Probing clusterization in $^{40}$Ca + $^{40}$Ca reaction at 35MeV/A

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Abstract. The preliminary results of the analysis of $\alpha$-conjugate system $^{40}$Ca + $^{40}$Ca at 35MeV/A and comparison with results of Antisymmetrized Molecular Dynamics (AMD) calculations are presented. The experiment involving NIMROD-ISIS array was performed at the Cyclotron Institute, Texas A&M University and the main goal was to find Bose Einstein Condensate in nuclei.

1. Introduction

Bose-Einstein condensation is known to occur in weakly and strongly interacting systems such as dilute atomic gases and liquid $^4$He [1]. During the last decade it was theoretically shown that dilute symmetric nuclear matter may also experience Bose particle condensation [2, 3, 4]. More precisely, for low temperatures and densities smaller than one fifth of the nuclear saturation density, nuclear matter organizes itself in $\alpha$-clusters, while for higher densities deuteron condensation is preferred. This possible new phase of nuclear matter may have its analog in low-density states of alpha-conjugate lighter nuclei, in the same way as superfluid nuclei are the finite-size counterpart of superfluid nuclear and neutron matter. This means that under some circumstances, the alpha condensation, i.e. bosonic properties, might dominate nucleon properties even in finite nuclei [5]. A natural way to pursue this is to apply experimental techniques developed for the investigation of low density nuclear gases to collisions of nuclei expected to have a significant alpha cluster character. Such nuclei might show a more natural predilection to evolve into a Bose Condensate. We have initiated a search for evidence of Bose Condensates using the NIMROD array. Our experiments employed 10, 25, 35 MeV/u beams of...
Ca and Si incident on Ca, Si, C and Ta targets. The first three targets allow an exploration of collisions of alpha conjugate nuclei. In the Ta case the projectile excitation and decay is of primary interest. The data are currently being analyzed. Our expectation is that a Bose Condensate would manifest itself as an assemblage of alpha conjugate products with particular kinematic correlations. Therefore the first step of the analysis was to probe α clusterization in Ca + Ca at 35MeV/A reaction.

2. Experiment

We have initiated a search for evidence of Bose Condensates using the NIMROD array (see Figure 1). The NIMROD-ISiS charged particle array consists of 14 concentric rings ranging from 3.6° to 176.0° in lab. The entire device is housed inside the Texas A&M Neutron Ball, which provides an average neutron multiplicity for each event. Two different detector module configurations were used in the array. The single telescope configuration consisted of a 150μm or 300μm silicon placed in front of the CsI(Tl)-PMT detector. The supertelescope configuration had two silicon detectors, 150μm and 500μm, placed in front of a CsI(Tl)-PMT detector.

![Figure 1. Side view of charged particle detectors of the NIMROD-ISiS array. Each ring is labeled with the corresponding lab angle.](image)

3. Theoretical calculations

The Antissymmetrized Molecular Dynamics Model (AMD) [6] [7] incorporating a statistical decay code GEMINI [8] as a afterburner were employed to compare the experimental observables with theoretical predictions. AMD model is known to reproduce the fragmentation data very well. In the future however we intent to compare our results with other theoretical calculations, such as the Constrained Molecular Dynamics Model (CoMD), a microscopic model that includes...
Fermionic statistics \cite{9} \cite{10} and its particular version - CoMD-\(\alpha\) Model, which is currently being developed at Texas A\&M University.

4. Global variables

In order to find various \(\alpha\)-conjugate combinations in the experiment we define several observables. For each event we calculate the multiplicity of \(\alpha\)-like fragments and the total mass of those fragments. We define similar observables for \(d\)-like fragments as well. Another interesting parameter, \(b_j\) is defined as:

\[
b_j = \frac{1}{N} \sum_{i=1}^{N} \frac{(-1)^{Z_i} + (-1)^{N_i}}{2}.
\]

Its value ranges from -1 to 1, which corresponds to events consisting of: odd-odd nuclei only (-1), odd-even fragments (0) and even-even nuclei only (1). Figure 2 shows the comparison between the experimental data (blue line) and AMD theoretical results (red line) for \(A\) and \(Z\) distributions and the observables defined above. The model calculations have been filtered through the same detection and analysis criteria as the experimental data.

The model underestimates the production of heavier fragments starting from \(Z=15\). We observe better agreement in the distributions of \(d\)-like than \(\alpha\)-like multiplicity. 14.6\% of all experimental events constitute those with \(\alpha\)-like mass equals 8 (2 \(\alpha\)'s in the event). The AMD model predicts 17.3\% of such events. The second most populated \(\alpha\)-like mass is 12 (3\(\alpha\)'s or one \(^{12}\text{C}\)) and it constitutes 13.1\% of all experimental events and 15.9\% of the theoretically predicted ones. 12.6\% of all experimental events are those with 3\(\alpha\)'s. Those numbers are very promising for the search of Bose-Einstein Condensate in nuclei since one of the candidate is \(^{12}\text{C}\) in Hoyle state.

![Figure 2](image-url)

**Figure 2.** \(A\), \(Z\), \(\alpha\)-like mass, \(d\)-like mass, \(\alpha\)-like multiplicity, \(d\)-like multiplicity, \(b_j\) distributions. Blue line - experimental data, red line - AMD calculations.
which decays into 3α’s. The theoretical distribution for the \( b_j \) parameter is narrower than that for the experiment, which might be due to the underestimate of heavier fragment production. It is also nearly symmetric, meaning that almost the same number of α-like and d-like fragments are predicted. The experimental distribution is weighted towards the positive values, which indicates that more α-like fragments have been created.

