Triple $\alpha$ Resonances in the Decay of Hot Nuclear Systems

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Abstract: The Efimov (Thomas) trimers in excited $^{12}$C nuclei, for which no observation exists yet, are discussed by means of analyzing the experimental data of $^{70(64)}$Zn($^{64}$Ni) + $^{70(64)}$Zn($^{64}$Ni) reactions at beam energy of E/A=35 MeV/nucleon. In heavy ion collisions, the $\alpha$s interact with each other and can form complex systems such as $^8$Be and $^{12}$C. For the $3\alpha$ systems, multiple resonance processes give rise to excited levels of $^{12}$C. The interaction between any two of the $3\alpha$ particles provides events with one, two or three $^8$Be. Their interfering levels are clearly seen in the minimum relative energy distributions. Events of three couple $\alpha$ relative energies consistent with the ground state of $^8$Be are observed with the decrease of the instrumental error at the reconstructed 7.458 MeV excitation energy of $^{12}$C, which was suggested as the Efimov (Thomas) state.

Key words: heavy ion reactions, Efimov state, $\alpha$ resonances, relative kinetic energy

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1 Introduction

In 1969, Vitaly Efimov, following a work by Thomas(1935) [1], first predicted a puzzling quantum-mechanical effect, when a resonant pairwise interaction gives rise to an infinite number of three-body loosely bound states even though each particle pair is unable to bind [2, 3]. These properties are universal and independent of the details of the short-range interaction when the two-body scattering length ‘a’ is much larger than the range of the interaction potential ‘r0’. The existence of resonant two-body forces is the basic condition for the Efimov effect. Although there has been an extensive search in many different physical systems including atoms, molecules and nuclei, the experimental confirmation of existence of Efimov states has proved to be challenging especially for nuclei [1, 2]. Recently, Tuminori et al. reported about the discovery of the existence of triple-alpha resonances, very close to the Efimov scenario, by studying $^6$Li+$^6$Li$\rightarrow$3$\alpha$ reactions at low beam energy and using hyperspherical formalism. A geometrical interpretation of these mechanisms [10] suggests that the Thomas state corresponds to three equal energies, while a sequential decay mechanism ($^{12}$C$\rightarrow$$^8$Be+$\alpha$$\rightarrow$$^3$α) might correspond to Efimov states [2]. This prescription refers mainly to $^{12}$C levels in the vicinity of the breakup threshold of three $\alpha$-particles or $\alpha$+$^8$Be, taking into account the Coulomb force among $\alpha$ particles which destroys the $1/R^2$ (R is the hyperradius) scaling at large distance where Coulomb force is dominant [2]. This is surely relevant with stellar processes, where $^{12}$C nucleus is formed and it might occur inside a dense star or on its surface, thus in different density and temperature conditions. A way to simulate some stellar conditions is to collide two heavy ions at beam energies near the Fermi energy. In this work, we present the possible signature of Efimov (Thomas) states at reconstructed 7.458 MeV excitation energy of $^{12}$C from the reactions $^{70(64)}$Zn($^{64}$Ni) +...
$^{70(64)}$Zn($^{64}$Ni) at beam energy of E/A=35 MeV/nucleon

2 Experiment

The experiment was performed at the Cyclotron Institute, Texas A&M University. $^{64}$Zn, $^{70}$Zn, and $^{64}$Ni beams at 35 MeV/nucleon from the K-500 superconducting cyclotron were used to respectively irradiate self-supporting $^{64}$Zn, $^{70}$Zn, and $^{64}$Ni targets. The 4π NIMROD-ISiS setup [12, 13] was used to collect charged particles and free neutrons produced in the reactions. A detailed description of the experiment can be found in Refs. [14–16].

