charge $Z \geq 2$ were identified together. There was no possibility to identify the nuclei species separately because they produce about similar ionization in the bubble chamber. In this manuscript, all identified nuclei (singly or multi-charged) in an event were considered as light nuclei. The centrality of the collisions was defined by the number of identified Protons (N_p) in an event, and identified Protons (N_p) was calculated as;

$$N_p = \text{Protons (with any momentum)} + \pi^+ \text{ mesons (with momentum } > 0.5 \text{ GeV/c)} - \pi^- \text{ mesons (with momentum } > 0.5 \text{ GeV/c)} - \text{Protons (with momentum } > 3 \text{ GeV/c and emission angle } \theta \text{ less than } 4^\circ).$$

As mentioned above that several π^+ mesons with momentum greater than 0.5 GeV/c were identified as Protons, whereas π^- mesons were identified very well. To address the contamination of π^+ mesons with Protons, it was assumed that an equal number of π^- and π^+ mesons were

produced because the projectile (except proton) and target nuclei are Isospin singlet, that is why the π^- mesons (with momentum > 0.5 GeV/c) were subtracted from Protons. To deal with the contamination of d and t , the Protons with momentum greater than 3Gev/c and emission angle θ less than 4° were excluded (subtracted from Protons) also in defining N_p .

To observe the coalescence mechanism we used the simple idea of baryon number conservation and centrality. As the number of identified Protons in an event was used to fix the centrality of the collision, therefore an increase in the number of Protons (Increasing centrality) in an event will result in a decrease in the number of nuclei (multiplicity of nuclei) to conserve the baryon numbers. So the study of multiplicity of light nuclei as a function of centrality can give some direct information about the production mechanism of nuclei in these collisions.

The experimental results were compared with the predictions of two theoretical models, Cascade [18 Sec.3.1] and Fritiof [18 Sec.3.2]. These codes are available on the website: <http://hepweb.jinr.ru> (created by V.V. Uzhinskii). Cascade model is used to describe the general features of relativistic nucleus-nucleus collisions. This model does not include any medium or collective properties and each of the colliding nuclei is treated as a gas of nucleons bound in a potential well. The Pauli principle and the energy momentum conservation are obeyed in each inter-nuclear interaction. The remaining excited nuclei, after the cascade stage, are described by the statistical theory in the evaporation approximation. Fritiof is a famous Monte-Carlo code which assumes all Hadron-Hadron interactions as binary reactions ($h_1+h_2 \rightarrow h'_1+h'_2$), where $h'_1+h'_2$ are excited states of hadrons with discrete or continuous mass spectra. The excited hadrons are treated as QCD strings, and the corresponding Lund-string fragmentation model is applied in order to simulate their decays. The evaporation of residue nucleus is taken into account also. A similar approach is applied to simulate nucleus-nucleus collision, where successive interactions of projectile hadrons with target are considered. Unlike Cascade model, Fritiof code uses the approach, which gives zero excitation energy to residual nucleus when all spectator nucleon are ejected. The Cascade results can be reproduced by Fritiof model by changing limits of energy and distance between the nucleons. The Fritiof code has been modified [19] for lower energies and we used the modified version of this code. Both Models include nuclear fragments from projectile and target, but do not include the possibility of nuclei formation as a result of coalescence of nucleons. In both, the Cascade and the Fritiof codes 40,000 (forty thousands)

events of each interaction (pC dC , HeC and ^{12}CC) were analyzed, using the same criteria of event selection and particle identification as used for experimental data.

Results and Discussions

The average multiplicity of the light nuclei ($\langle N \rangle_{\text{nuclei}}$) in pC -interactions at 4.2A GeV/c as a function of centrality is presented in Figure 1, which includes statistical uncertainties only. The measurements are compared with the predictions of two models, Cascade and Fritiof. Experimental results for average multiplicity are almost constant in pC -interactions. In these interactions the observed light nuclei are Deuterons (d) and Tritons (t) only, which are the fragments of target nuclei (Carbon). More nuclei are identified in events with $N_p \geq 4$ and can be concluded that the target fragments evaporated in these events are recorded relatively well. The Fritiof model describes the qualitative behavior of experimental data very well but overestimates the average multiplicity. The Cascade model is incapable to illustrate the qualitative or quantitative behavior of the experimental data.

Figure 1. Average multiplicity of light nuclei as function of centrality (N_p) in pC - interactions. Stars, solid circles and open circles represent Cascade (CAS), Fritiof (FRI) and data (EXP) respectively.

The average multiplicity of the light nuclei ($\langle N \rangle_{\text{nuclei}}$) produced in dC -interactions at 4.2A GeV/c as a function of centrality is presented in Figure 2. Only statistical errors are included in the Figure 2. Now the projectile is itself a nucleus (Deuteron) and the total energy of the collision is double of the above interaction (pC -interactions), which increases the average multiplicity of light nuclei about 10 times greater than the multiplicity in pC -interactions. Like pC -interactions, the observed light nuclei in dC -interactions are Deuterons and Tritons only. The experimental results are almost constant except at the first point ($N_p=0$), where the average multiplicity is maximized, which shows the contribution from the projectile. The Fritiof model predictions are still deviating from the experimental results but lower as compared to the pC -interactions and the Cascade code is again unable to describe the experimental results.

Figure 2. Average multiplicity of light nuclei as function of centrality (N_p) in dC - interactions. Stars, solid circles and open circles represent Cascade (CAS), Fritiof (FRI) and data (EXP) respectively.

