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NUCLEAR PHYSICS

LIGHT CLUSTER COMPETITION IN SELF-CONJUGATE 4N-NUCLEI INTERACTIONS AT INTERMEDIATE ENERGY*

M.I. CHERCIU[1], A. JIPA[2]

[1]*Institute of Space Sciences, Bucharest, Romania,*
[2]*University of Bucharest, Faculty of Physics, Department of Atomic and Nuclear Physics*
P.O. Box MG-11, Bucharest-Mãgurele

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Abstract. In our work we have analysis the ability of light nuclei (^{2}H,^{3}H,^{3}He,^{4}He) formation in self-conjugate 4n-nuclei interactions. We have use the FLUKA simulation code with RQMD-2.4 implementation model to describe nucleus-nucleus collision at 100 MeV/nucleon, intermediate energy. For this purpose, a direct reaction system ^{12}C+^{40}Ca and an inverse reaction system ^{40}Ca+^{12}C is chose. Interesting results and conclusions are obtained on competition emission of light nuclei, reaction channel of light nuclei from QP and how the kinematics of reaction influenced the light nuclei formation.

Key words: nuclear collisions at intermediate energy, light nuclei, FLUKA, quasi-projectile.

1. INTRODUCTION

At intermediate bombarding energy (10 AMeV < E < 100 AMeV), the formation and the decay of excited nuclei, created in nucleus-nucleus collisions, are dominated by binary dissipative processes.

Nucleon exchange as well as nucleon-nucleon (N-N) collisions are responsible for the dissipation of the energy, creating two main excited fragments namely the quasi-projectile (QP) and the quasi-target (QT). Decaying QP's and QT's are observed as sources of nucleons, light charged particles (LCP - 2H, 3H, 3He, 4He …), intermediate mass fragments (IMF) or fission fragments for heavier systems, and gamma rays. Besides, a third source of particles appears in the region between the QP and QT fragments [2, 3, 4]. The contribution of such an

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intermediate velocity sources (IVS) depends on the initial angular momentum and masses of the colliding nuclei in the entrance channel. Two scenarios are possible to explain the separation mechanism between the overlap region and the two partners: either the formation of a neck of matter between QP and QT, or a sharp and geometrical break-up between the QP and QT and the overlap region (i.e. the participant-spectator scenario). The competition between these two mechanisms is governed by the interaction time.

If the system has not enough time to deform itself, then the reaction mechanism corresponds to the participant-spectator scenario [5, 6]. One observes three sources: two spectators and a participant zone. The participant zone comes from the stopping of nuclear matter in the overlap region between the two colliding nuclei. Intermediate velocity products come from the decay of this participant zone created at mid-rapidity. The spectators correspond to the remaining matter of initial projectile and target which conserve a large part of their initial rapidities. Above 50 AMeV, the transition from the neck or dynamic fission processes to the participant-spectator scenario is expected.

In our work we have used FLUKA simulation code to analysis the competition emission of light nuclei from QP, reaction channel of light nuclei from QP and how the geometry of nucleus-nucleus reaction influenced the light nuclei formation. FLUKA is a fully integrated particle physics MonteCarlo simulation package and is based, as far as possible, on original and well-tested microscopic models. Due to this "microscopic" approach, each step is self-consistent and has solid physical bases.

The basic building block is the description of the hadron-nucleon (h–N) interaction over a wide energy range. This is essential to achieve a sound description of the hadron–nucleus and nucleus–nucleus interaction.

In FLUKA, the nucleus-nucleus collisions are considered and a heavily modified version of RQMD-2.4 code and DPMJET model, have been interfaced to the evaporation/fission/Fermi breakup to treat the nuclear reactions. RQMD (Relativistic Quantum Molecular Dynamics) is an evolution of the original Intra-Nuclear Cascade (INC) models, which iterated individual discrete particles (e.g. nucleons) in constant mean-value approximated potential. RQMD adds a dynamic re-calculation of the intra-nuclear potentials at discrete intervals throughout the collision evolution iteration process. When individual nucleons collide, both models use the Free-Particle Cross Sections.