In the experiments, it is straightforward to select all the events where one or more $\alpha$ particles are detected. In Fig. 3, we plot the $\alpha$ particle multiplicity distribution for the three colliding systems considered. The total number of events is $\sim 2.7 \times 10^8$ and we have observed events where at least 15 $\alpha$ are produced. In Refs. [20–28], an analysis was performed for events as in Fig. 3 in terms of Boson-Fermion mixtures, i.e. including all fragments as reported in Fig. 2 which can give also a signature of Bose Einstein Condensation (BEC) [29, 30]. Temperature, density and excitation energy are recovered using different approaches [17] with most of the events in the high excitation energy region up to about 8 MeV/nucleon. We notice that most of the novel techniques discussed in this work might be easily generalized to cases where the $\alpha$ multiplicity is larger than 3. We plan to discuss this in future papers. More conventional analysis based on Dalitz plots [31–38] cannot be easily generalized when the $\alpha$-multiplicity is larger than 3.

Fig. 1. The time evolution of the average density in the central region in $^{70}$Zn + $^{70}$Zn at 35 MeV/nucleon.

Fig. 2. (color online) The charge (Z) and mass (A) distributions from the $^{70}$Zn+$^{70}$Zn system are shown for the filtered CoMD simulation in comparison to the experimental data. The results have been normalized by the total number of events [14].

CoMD model. Within the same model, the excitation energy of each fragment formed at $t_{\text{max}}$ is obtained and fed into the Gemini model, which gives the final de-excited fragments. As can be seen from the figure, the effect of secondary evaporation is negligible after $t_{\text{max}}>600$ fm/c. The abundance of $^{12}$C fragments are about two orders of magnitude less than those of proton and $\alpha$-particles. These ions survive the violence of the collision while other $^{12}$C might be in one of the excited states and decays before reaching the detector or collides with other fragments and gets destroyed. Our technique is tailored to select the $^{12}$C$\rightarrow$3$\alpha$ decay channel among all the possibilities.

In Fig. 3, we plot the $\alpha$ multiplicity distribution for the three colliding systems considered. The total number of events is $\sim 2.7 \times 10^8$ and we have observed events where at least 15 $\alpha$ are produced. In Refs. [20–28], an analysis was performed for events as in Fig. 3 in terms of Boson-Fermion mixtures, i.e. including all fragments as reported in Fig. 2 which can give also a signature of Bose Einstein Condensation (BEC) [29, 30]. Temperature, density and excitation energy are recovered using different approaches [17] with most of the events in the high excitation energy region up to about 8 MeV/nucleon. We notice that most of the novel techniques discussed in this work might be easily generalized to cases where the $\alpha$ multiplicity is larger than 3. We plan to discuss this in future papers. More conventional analysis based on Dalitz plots [31–38] cannot be easily generalized when the $\alpha$-multiplicity is larger than 3.
For the purpose of our work, we further selected all the events with only three \( \alpha \) particles detected. It is important to stress that multiple \( \alpha \) revealed are accepted if they hit different detectors, i.e. all possible double hits in an event are excluded. Furthermore, in the present analysis, a random position on the surface of the detector was assigned to each \( \alpha \). This limits the precision of \( \alpha-\alpha \) correlations especially when their relative energies or momenta are very small. A critical comparison of different methods to assign the hitting position on the detector will be discussed in a future work, here it is sufficient to say that the results discussed are independent on the different methods. In these cases, the total number of events reduced to \( \sim 4.5 \times 10^7 \). From the above discussion, it is clear that if only three \( \alpha \) are in an event, other fragments must be presented and the sum of all the fragment masses is up to 140 (maximum) including the three \( \alpha \). This is a rich environment depending on the proximity of different fragments to the \( \alpha,^8\text{Be} \) or \(^{12}\text{C} \) ions, the properties and shell structure of the fragments might be modified. In particular, short living states of \(^{12}\text{C} \) or \(^{8}\text{Be} \) might be modified by the presence of other nearby fragments. On the other hand, long living states such as the Hoyle state of \(^{12}\text{C} \) might not be influenced at all since its lifetime is much longer than the reaction time. Of course, in such ‘soup’, \( \alpha \)-particles might come from the decay of \(^{12}\text{C} \) or \(^{8}\text{Be} \) and from different excited fragments, or directly produced during the reaction, thus it is crucial to implement different methods to distinguish among different decay channels.