The average multiplicity of the light nuclei ($\langle N \rangle_{\text{nuclei}}$) produced in HeC -interactions at 4.2A GeV/c as a function of centrality is shown in Figure 3. Only statistical errors are considered in Figure 3. Unlike the above-mentioned interactions, the experimental data (HeC -interactions)

contains both singly charged (d , t) and multi charged ($z \geq 2$) nuclei. The Average multiplicity decreases sharply in the region ($0 \leq N_p \leq 4$) as compared to the region ($N_p > 4$). Both models reproduce the data, which diverge from the experimental results in the region ($2 \leq N_p \leq 7$), however the divergence is small as compared to the interactions discussed above. In HeC -interactions the mass and energy of the projectile is double of the dC -interaction, which increases the average multiplicity about 10 times to dC -interactions. Keeping in view the above Figures 1 and 2, the first region ($N_p < 4$) of Figure 3 can be considered as a projectile fragmenting region, whereas the second one ($N_p > 4$) is as target fragmenting region. The projectile fragmenting region is more sensitive for centrality than the target fragmenting region, which has almost constant behavior as can be seen from Figures (1-3).

Figure 3. Average multiplicity of light nuclei as function of centrality (N_p) in HeC -interactions. Stars, solid circles and open circles represent Cascade (CAS), Fritiof (FRI) and data (EXP) respectively.

The average multiplicity of the light nuclei ($\langle N \rangle_{\text{nuclei}}$) in ^{12}CC -interactions at 4.2A GeV/c as a function of centrality is presented in Figure 4, statistical uncertainties are incorporated only. Now the projectile mass and energy is much greater than the above interactions, which results in an increase in multiplicity and better identification of light nuclei. These light nuclei contain both

the singly charged (d , t) and multi charged ($z \geq 2$) nuclei. Experimental results are described qualitatively by dividing them into different regions as shown in Figure 4. The measurements are compared with the models' predictions also. Both the models underestimate the average multiplicity in the region ($N_p \leq 2$) by a small amount. In experimental data maximum number of light nuclei is found in peripheral collisions ($N_p \leq 2$) where the impact parameter is large. In this region the experimental data measures the average multiplicity about 1.17 times to Cascade and about 1.45 times to Fritiof model. As the impact parameter decreases and collisions become more central ($N_p \leq 7$) the projectile starts to fragment into hadrons rather than light nuclei so the average multiplicity of light nuclei decreases linearly with a slope of -0.305 ± 0.009 . This region is considered as semi-central region. In this area both models underestimate the average multiplicity but both have the behavior similar to that of the experimental data. The deviation of models from experimental data becomes greater than in the peripheral region. Furthermore, when the interactions are more central ($8 \leq N_p \leq 12$) the $\langle N \rangle_{\text{nuclei}}$ decreases more slowly with a slope of -0.175 ± 0.008 . It can be expected that the light nuclei are more contributing in this region than the above region, which changes the slope of decrease. This central region can be considered as some mixture of projectile and target fragmentation. In this region models' measurements are low as compared to the experimental results. The different behaviors of multiplicity of light nuclei as a function of centrality emitting from projectile and target are also discussed in Ref. 6 and the yields of Deuteron and Triton from the target spectator area are discussed in Ref. 7. So the studies of light nuclei production in other experiments also give some clues to distinguish projectile and target regions. In the most central collisions ($N_p > 12$), in contrast to models, a minor increase in the average multiplicity of light nuclei is observed. This increase in average multiplicity and the decrease in the slope of central region indicate a new source of light nuclei production other than the fragmentation of projectile and target. It is suggested that the new source can be the coalescence mechanism, because in the most central events the collisions are head on, and more possibly the projectile and the target disintegrate into hadrons rather than nuclei. A dense medium is expected in the most central events due to the maximum number of participants, in which the nucleons within the same phase space can coalesce to make nuclei. Light nuclei production via coalescence mechanisms is predicted in experiment E864 [2] for 10% most central events in Au+Pt (Pb) (for heavy ion collisions) interactions at 10.6 A GeV/c. In our study we find some direct and sharp signatures of nuclear coalescence effect in ^{12}CC (light

ion collisions) interactions at 4.2A GeV/c. This information is necessary for theoretical models to describe the dynamics of the coalescence effect at high energy hadron-nuclear and nuclear-nuclear interaction.

Figure 4. Average multiplicity of light nuclei as function of centrality (N_p) in ^{12}CC - interactions. Stars, solid circles and open circles represent Cascade (CAS), Fritiof (FRI) and data (EXP) respectively.

Summary

In summary, analyses of experimental data for the average multiplicity of light nuclei as a function of centrality in $p\text{C}$, $d\text{C}$, HeC and ^{12}CC -interaction and their comparison with models are presented. With the increase in the mass of projectile average multiplicity of nuclei increases and diversity between models and experiment decreases. A systematic change in behavior of the projectile can be seen clearly from Figures (1-4) ($p\text{C}$ to ^{12}CC). In ^{12}CC interactions as shown in Figure 4, we identified four regions ($N_p \geq 2$, $2 < N_p \leq 7$, $8 \leq N_p \leq 11$ and $N_p > 12$), in regions ($N_p > 7$) the slope of average multiplicity is reduced. In the region ($N_p \geq 12$) a minor increase in

multiplicity is seen which, indicates a mechanism of light nuclei formation other than the fragmentation of the colliding nuclei, which could possibly be the nuclear coalescence effect.

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