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NUCLEAR SOURCES EMITTING ALPHA STRUCTURES IN NUCLEAR COLLISIONS AT INTERMEDIATE ENERGIES*

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-Măgurele

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Abstract. The main objective of this work is the analysis of the alpha structures that can go out from the quasi-projectile systems in nuclear collisions at intermediate energies (~100 A MeV). In the modelation of the mechanisms of such structures we used different simulation codes, as FLUKA and Geant4. Another objective in our analysis was to check the properties of alpha structures in comparison with properties of alpha particles that are expected to be created by nuclear Bose-Einstein condensation mechanisms. Interesting results are obtained for $^{12}C+^{40}Ca$ nuclear system.

Key words: nuclear collisions at intermediate energy, alpha particles, Bose-Einstein condensation, nuclear diluted matter.

1. INTRODUCTION

The study of alpha structure that goes out after nuclear collision is carefully analyzed from kinematical aspects. Correlations of these alpha particles can give us very deep information about the formation and emission of these structures. We will focus our attention on Quasi-Projectile system (QP) because after collision with target nucleus it can reach a special nuclear structure where alphas particles can be considered like a diluted gas. Therefore, such structures can help in the investigation in field of the nuclear Bose-Einstein condensation [1-5].

In this paper, we make the analysis of alpha particles formation and emission in nuclear collisions at intermediate energies using information obtained with FLUKA and Geant4 simulation codes. We do that because we want to see if there are some structures containing two or more alpha particles (N_α), within the conditions of the search for alpha nuclear Bose-Einstein condensation, from the simulation codes perspective. Of course the simulation codes doesn't contain any

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information about nuclear dilution or, furthermore, about nuclear Bose-Einstein condensation. So, all N_α structures can be considered like a background for nuclear Bose-Einstein condensation.

The Quasi-Projectile (QP) has been studied through a wide variety of systems at intermediate energies 30-100 AMeV [6–16]. In this energy domain a transition from a binary process, leading to two main excited fragments (the quasi-projectile (QP) and the quasi-target (QT)) in the exit channel.

Besides preequilibrium and direct emissions already observed at low energies, processes like neck emission and aligned fission had to be taken into account in order to explain some experimental data [11]. Indeed an excess of particles and fragments at mid-rapidity, not explained by the statistical deexcitation of fully equilibrated QP and QT, is observed at intermediate velocity with unusual kinematical properties [9–10], [12–16].

Although it was generally admitted that below 100 AMeV, heavy ion collisions have essentially a binary character, it has been shown since several years that the decay products could not be fully imputed to the decay of excited quasi-projectile and quasi-target.

Because we want to focus on QP, we will neglect the mid-rapidity products. In this way, we observe two components centered respectively around the target and the projectile rapidities as shown in Fig. 1. This strongly suggests evaporation from excited QP and QT. Then, assuming a binary scenario and neglecting any non equilibrated emissions, all particles and fragments are attributed to the QP or the QT event-by-event.

We use relativistic quantities like:

– rapidity:

$$y = \frac{1}{2} \cdot \log\left(\frac{E + p_{\parallel} \cdot c}{E - p_{\parallel} \cdot c}\right); \tag{1}$$

– transverse velocity:

$$x = \frac{p_{\perp} \cdot c}{M_0 \cdot c^2} = \frac{\beta_{\perp}}{\sqrt{1-\beta^2}} = \gamma \cdot \beta_{\perp}; \tag{2}$$

– invariant cross section

$$\sigma^I = \frac{E \cdot \mathrm{d}^3\sigma}{\mathrm{d}^3(p \cdot c)} = \frac{1}{2 \cdot \pi \cdot M_0^2 \cdot c^4} \cdot \frac{\mathrm{d}^2\sigma}{x \cdot \mathrm{d}x \cdot \mathrm{d}y}; \tag{3}$$

– mean rapidity deviation:

$$\sigma_y = \sqrt{\frac{\sum_{i=1}^{nr.part} (y_i)^2}{N} - \overline{y}^2}. \tag{4}$$

2. ALPHA PARTICLES AND BOSE-EINSTEIN STATISTICS

In 1925, Albert Einstein, excited by the idea of Satyendranath Bose relate of the gregarious behavior in photons, predicted that at sufficiently low temperature, an ideal gas consisting of noninteracting point-like identical bosons will undergo a phase transition to a Bose-Einstein condensate (BEC), in which all the particles are in the same quantum state.