At energies below a few GeV/nucleon, an interface to the RQMD-2.4 model was developed to enable FLUKA to treat ion interactions from ≈100 MeV/n up to 5 GeV/n The RQMD-2.4 [7] is a relativistic model based on "Quantum Molecular Dynamics" (QMD).

At medium/high energy (above a few GeV/n) the DPMJET model is used. DPMJET [8] is a Monte Carlo model for sampling hadron-hadron, hadron-nucleus and nucleus-nucleus collisions at accelerator and cosmic ray energies (5-10 GeV/n up to 1011 GeV/n. De-excitation and evaporation of the excited residual nuclei is performed by calling the FLUKA evaporation module.

2. NUCLEAR SOURCES OF LIGHT NUCLEI

Like we have describe in the previous section, at intermediate energies nucleus-nucleus collision, there are two main sources of particle, identified with quasi-projectile and quasi-target, and a third source identified with mid-rapidity sources that came from the participant zone.

On our work, we have used two N-^{4}He reaction systems: a direct reaction system ^{12}C+^{40}Ca and an inverse reaction system ^{40}Ca+^{12}C, at 100 MeV/nucleon and various impact parameters and a statistical error bellow 0.2%.

Using FLUKA [9,10,11] we can identify the two main sources but also a third mid-rapidity source of particles. At our energies, the RQMD model is especially called from FLUKA and kinematical properties of particles are expressed in the reaction frame (no QP flight).

A challenge on the analysis is to separate the all three sources, especially on the overlap regions. Because, our study is focused on the QP we will separate only this source of particles, which is much easy even for the inverse reaction, the midrapidity component can overlap with the QP component.

The QP selection is not the same for both systems because, like we can observe from Fig.1-2(left) the rapidity cut is different for the two reactions. We have seen form our previous work [1] that a cut like $\beta_{||}= \beta_{cm}$ contain spurious particles (very large mean rapidity deviation). Therefore, for the reaction system ^{12}C+^{40}Ca we have chosen a cut at $\beta_{||}$=0.2 and for the reaction system ^{40}Ca+^{12}C we have chosen a cut at $\beta_{||}$=0.28. With this selection, the QP is not so pure it contains even some preequilibrium events, which can go from target velocity up to projectile velocity (white arrow, see Figs. 1-2).

From Figs. 1-2, we have represented the rapidity to the transverse velocity: reaction frame (left side) and laboratory frame, without midrapidity component transformation to the laboratory frame transformation, and rapidity respectively transverse velocity projection (right side).

Beside, the importance of light nuclei sources evidences, we observe a relative sharp representation of QP, which is identified with components close to the projectile rapidity. Moreover, the saddle shape component at target rapidity is so, because of the reaction frame representation of midrapidity and target components. The transverse velocity projections contain all three sources components and so a larger representation is observed.

