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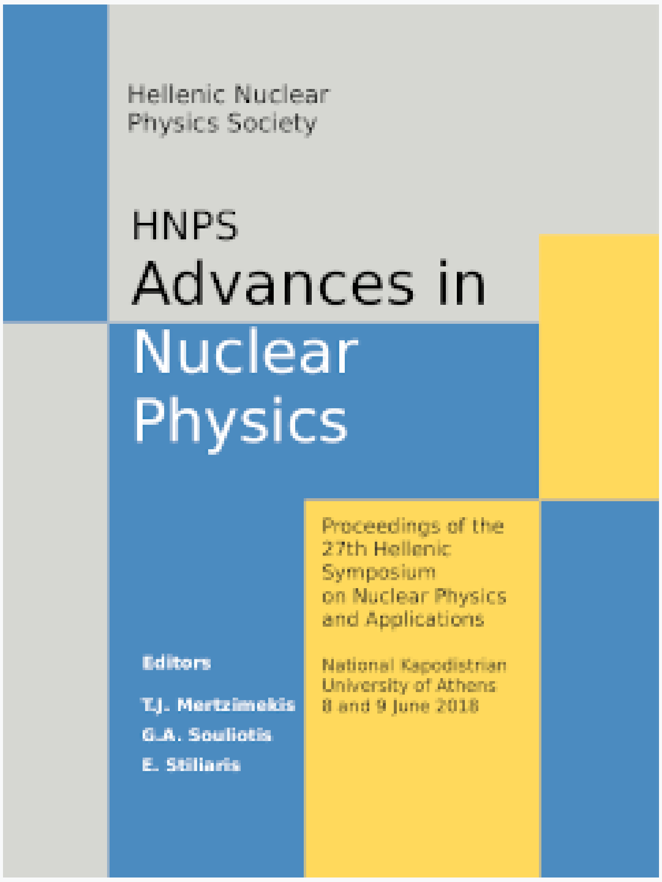

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Efimov States From Triple α Resonances

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Abstract

The Efimov trimers in excited ^{12}C nuclei, 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 αs interact with each other and can form complex systems such as ^{8}Be and ^{12}C. For the 3α systems, multi resonance processes give rise to excited levels of ^{12}C. The interaction between any two of the 3α 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 α relative energies consistent with the ground state of ^{8}Be are observed with the decreasing of the instrumental error at the reconstructed 7.458 MeV excitation energy of ^{12}C, which was suggested as the (Thomas) Efimov state.

Keywords: Hoyle state, Efimov state, ^{12}C excited state, few body system, Heavy ion reactions

The basic condition for the Efimov effect is the existence of resonant two-body forces [1–4]. The so-called Efimov trimers appear for a system of three particles with resonant two-body interactions in a way that three or more interacting particles may form bound states even when any two of

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the particles are unable to bind. When the two-body scattering length a is much larger than the range of the interaction potential r_0, the three-body physics becomes independent of the details of the short-range interaction and takes kind of universal character. This universality has been experimentally exploited in ultracold atomic systems. Three-body and even four-body composites naturally form in an ultracold gas of alcali atoms [5–8] with resonant interactions and are detected after they decay into hot atoms and dimers, which rapidly leave the ultra cold sample. Quantum mechanics explains the existence of these few-body systems in a quite simple way [9]. Efimov [2] has predicted the possibility of the existence of trimers in three α particle system. His prescription refers mainly to ^{12}C levels in the vicinity of the threshold of breakup into three α-particles or α+^{8}Be, taking into account the Coulomb force among α particles which destroys the $1/r_0^2$ scaling at large distance where Coulomb force is dominant [2]. In this report, we present the signature of Efimov 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.

The experiment was performed at the Cyclotron Institute, Texas A&M University. Beams at 35 MeV/nucleon of ^{64}Zn, ^{70}Zn, and ^{64}Ni from the K-500 superconducting cyclotron were used to respectively irradiate self-supporting targets of ^{64}Zn, ^{70}Zn, and ^{64}Ni. The 4π NIMROD-ISiS setup [10, 11] was used to collect charged particles and free neutrons produced in the reactions. A detailed description of the experiment can be found in refs. [12–14].

When two heavy ions near the Fermi energy collide, 35 MeV/nucleon, the excitation energy deposited in the system is large enough for the system to get gently compressed at the beginning and then it expands and enters an instability region, the spinodal region, similar to the liquid-gas (LG) phase transition [15, 16]. In such conditions, fragments of different sizes are formed and can be detected. The NIMROD detector used in this experiment can distinguish rather well charges from 1 to 30 and masses up to 50. A typical result is plotted in Fig. 1 [12] together with a microscopic simulation, the Constrained Molecular Dynamics approach (CoMD) [15], showing a satisfactory agreement to the data. In order to test if some fragments are formed in excited states, an evaporation model, Gemini [15] is adopted. The reaction was followed up to a maximum time t_{max} using the CoMD model. Within the same model, the excitation energy of each fragment formed at t_{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_{max} >600 fm/c. ^{12}C fragments are about two orders of magnitude less abundant than proton and α-particles. These ions survive the violence of the collision while other ^{12}C might be in an excited state and decay before reaching the detector or collide with other fragments and get destroyed. Our technique, discussed for the first time in this paper, is tailored to select among all the possibilities the particular $^{12}\text{C}\rightarrow 3\alpha$ decay channel.