In order to distinguish different decay channels, the kinetic energy of the \( \alpha \) particles must be measured in a good precision. The kinetic energy distribution from the NIMROD detector for the events with \( \alpha \)-multiplicity equal to three is given in Fig. 4. It extends above 100 MeV/nucleon and displays a large yield around 8 MeV/nucleon. Since the kinetic energies are relatively large, the detector is performing its best, and the error estimate (including the instrumental error especially because of the detector granularity, detectors’ energy, position, and angle resolution) gives results in less than 1% of the kinetic energy value. The error becomes larger for smaller kinetic energies and particles whose kinetic energy is below a threshold (about 1 MeV/nucleon) are not detected. Thus it is a clear advantage to use the beam of heavy ions near or above the Fermi energy. Fragments are emitted in the laboratory frame with high kinetic energies (due to the center of mass motion) and can be carefully detected. When we reconstruct \(^8\text{Be} \) from \( \alpha-\alpha \) correlations, the center of mass motion is cancelled out and small relative kinetic energies can be obtained with an estimated error of about 45 keV for the smallest relative kinetic energies. This error is due to the detector granularity as discussed above.

![Fig. 3. \( \alpha \)-multiplicity distribution for the \(^{70}(64)\text{Zn}^{(64)\text{Ni}} \) at 35 MeV/nucleon from the NIMROD detector.](image)

![Fig. 4. \( \alpha \)-kinetic energy distribution in the laboratory frame from all the events with \( \alpha \)-multiplicity equal to three. Inset: zoom of the lower energy region in this figure.](image)

### 3 Method

For the three body system with equal masses, we can define the excitation energy \( E^* \) as:

\[
E^* = \frac{2}{3} \sum_{i=1, j>i}^3 E_{ij} - Q \tag{1}
\]

where \( E_{ij} \) is the relative kinetic energy of the two particles, \( Q \) is the Q-value. Notice that the important ingredients entering Eq. (1) are the relative kinetic energies; since we have three indistinguishable bosons, we analyze the \( E_{ij} \) distribution by cataloging for each event the smallest relative kinetic energy, \( E_{ij}^{\text{Min.}} \), the middle relative kinetic energy, \( E_{ij}^{\text{Med.}} \), and the largest relative kinetic energy, \( E_{ij}^{\text{Max.}} \).

In this work, we reconstruct the \( E^* = 7.458 \text{ MeV} \) of the \(^{12}\text{C} \) from 3\( \alpha \)s when the sum of the three \( E_{ij} \) is 0.276
MeV (0.092×3 MeV, i.e. 0.092 MeV is the relative energy of 2αs corresponding to the ground state decay of 8Be [11,59]) with the Q-value= -7.275 MeV. In Fig. 5 the minimum relative kinetic energy distribution is shown. In the top panel, the solid black circles give the distribution obtained from the real events. They show bumps but no real structures. This is due to the fact that in the fragmentation region, some αs may come from the decay of 8Be or 13C, or from completely non-correlated processes, for example, the α emission from a heavy fragment. To distinguish the correlation from the non-correlated events, we randomly choose three different αs from three different events and build the distribution displayed in Fig. 5 (mixing events-red open circles). The total number of real and mixing events are normalized to one, respectively. We fit the highest points of Fig. 5 (top) with an exponential function. This allows us to derive the instrumental error ΔE=1/22 MeV=0.045 MeV.