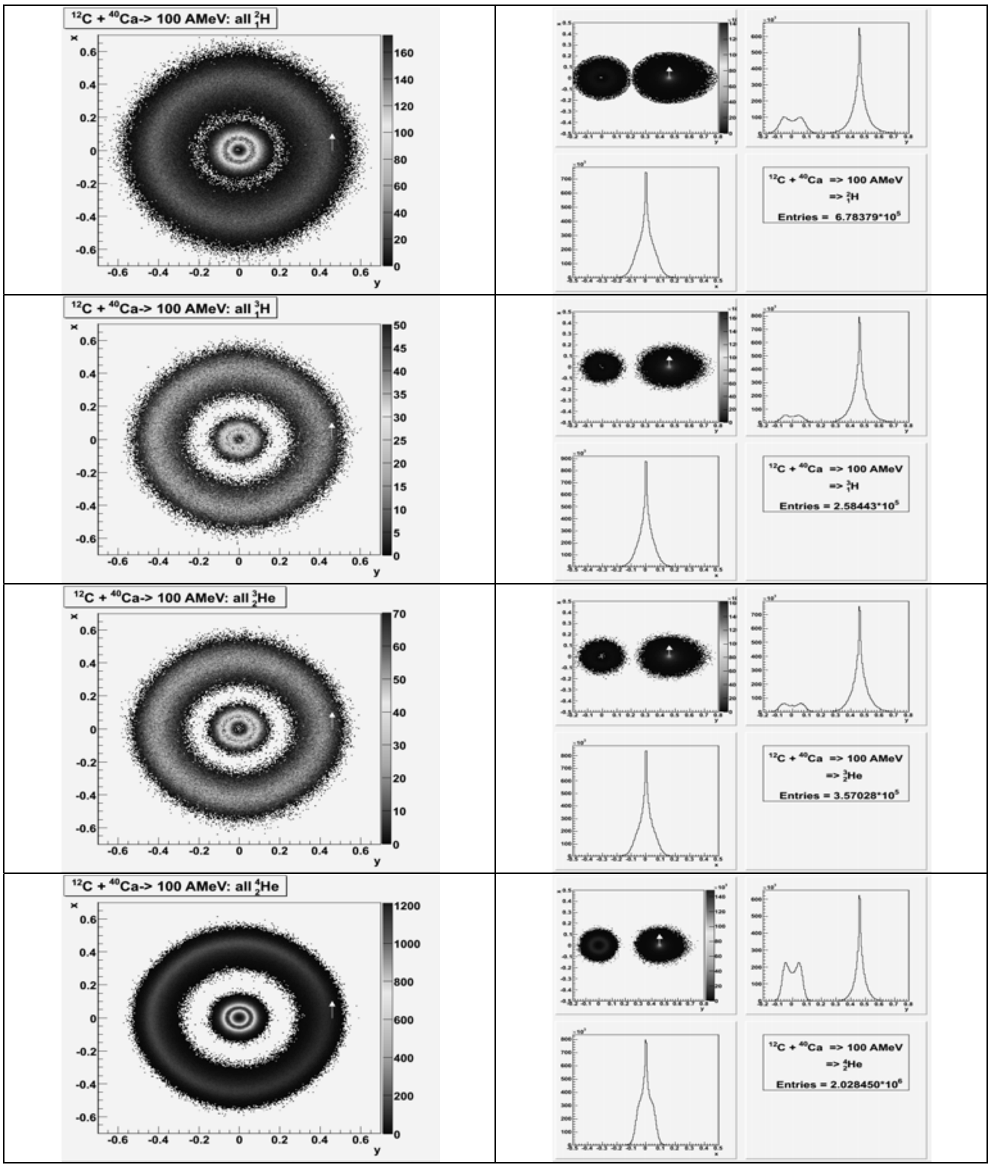

Fig. 1 – Simulation of nuclear sources ^{12}C+^{40}Ca reaction system, with FLUKA: in reaction frame (left), in laboratory frame (right) (no midrapidity transformation from reaction frame).

