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α and α Conjugate Fragment Decay from the Disassembly of ^{28}Si at Very High Excitation Energy

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Exclusive measurements for α and α conjugate exit channels are carried out for 35 MeV/nucleon ^{28}Si induced reactions. Systematic analyses of these channels reveal high energy resonance structures in 7α de-excitation channels. The resonances are compared with results of several recent theoretical calculations for toroidal high-spin isomers. The possible underlying physics of these observations are discussed.

KEYWORDS: α conjugate nucleus, toroidal nucleus, high spin, high excitation energy

1. Introduction

Various different shapes are predicted for nuclei, e.g., besides sphere, oblate spheroid, 'rugby ball', pear, banana, pyramid, chain, bubble and toroidal. Recently, electromagnetic probes such as electric octupole measurements provide direct evidence for the pear shape in ^{224}Ra [1] and ^{144}Ba [2]. A proton bubble in the ground state of ^{34}Si is reported using gamma-charge particle coincident measurements [3]. α clusters, halos and molecular states have been extensively studied in α conjugate nuclei and nuclei far from the β-stability line [4–7]. The possibility of existence of nuclear toroidal under some specific conditions was predicted by Wheeler long ago [8]. Then Wong systematically studied toroidal nuclei in intermediate and heavy mass region and found that large shell effects, large angular momentum and large Coulomb energies play important roles in populating the toroidal configurations [9]. More recently, various sophisticated microscopic methods address this question of toroids in light and intermediate mass nuclei again, such as Zhang et al. [10], Ichikawa et al. [11] and Staszczak and Wong [12].

However, the experimental progress on toroidal nuclei is limited. A recent search for heavy toroidal-shaped objects in ^{197}Au + ^{197}Au indicated that the probability of events with planar fragmentation configurations in the experimental data was much larger than predicted by quantum molecular dynamics simulations [13]. A series of experiments using 15, 25, 35 MeV/nucleon ^{28}Si and ^{40}Ca beams on C, Si, Ca and Ta targets were carried out at Cyclotron Institute of Texas A & M University using the 4π detection array, NIMROD-ISiS (Neutron Ion Multidetector for Reaction Oriented Dynamics with the Indiana Silicon Sphere), which covers θ from 3.6° to 167° with 14 concentric rings [14, 15]. The pulse shape discrimination method was used to identify the Z ≤ 3 light charged particles in CsI(Tl). Intermediate mass fragments (IMFs), were identified with the telescopes and super-telescopes using the ΔE - E method. An isotopic resolution up to Z = 12 and an elemental identification up to Z = 20 can be achieved in the forward rings. Here we just focus main results from ^{28}Si + C reactions. Please refer to references [16, 17] for more details on the detection system, energy calibrations, and more results [18–20].

2. Results and analysis

For ^{28}Si+^{12}C at 35 MeV/nucleon, the maximum angular momentum, L_{max}, corresponding to a reaction cross section of 2417 mb is 94$\hbar$ while the L_{crit} for fusion is 26 $\hbar$ and the angular momentum limit of rotating ^{28}Si liquid drop is around 40$\hbar$ [21] . It is found that the binary reaction mechanism leading to excited projectile-like and target-like nuclei exit channels is dominant at this incident energy. Macroscopic toroids fragmentation as a result of the development of Plateau-Rayleigh instabilities has been well established [22], and is dominated by symmetric fragmentation into equal size pieces. Nuclear toroids might also manifest Plateau-Rayleigh instabilities. In order to access the toroidal states populated in early stages of the reaction, judicious choices of exit channel and observable will be high necessary. α and α-conjugate exit channels should carry valuable information since α can be treated as an inert unit and α-quartetting around low density and moderate temperature is dominant [23]. Recent experiment [20] and simulation [24] both found that clustering plays important roles in reactions dynamics and exit channels. Totally about 17 million events were recorded for ^{28}Si+^{12}C at 35 MeV/nucleon and it is surprising that a significant proportion evens, about 3.19×10^5, had α-conjugate mass summing to 28. Among them, around 6500 events with 7α emission were observed.

The longitudinal velocity, v_L, distributions of 7α channel as well as all other α-conjugate channels are shown in Fig. 1. The beam velocity is 8.0 cm/ns for 35 MeV/nucleon ^{28}Si. The v_L distribution for the 7α channel peaks forward around 6.5 cm/ns while the v_L distributions for the other α-conjugate nuclei and α particles all peak around projectile-like velocities. The Gaussian-type v_L distribution of 7α clearly verifies that they are mostly from one single source, the excited projectile-like ^{28}Si nucleus. The small asymmetric bump at $v_L \sim 2$ cm/ns indicates the very small degree of contamination from the target-like source due to the given thresholds and geometry of the NIMROD detector. Such contaminated events are rejected by removing events with α energy larger than 40 MeV in 7α center-of-mass frame when we construct the excitation function of 7α channel shown by Fig. 2.