Seventy years later after the Bose-Einstein statistics formulation, the phenomenon of Bose-Einstein condensation (BEC) for atoms was experimentally produced by JILA/University of Colorado team [17] using Rubidium, Lithium and Sodium atoms cooled to temperatures of the order of 100 nK. The study of BEC in weakly interacting systems that can be controlled and observed with precision holds the promise of revealing new macroscopic quantum phenomena. The study of BEC in such systems may also advance our understanding of superconductivity and superfluidity in more complex systems.

Similar to the Bose-Einstein condensation for finite number of dilute bosonic atoms such as ^{87}Rb, ^{7}Li or ^{23}Na at very low temperature, several authors have discussed the possibility of α-particle condensation in low-density nuclear matter [1–5, 18–19].

Our wok is concentrate on the analysis of alpha particles, which is a boson, and so it can obey to the Bose-Einstein statistics.

The predominant cluster is the α nucleus, which plays an important role in the cluster model, because it is the lightest and also smallest shell-closed nucleus with a binding energy as large as 28 MeV, reflecting the strong four-nucleon correlation. Molecular-like states in nuclei are expected to appear around the threshold energy of breakup into cluster constituents [19], because the intercluster binding is weak in the cluster states.

It was found that such α condensation can occur in the low-density region below a fifth of the saturation density, although the ordinary pairing correlation can prevail at higher density. The result indicates that α condensate states in finite nuclear system may exist in excited states of dilute density composed of weakly interacting gas of α particles. Thus, it is an interesting subject to study the structure of light nuclei from different point of view, but especially from α-particle condensation.

Theoretical studies for ^{12}C and ^{16}O showed that the second 0^+ state of ^{12}C (E_x=7.65 MeV) and fifth 0^+ states of ^{16}O (E_x=14.0 MeV), located around the 3α and 4α particle thresholds, respectively, are specified by the Nα condensate state, which is quite similar to the Bose-Einstein condensation of bosonic atoms in magnetic traps where all atoms occupy the lowest S-orbit [19].

The calculated root-mean-square (rms) radius for those condensate states is about 4 fm, which is much larger than that for the ground state (about 2.7 fm). This gives us first information about the dilute nature of these systems.

3. RESULTS

Simulations of N_α structures, using FLUKA [20, 21] and Geant4 [22, 23] simulation codes, were performed on a important system of N_α structures $^{12}C+^{40}Ca$, where it is possible to observe up to 3α particles from QP (^{12}C), at 100 AMeV.

On the representation (Fig. 1), of transverse velocity (2) *versus* rapidity (1), we found two nuclear alpha sources that correspond with QP, the source with radius about the rapidity of projectile (white arrow), and QT, the source with smallest radius. The representation reflects all alpha particles that go out from QP or QT without any condition on N_α per event.

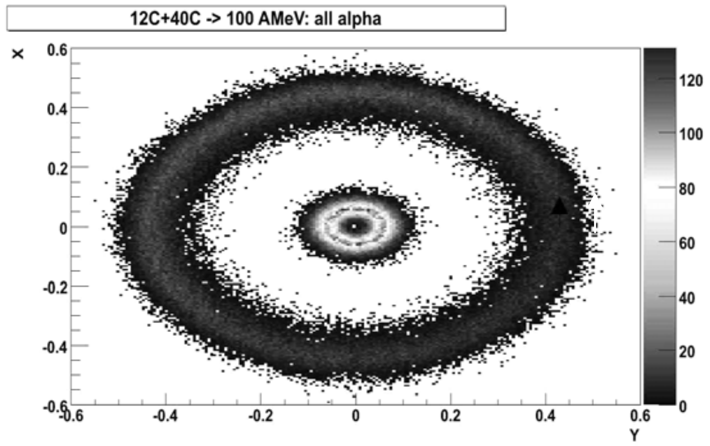

Fig. 1 – Simulation of nuclear sources emitting alpha particles with FLUKA.

This evidence of alpha sources, identified with quasi-projectile and quasi-target, is very important for further analysis on nuclear alpha structure for the Bose-Einstein perspective. We are expecting that such alpha particles, which rise from nuclear BEC, to have similar kinematics properties because they correspond to the same quantum state. We hope to obtain useful information in an invariant representation like mean rapidity deviation *versus* mean rapidity of such N_α structures. Otherwise, the nuclear Bose-Einstein condensation should be locate in a region (empty square from Fig. 2) with a very small mean rapidity deviation of the N_α structures at the mean rapidity close to the rapidity of the source (QP).