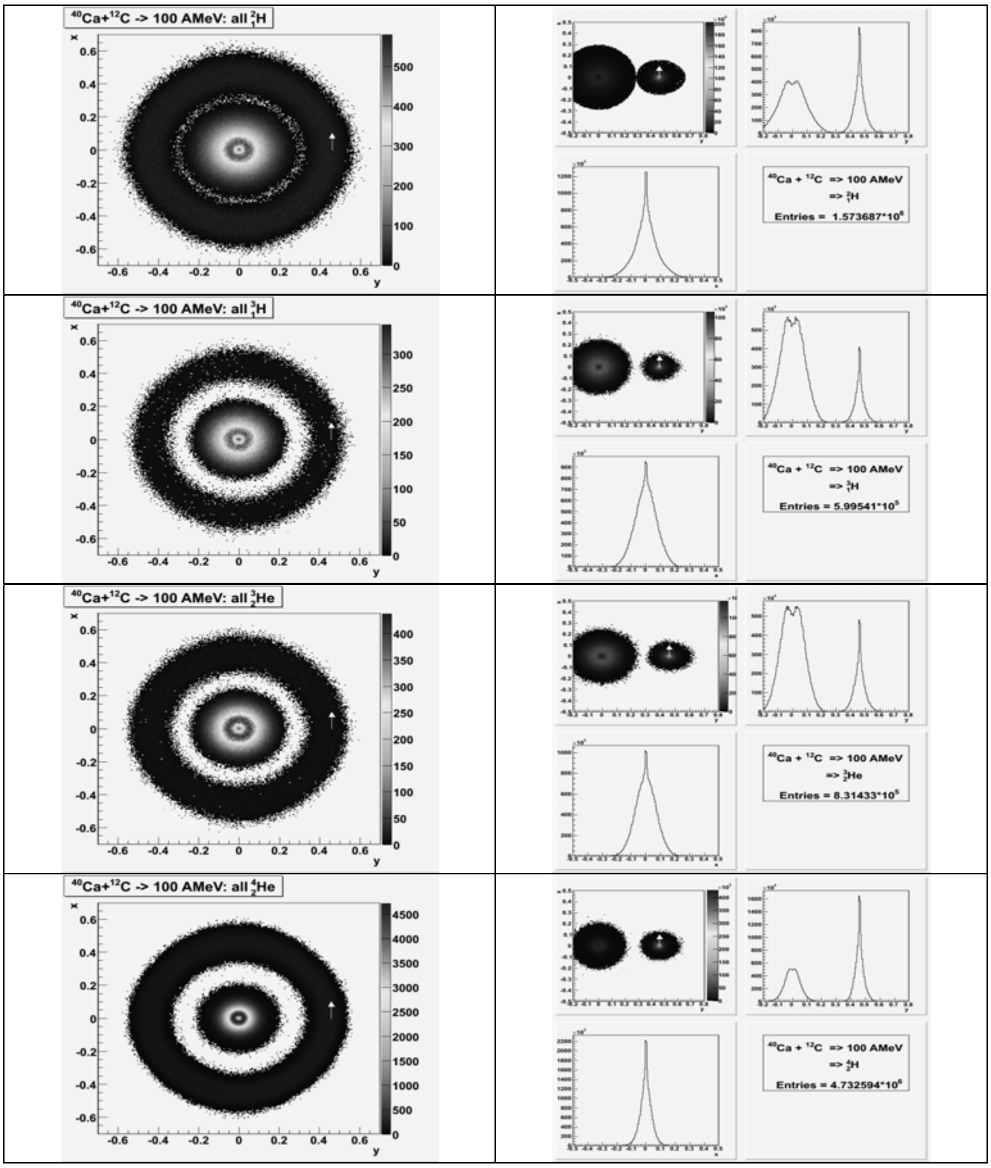

Fig. 2 – Simulation of nuclear sources for ^{40}Ca+^{12}C reaction system, with FLUKA: in reaction frame (left), in laboratory frame (right) (no midrapidity transformation from reaction frame).

All over, the ^{4}He light nuclei multiplicity is sensitive larger then other light nuclei competition with: 3 time than ^{2}H, 7.8 time than ^{3}H and 5.6 time than ^{3}He, for both reaction systems within ±0.05, that comes from the statistical error and represent less 2%. Therefore, the ^{4}He structure is the preponderant structure in this light nuclei competition.

Furthermore, an interesting aspect of our analysis was to check the reaction channel competition of light nuclei with ^{4}He, from QP. For that, we have done an event-by-event analysis. The results are represented in Figs. 3-4, where the results are express in percent of events, only for ^{4}He-^{2}H competition, for the other reaction channel (^{4}He-^{3}H, ^{4}He-^{3}He) the behavior is similar.

In both reaction systems, we observed that the most important reaction channel, for ^{4}He-^{2}H competition, is 1-0 and decrease from bottom to top and from left to right. This behavior is independent of the tip of kinematics used for reaction.