In order to determine if we have events with equal relative kinetic energies, we have selected 3α events with $E_{ij}^{Min.} = E_{ij}^{Min.} = 0.092\pm \frac{dE}{E} \text{ MeV}$ and decreased the value of $\delta E$ to the smallest value allowed by statistics. In Fig. 6 we plot the results for the real (solid black circles) and the mixing (red open circles) events in the upper panels, and their ratio (1+R3) in the bottom panels. Even though the number of real events decreases to almost 90 when the $\delta E=0.06$ MeV case, we can see a hint of a signal around $(E_{ij}^{Min.}+E_{ij}^{Min.}+E_{ij}^{Min.})\times \frac{2}{3} - Q = 7.47$ MeV which is consistent with the suggested Efimov (Thomson) state $\text{10}^{14}$ that at an excitation energy of 12C of about 7.458 MeV.

Similar to Fig. 6 we have selected 3α events with $E_{ij}^{Min.} = 0.092\pm \frac{dE}{E} \text{ MeV}$, $E_{ij}^{Min.} = 0.092\times 2\pm \frac{dE}{E} \text{ MeV}$ in Fig. 7. We can also observe the events where the largest relative energy is three times of the minimum one around $(E_{ij}^{Min.}+E_{ij}^{Min.}+E_{ij}^{Min.})\times \frac{2}{3} - Q = 7.64$ MeV with different $\delta E$. These events suggest that there are events where the 3α relative energies are in the ratio of 1:2:3.

In Figs. 6 and 7 we can see significant signals around $E^*=7.65$ MeV, which is consistent with the famous 0+$^4$ Hoyle state of 12C predicted by Fred Hoyle in 1953 [10].

![Fig. 5](image)

**Fig. 5.** (color online) (Top) Relative kinetic energy distribution as a function of the minimum relative kinetic energy. The solid black circles represent data from real events, red open circles are from mixing events, and the blue open squares represent the difference between the real events and the exponential fit function (solid line), which takes into account the experimental error. (Bottom) The ratios of the real data (pink open triangles) and the real data minus the fit function (green solid squares) are divided by the mixing events as a function of the minimum relative kinetic energy. The solid lines are Breit-Wigner fits.

![Fig. 6](image)

**Fig. 6.** (color online) The reconstructed excitation energy distributions of 12C from 3αs with $E_{ij}^{Min.} = E_{ij}^{Min.} = 0.092\pm \frac{dE}{E} \text{ MeV}$. The solid black circles are from the real events, red open circles are the mixing events, pink open triangles indicate the ratios of the real events to the mixing events.
Fig. 7. (color online) The reconstructed excitation energy distributions of $^{12}$C from $3s$ with $E_{ij}^{	ext{min}} = 0.092 \pm \frac{2}{3} \Delta E$ MeV, $E_{ij}^{	ext{max}} = 0.092 \times 2 \pm \frac{2}{3} \Delta E$ MeV. The solid black circles and the red open circles respectively denote the real events, the mixing events, pink open triangles indicate the ratios of the real events to the mixing events.

4 Summary

We have discussed the Efimov (Thomas) states in excited $^{12}$C nuclei in the reactions $^{70(64)}$Zn($^{64}$Ni) + $^{70(64)}$Zn($^{64}$Ni) at beam energy of E/A=35 MeV/nucleon. In order to investigate the $^{12}$C, we analyzed the events with $\alpha$ multiplicity equal to three. The excitation energies of $^{12}$C are reconstructed by considering the three $\alpha$ relative kinetic energies. The interaction between any two of the three $\alpha$ particles provides events with one, two or three $^8$Be interfering levels. The events with three relative kinetic energies equal to the ground state energy of $^8$Be are found when decreasing the acceptance width. It might be a signature of the Efimov (Thomas) states in $^{12}$C excited energy level of 7.458 MeV. Dedicated experiments with better experimental resolution are suggested in order to exclude any possible experimental effect in the data analysis.