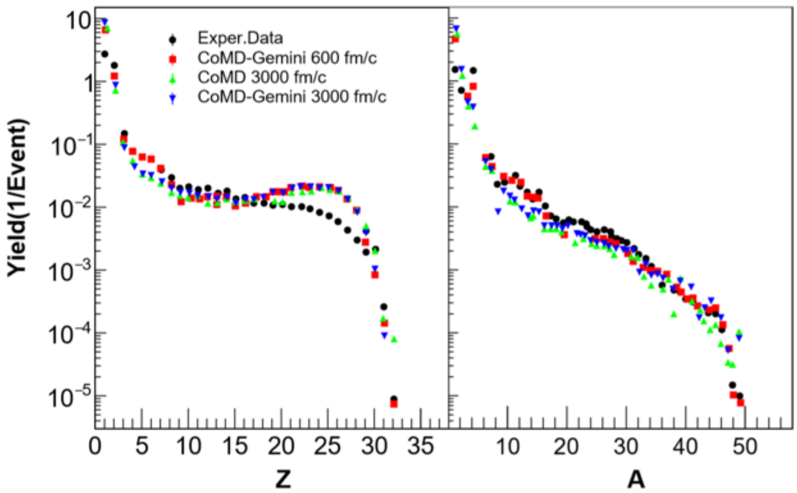

Figure 1: (color online)The minimum bias charge (Z) and mass (A) distributions from the ^{70}Zn+^{70}Zn system are shown for the filtered CoMD simulation in comparison to the experimental data. The results were normalized by the total number of events, ref. [12].

For the purpose of our work, we further selected all the events with only three α particles detected. 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 αs are in an event, other fragments type must be present and the sum of all the fragment masses is of the order of 140 including the three αs. This is a rich environment and depending on the proximity of different fragments to the α, ^{8}Be or ^{12}C ions, the properties and shell structure of the fragments might be modified. In particular, short living states of ^{12}C or ^{8}Be might be modified by the presence of other nearby fragments. In Fig. 1, we have seen some dependence on the yield using an afterburner and we have obtained typical interaction times of the order of 1000 fm/c from the CoMD calculations. On the other hand, long living states, say the Hoyle state of ^{12}C might not be influenced at all due to its lifetime, much longer than the reaction time. Of course, in such 'soup', α-particles might come from the decay of ^{12}C or

^{8}Be, from different excited fragments as well 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 α particles must be measured to a good precision. The kinetic energy distribution from the NIMROD detector for the events with α multiplicity equal to three is given in Fig. 2. It extends above 400 MeV and displays a large yield around 32 MeV. Since the kinetic energies are relatively large, the detector is performing best, and the error estimate 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 heavy ions near or above the Fermi beam energy, in fact 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, say ^{8}Be from α-α correlations, the center of mass motion cancels out and small relative kinetic energies can be obtained with an estimated error of about 45 keV for the smallest relative kinetic energies.

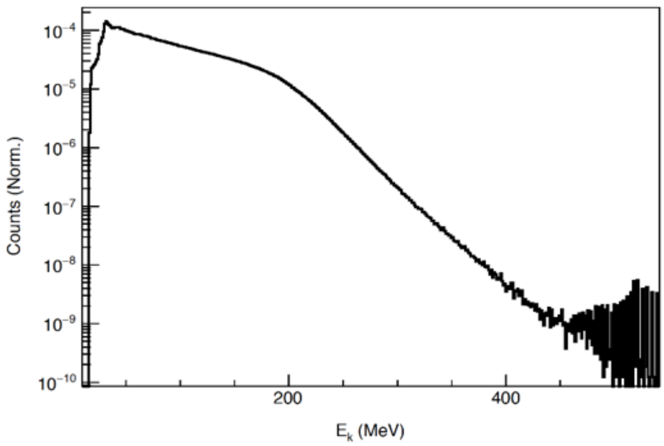

Figure 2: (color online)Experimental α-kinetic energy distribution in the laboratory frame from all the events with α-multiplicity equal to three.

For the equal mass three body system, we can define the excitation energy

E* as following:

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

where E_{ij} is the relative kinetic energy of two particles. 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, $E_{ij}^{Min.}$, the middle relative kinetic energy, $E_{ij}^{Mid.}$, and the largest relative kinetic energy, $E_{ij}^{Lar.}$.