5. Reaction mechanism

We initiate the analysis of the reaction from reconstructing the excitation energy of each event \( E^* \) through calorimetry:

\[
E^* = \sum_{i=1}^{M} K_{cp}(i) + M_n(K_n) - Q.
\]

The excitation energy \( E^* \) was defined as the sum over accepted particles center of mass kinetic energy \( (K_{cp} \text{ and } K_n) \) minus the reaction Q-value. The average kinetic energy of the neutrons was calculated as the proton average kinetic energy with a correction for Coulomb-barrier energy [11]. In Figures 3 and 4 we plot the 3 heaviest fragment masses as a function of parallel velocity in different windows of \( E^* \). Low excitation energies are associated with less violent collisions, therefore in both the experimental data and theoretical calculations we see heavy projectiles (mainly of \( A=28, 32 \) and 36 in the experiment) as well as light nuclei. With increasing excitation energy the violence of the collisions increase, we observe a very strong neck-like emission which consists mainly of α-like fragments (\( A=12, 16, 20, 24 \)). Their parallel velocity decreases with the decreasing mass. This has been described in [12] as the ”hierarchy effect”: the ranking in charge induces on average a ranking in average parallel velocity where the heaviest fragment is the fastest and is more focused in the forward direction.

![Experimental data](image)

**Figure 3.** Three heaviest fragment masses as a function of their parallel velocity in different windows of excitation energy \( E^*/A \), experimental results.
Filtered AMD+GEMINI

Figure 4. Three heaviest fragment masses as a function of their parallel velocity in different windows of excitation energy $E^*/A$, theoretical predictions.

Since very strong $\alpha$ clusterization is observed, we now attempt to quantify this behavior. In the following we focus on events with $\alpha$-like mass = 40. 1.3% of experimental events are characterized by $\alpha$-like mass = 40 whereas the AMD predicts around half that amount, 0.77%. In order to provide a complete comparison we also present results of AMD calculations not filtered by the experimental conditions. In this case we obtain 7.8% events of $\alpha$-like mass = 40, which is about 6 times more than that observed in the experiment. There are 19 possible channels for $\alpha$-like mass = 40 to decay into $\alpha$-like fragments. Table 1 presents the percentage of: a) $\alpha$-like mass 40 events, b) all events, which decayed via one of the possible channels. The first two columns represent the experimental data and the next two show AMD predictions filtered by experimental conditions and the last two contain the results of AMD calculations without the experimental filter.

Both experiment and theoretical calculations suggest that the most probable decay modes are those with one heavy $\alpha$-like mass fragment and several $\alpha$ particles in the exit channel. The contribution of each branch however shows differences between experiment and calculations. One can also notice that adding the experimental filter to the model strongly affects the results.

In the experiment the second most probable channel is the one when we observe $^{28}\text{Si}$ and $3\alpha$. Since we are interested in $3\alpha$ events we focus on this channel and compare it to $^{28}\text{Si} + ^{12}\text{C}$ (No. 16 in Table 1). We note a dramatic drop of the $^{28}\text{Si} + ^{12}\text{C}$ contribution in all decay modes. One explanation is that the majority of $^{12}\text{C}$ decayed into $3\alpha$’s. To justify this assumption we show in Figure 5 the invariant velocity plots of these two decaying branches products. We observe that to a close approximation $^{28}\text{Si}$ moves with the beam velocity (8.21[cm/ns]) in both cases. The parallel velocity of $^{12}\text{C}$ is consistent with the velocity of the “neck” (see Figure 3) and oscillates around 4-7[cm/ns]. Although we observe $\alpha$ particles emerging from the projectile, the majority of them come from a source of intermediate parallel velocity similar to that of $^{12}\text{C}$. Therefore it will be our priority to focus on the effects related to “neck” emission in further analysis. We plan to treat it as a separate source of $\alpha$ particles and study its properties. Given that we have 12.6% of events with $3\alpha$ particles, plus events with higher $\alpha$ multiplicity, where we observe a $3\alpha$
Table 1. Percentage of a) $\alpha$-like mass 40 events, b) all events which decayed into one of the possible channels. Comparison with filtered and not filtered theoretical calculations.

correlation, it should be possible to find the similarities/differences between the intermediate velocity source and a typical projectile-like one and to confirm and perhaps expand the results obtained by [5] or [13] regarding the Hoyle state decay.

![Figure 5. Invariant velocity plots of $3\alpha$-$^{28}$Si (left) and $^{12}$C-$^{28}$Si (right) decaying channel.](image-url)
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References
[1] Pitaevski L P and Stringari S, (2003) Bose-Einstein Condensation, Clarendon Press, Oxford.
[2] Roepke G et al (1998) Phys. Rev. Lett. 80 3177
[3] Beyer M et al (2000) Phys. Lett. B 448 247
[4] Sogo T et al (2009) Phys. Rev. C 79 051301
[5] Raduta Ad et al (2011) Phys. Lett. B 705 65
[6] Ono A et al (1996) Phys. Rev. C 53 2958
[7] Ono A (1999) Phys. Rev. C 59 853
[8] Charity R J et al (1988) Nucl. Phys. A 483 371
[9] Bonasera A (2000) Phys. Rev. C 62 052202
[10] Papa M et al (2001) Phys. Rev. C 64 024612
[11] Dore D et al (2000) Phys. Lett. B 491 15
[12] Colin J et al (2003) Phys. Rev. C 67 064603
[13] Manfredi J et al (2012) Phys. Rev. C 85 037603