References

1. L. H. Thomas, Phys. Rev., 47: 903 (1935).
2. V. Efimov, Phys. Lett. B, 33: 563 (1970).
3. V. Efimov, Nat. Phys., 5: 533 (2009).
4. E. Braaten, H.W. Hammer, Phys. Rep., 428: 259 (2006).
5. A. Tumino, A. Bonasera, G. Giuliani et al., Phys. Lett. B, 750: 59 (2015).
6. T. Kraemer, M. Mark, P. Waldburger et al., Nature, 440: 315 (2006).
7. M. Zaccanti, B. Deissler, C. D’Errico et al., Nat. Phys., 5: 586 (2009).
8. Bo Huang et al., Phys. Rev. Lett., 112: 190401 (2014).
9. M. Gattobigio, A. Kiewsky, Phys. Rev. A, 90: 012502 (2014).
10. H. Zheng and A. Bonasera, arXiv:1811.10412.
11. S. Zhang et al., arXiv:1810.01713.
12. S. Wenzel et al., Nucl. Instrum. Methods A, 604: 578 (2009).
13. R. Schmitt et al., Nucl. Instrum. Methods A, 354: 487 (1995).
14. Z. Kohley, 2010 PhD Thesis Texas A &M University.
15. Z. Kohley et al., Phys. Rev. C, 83: 044601 (2011).
16. Z. Kohley et al., Phys. Rev. C, 86: 044605 (2012).
17. G. Giuliani et al., Prog. Part. Nucl. Phys., 76: 116 (2014).
18. A. Bonasera, F. Gulminelli, J.Molitoris, Phys. Rep., 243: 1 (1994).
19. Y.G. Ma, Phys. Rev. Lett., 83: 3617 (1999).
20. Y.G. Ma, J. B. Natowitz, R. Wada et al., Phys. Rev. C, 71: 054606 (2005).
21. C.W. Ma, Y.G. Ma, Prog. Part. Nucl. Phys., 99: 120 (2018).
22. Y.G. Ma, R. Wada, K. Hagel et al., Phys. Rev. C, 65: 051602(R) (2002).
23. Z.F. Zhang, D.Q. Fang, Y.G. Ma, Nucl. Sci. Tech., 29: 78 (2018).
24. W.D. Tian, Y.G. Ma, Z.X. Cai et al., Chinese Phys. C, 30(S2): 280 (2006).
25. X. Jiang, N. Wang, Chinese Phys. C, 42(10): 104105 (2018).
26. P. Marin et al. [INDRA Collaboration], Phys. Lett. B, 756: 194 (2016).
27. K. Schmidt et al., Phys. Rev. C, 95: 054618 (2017).
28. J. Mabiala, H. Zheng, A. Bonasera et al., Phys. Rev. C, 94: 064617 (2016).
29. A. Tohsaki, H. Horuchi, P. Schuck, and G. Ropke, Phys. Rev. Lett., 87: 192501 (2001).
30. Y. Funaki, T. Yamada, H. Horuchi et al., Phys. Rev. Lett., 101: 082502 (2008).
31. M. Freer et al., Phys. Rev. C, 49: R1751 (1994).
32. Ad. R. Raduta et al., Phys. Lett. B, 705: 65 (2011).
33. J. Manfredi et al., Phys. Rev. C, 85: 037603 (2012).
34. O. S. Kirsebom et al., Phys. Rev. Lett., 108: 202501 (2012).
35. T. K. Rana et al., Phys. Rev. C, 88: 021601 (2013).
36. M. Itoh et al., Phys. Rev. Lett., 113: 102501 (2014).
37. R. Smith et al., Phys. Rev. Lett., 119: 132502 (2017).
38. D. Dell’Aquila et al., Phys. Rev. Lett., 119: 132501 (2017).
39. H. Zheng, A. Bonasera, M. Huang and S. Zhang, Phys. Lett. B, 779: 460 (2018).
40. F. Hoyle, Astrophys. J. Suppl. Ser. 1: 121 (1954).