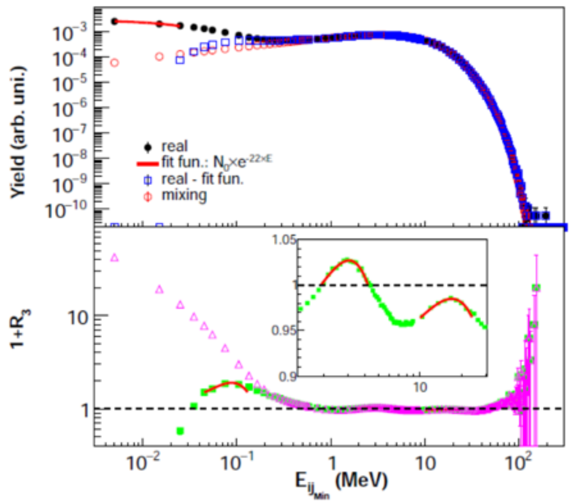

Figure 3: (color online)Selected events from $^{70(64)}$Zn(^{64}Ni) + $^{70(64)}$Zn(^{64}Ni) at E/A=35 MeV/nucleon with α multiplicity equal to three. Top panel is the relative kinetic energy distribution as a function of the minimum relative kinetic energy of 2αs. The solid black circles represent data 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 function (solid red line), which takes into account the experimental error. Bottom panel is the ratios of the real (pink open triangles) data and the real data minus the fitting function (green solid squares) divided by the mixing events as a function of the minimum relative kinetic energy. The solid lines on the green solid squares are Breit-Wigner fits of the peaks.

In this work, we can reconstruct the E*=7.458 MeV of the ^{12}C from 3αs when the sum of the three E_{ij} is 0.276 MeV with the Q-value= -7.275 MeV. In Fig. 3, 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 ^{8}Be or ^{12}C or they might come from completely non-correlated processes, for example, the α emission from a heavy fragment. To distinguish the correlated from the non-correlated events, we randomly choose three different αs from three different events and build the distribution displayed in Fig. 3 (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. 3 (top) with an exponential function. This allows us to derive the instrumental error ΔE=1/22 MeV=0.045 MeV. By subtracting the fit from the real events, we obtain the open squares in Fig. 3 (top), which can be considered as the real events corrected by the detector acceptance. As we can see, the first peak around 0.088 MeV with the width of 1192 fm/c (very close to 0.092 MeV) corresponding to the decay of ground state ^{8}Be, the second peak around 3.05 MeV with the width of 14.2 fm/c corresponding to the first excited state of ^{8}Be, and also higher energy peaks are visible.

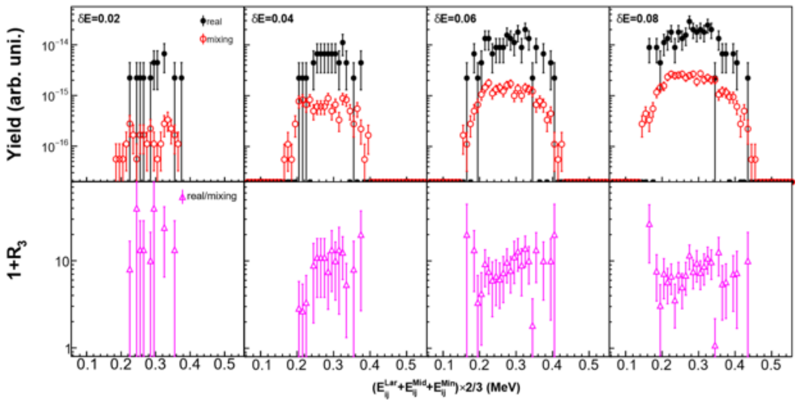

Figure 4: (color online)The total relative kinetic energy distributions with $E_{ij}^{Min.} = E_{ij}^{Mid.} = 0.092 \pm \frac{\delta E}{3}$ (MeV). The solid black circles are from the real events, red open circles are the mixing events, pink open triangles indicate the ratios of the real and mixing events.

In order to determine if we have events with equal relative kinetic energies, we have selected 3α events with $E_{ij}^{Min.} = E_{ij}^{Mid.} = 0.092 \pm \frac{\delta E}{3}$ MeV and decreased the value of δE to the smallest value allowed by statistics. In Fig. 4, we plot the results for the real (solid black circles) and the mixing (open circle) events in the upper panels, and their ratio (1+R$_3$) in the bottom panels. Even though the number of events decreases to almost 14 for the δ

E=0.02 MeV, we also see a signal around $(E_{ij}^{Lar.} + E_{ij}^{Mid.} + E_{ij}^{Min.}) \times \frac{2}{3} \leqslant 0.2$ MeV which is consistent with the suggested (Thomas) Efimov state[1, 2] at an excitation energy of ^{12}C of about 7.458 MeV.

In summary, we have discussed the (Thomas) Efimov 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 just analyzed only the events with α multiplicity equal to three. The excitation energies of ^{12}C are reconstructed by considering three α relative kinetic energies. The interaction between any two of the three α particles provides events with one, two or three ^{8}Be interfering levels, such as ground state and excited state of ^{8}Be, are searched by analyzing the minimum relative kinetic energy distribution for real and mixing events together. The events of three relative kinetic energies equal to the ground state energy of ^{8}Be are found with the decreasing of instrumental error, which is a signature of the (Thomas) Efimov states in ^{12}C excited level of 7.458 MeV.

Acknowledgments

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