The experimental 7α excitation function appears to have structure at the higher excitation energies. To explore the resonance structure in high excitation energy, we use a couple of different strategies. An uncorrelated spectrum derived from event mixing is represented by a solid red line in Fig. 2 (a). The filtered antisymmetrized molecular dynamics (AMD) simulations by NIMROD-ISiS detection efficiency and energy resolution based on its solid angle coverage and granularity with a GEMINI afterburner to estimate the background is shown by a dashed blue line. The backgrounds

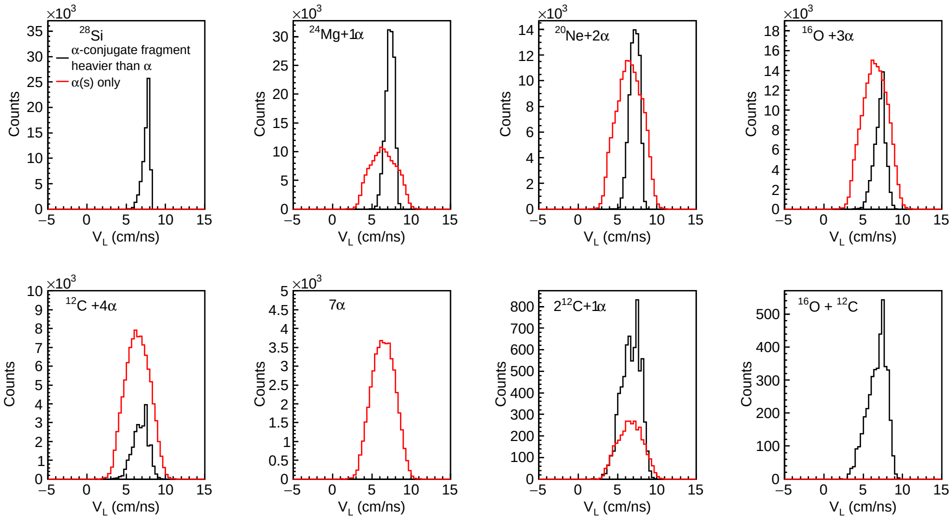

Fig. 1.: The longitudinal velocity for α-conjugate exit channels of ^{28}Si + ^{12}C at 35 MeV/nucleon.

from event mixing and simulations are both normalized to the experimental spectrum at the lower edge by an optimized χ^2 since no resonance is predicted there.

The correlated spectra are obtained by subtracting the normalized background spectra. The instrument width for 7α excitation energy at 140 MeV has a standard deviation ~ 4MeV obtained by Monte Carlo simulations based on the NIMROD-ISiS granularity. By adding 7α events with excitation energy in a δ function form at E_x = 143 MeV to the uncorrelated 7α events spectrum constructed by a standard random event mixing technique, which samples each 7α event from 7 different correlated 7α events of data with only allowing one α from each correlated 7α event, the resultant excitation energy spectrum filtered by detection efficiency and energy resolution based on NIMROD-ISiS granularity is consistent with the observed spectrum shape of data. The peaks around 114, 126, and 138 MeV have statistical significances 5.0σ, 7.9σ, and 7.1σ, respectively for the uncorrelated background derived from data. The resultant corresponding statistical significances are 4.2σ, 6.0σ , and 6.6σ for background of AMD+GEMINI. The resonance structures with such high excitation energy are quite unusual. The correlated 7α resonance structures appear around the energy region predicted for toroidal isomer . Recently, Staszczak and Wong predicted a 143.18 MeV toroidal state with 44$\hbar$ [12]. A couple of theoretical calculations using toroidal shell model and covariant density functional theory are carried out and satisfactory agreement with data is obtained. Please refer to Refs [18, 19, 25, 26] for more experimental and theoretical details due to the limited space here.

3. Summary

The α and α conjugate exit channels of ^{28}Si + ^{12}C at 35 MeV/nucleon are explored in detail. Several resonance structures with large significances are observed at very high excitation energies in excitation function of 7α decay channel. The features of these resonances appear to coincide with results from toroidal shell model and covariant density functional theory. Further experimental with a higher granularity detector system and the addition of gamma ray detectors is clearly needed to make further confirmation and improvement.

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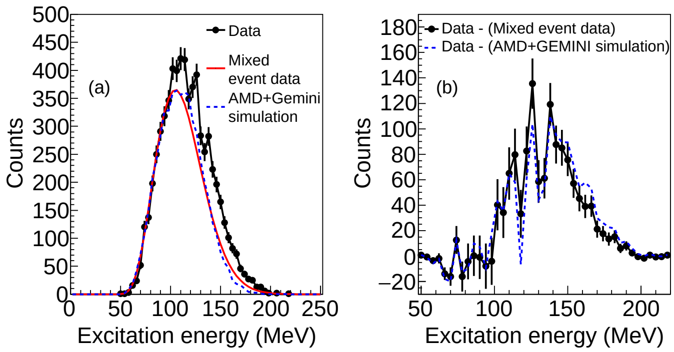

Fig. 2.: Excitation functions of observed 7α events.

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