On a dedicate analysis we put the conditions to work on QP otherwise, that the parallel relative velocity of particles to be great than or equal with the relative velocity of center of mass ($\beta_{||} \geq \beta_{CM}$). After that, we count how many α particles go out event by event and we plot, on invariant representation (3), the mean rapidity deviation (4) *versus* the mean rapidity (1) of N_α structures (Figs. 2 and 3). In this way, we will focus on the kinematical properties of particles.

It is know that the N_α particles that go from a nuclear Bose-Einstein condensation shall have a very small deviation from the projectile rapidity.

On Figs. 2 and 3 both simulations codes FLUKA and Geant4 doesn't reproduce any data that are expected from a nuclear Bose-Einstein condensation and this is perfectly true because there is no information about that on the codes.

Instead, give us a first picture on what the codes say if we make a study with the conditions for search of a nuclear Bose-Einstein condensation otherwise, in our representation we can observe the background for nuclear Bose-Einstein condensation. This background corresponds with the evaporation processes from QP.

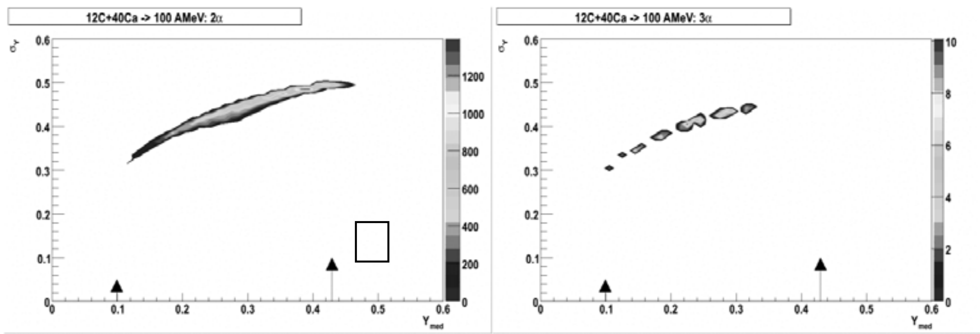

Fig. 2 – Mean rapidity deviation *versus* mean rapidity with FLUKA simulation code.

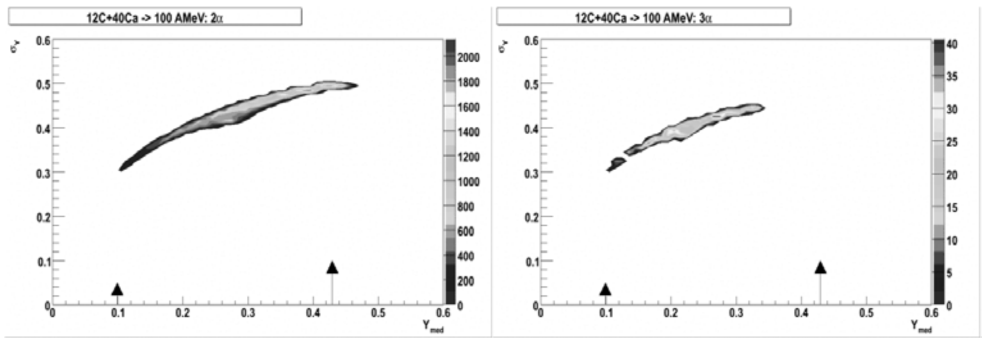

Fig. 3 – Mean rapidity deviation *versus* mean rapidity
with Geant4-QGSP-BIC-HP simulation code.

From the simulations we can see that is possible to have up to $N_{\max\alpha}$ of the QP and that from a non Bose-Einstein process. Furthermore, on observe total non-correlate N_α particles because they have a big deviation to the mean rapidity ($\sigma_Y > 0.3$) even the mean rapidity is more or less close to the projectile rapidity (big black arrow is projectile rapidity and small black arrow is center of mass rapidity).

4. CONCLUSIONS

This background of N_α particles could be very significant on a real experiment to search nuclear Bose-Einstein because the evaporation and other associated processes are a more probable processes then the nuclear Bose-Einstein condensation. The existence of the two emitting sources of α particles, from the simulation codes perspective, is well reproduce. The existence of 2α and 3α structures from QP that have mean rapidity close to the projectile rapidity and the deviation on mean rapidity greater then 0.3 should be considered like background for the nuclear Bose-Einstein condensation. The condition that $\beta_{\|} \geq \boldsymbol{\beta}_{CM}$ is not sufficient to focus on the nuclear BEC process but the events with mean rapidity close to the projectile rapidity and with mean rapidity deviation less then 0.3 could be very interesting.

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