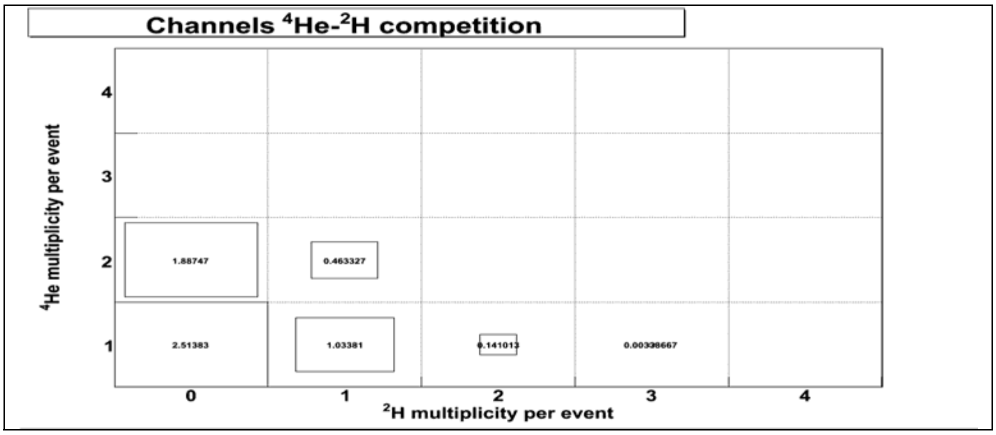

Fig. 3 – Reaction channel competition between ^{4}He and ^{2}H for ^{12}C+^{40}Ca reaction system.

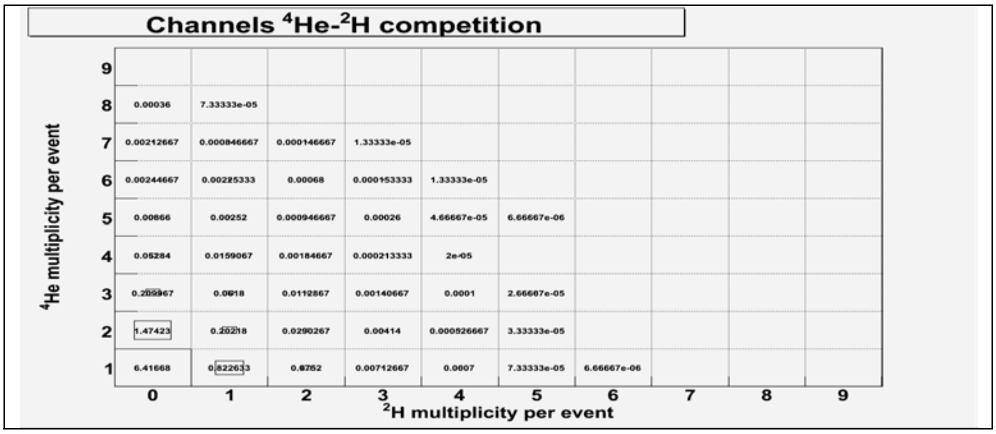

Fig. 4 – Reaction channel competition between ^{4}He and ^{2}H for ^{40}Ca+^{12}C reaction system.

In the same time, we observe that the number of ^{4}He per event is high, up to 8-^{4}He for ^{40}Ca+^{12}C reaction system and up to 2-^{4}He for ^{12}C+^{40}Ca reaction system. The FLUKA ability of reproduction of 8-^{4}He (or 2-^{4}He) nuclei like final states, which come especially from evaporation process, shows that such events can represent “noise” for special phenomena like nuclear Bose-Einstein condensation. We also observe, that from Fig. 3 events like 2-0 or 1-1 are same probable and from Fig. 4 events like 8-0 or 1-4 are same probable. This also sustains the idea that these states of N-^{4}He are very competitive states with other mixing states.

3. CONCLUSIONS

We observed, that the light nuclei competition, for both reaction systems, is predominant by ^{4}He with a sensitive larger multiplicity then other light nuclei competition with: 3 time than ^{2}H, 7.8 time than ^{3}H and 5.6 time than ^{3}He. A very interesting aspect is that the light nuclei ratio is rather constant within 2% statistical error. And such kind of ration can be used like a signal for other especially phenomena like nuclear Bose-Einstein.

We also observed that the most important reaction channel from QP is 1-0 (^{4}He-^{2}H, ^{4}He-^{3}H or ^{4}He-^{3}He) and decrease from bottom to top and from left to right (see Fig. 3-4). This behavior is independent of the tip of kinematics used for reaction.

The ability of FLUKA to describe many light nuclei final states (up to 8-^{4}He for ^{40}Ca+^{12}C reaction system and up to 2-^{4}He for ^{12}C+^{40}Ca reaction system) is very important to understand the properties of such special phenomena like nuclear Bose-Einstein condensation.

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