Searching for high-spin toroidal isomers in collisions induced by α-conjugate nuclei

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Nuclei in the valley of stability are usually treated as a fluid made of nucleons with sphere-like geometry in their ground states. However, correlations between nucleons and cluster formation play more important roles in excited nuclei. For light excited α-conjugate (even-even N=Z) nuclei, the importance of α clusters is apparent in both theoretical calculations and experimental observables.

Wheeler suggested that nuclear liquid can assume toroidal shapes under certain conditions [1]. Wong et al. quantitatively discussed where the existence of a toroidal nucleus and its stability against sausage deformation [2, 3]. In light α-conjugate nuclei the α particle can be expected to be important in the toroidal configuration which leads to a reduced nuclear density. Heavy ion collisions induced by light α-conjugate nuclei may provide the appropriate conditions to access toroidal isomers with high angular momentum and excitation energy. The toroidal isomer may manifest itself by decaying into α particles or α-like fragments (where the α-like fragments refer to α, ^{12}C, ^{16}o, and ^{20}Ne etc.). Therefore, an experimental exploration with special attention and methodology into observing α-like decays is indicated and very intriguing.

A series of experiments were carried out at Texas A&M University Cyclotron Institute with ^{40}Ca and ^{28}Si beams at 10, 25, 35 MeV/u provided by the K500 superconducting cyclotron incident on ^{28}Si, ^{12}C, ^{40}Ca, and ^{181}Ta targets [4], respectively. The combinations with different α-conjugate projectiles (^{28}Si and ^{40}Ca) and targets (^{12}C, ^{28}Si, and ^{40}Ca) may favor population of different α cluster states. The reaction products were detected using a 4π array, NIMROD-ISiS (Neutron Ion Multidetector for Reaction Oriented Dynamics with the Indiana Silicon Sphere), which consisted of 14 concentric rings covering from 3.6° to 167° in the laboratory frame. In addition, the neutron ball surrounding the NIMROD-ISiS charged particle array provided information on average neutron multiplicities for different selected event groups. The preliminary analysis of parts of the raw data was accomplished by C. Bottosso, E-J Kim, and K. Schmidt *et al.* [4] and some interesting preliminary results about the α-like mass (Almass) emission have been obtained for ^{40}Ca+^{40}Ca [5]. Here we focus on cluster decay from ^{28}Si and check its dependence on ^{12}C, ^{28}Si and ^{181}Ta targets [6].

For the ^{28}Si+^{12}C reaction, a total of 17 million events were recorded and a significant proportion of events have significant alpha-like mass emission. Half a million events have Almass=28. There are 7 alpha-like decay channels with Almass=28 as shown in Fig. 1. For the most interesting event group: 7 α decay channels, more than 10 thousand events are obtained.

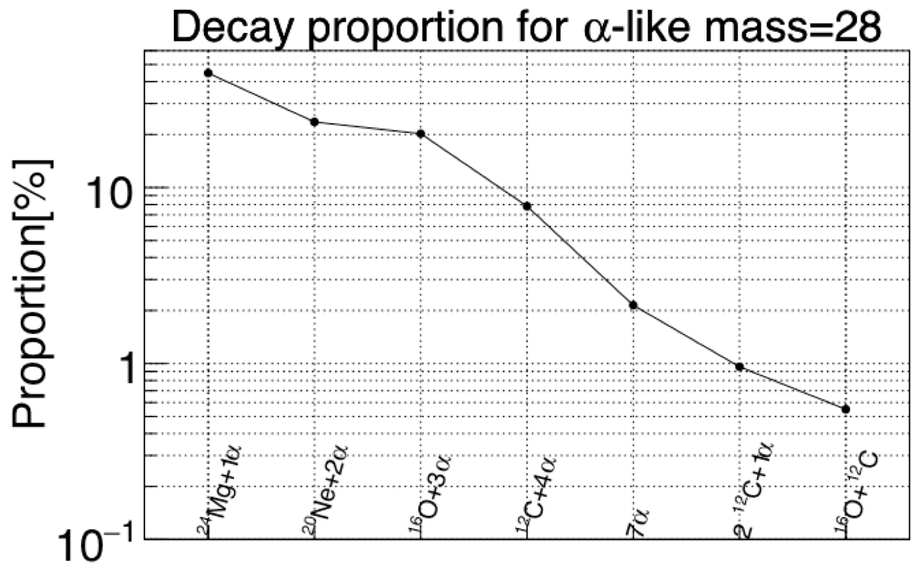

FIG. 1. The proportion of decay channels for Almass=28 from ^{28}Si+^{12}C @ 35MeV/u.

The hierarchy effect, which refers to a correspondence between fragment mass and parallel velocity, was found for α-like fragments from ^{40}Ca decay [5]. For most of the ^{28}Si channels this hierarchy effect is also observed. The angles between α and heavier fragments are shown in Fig. 2. The αs tend to

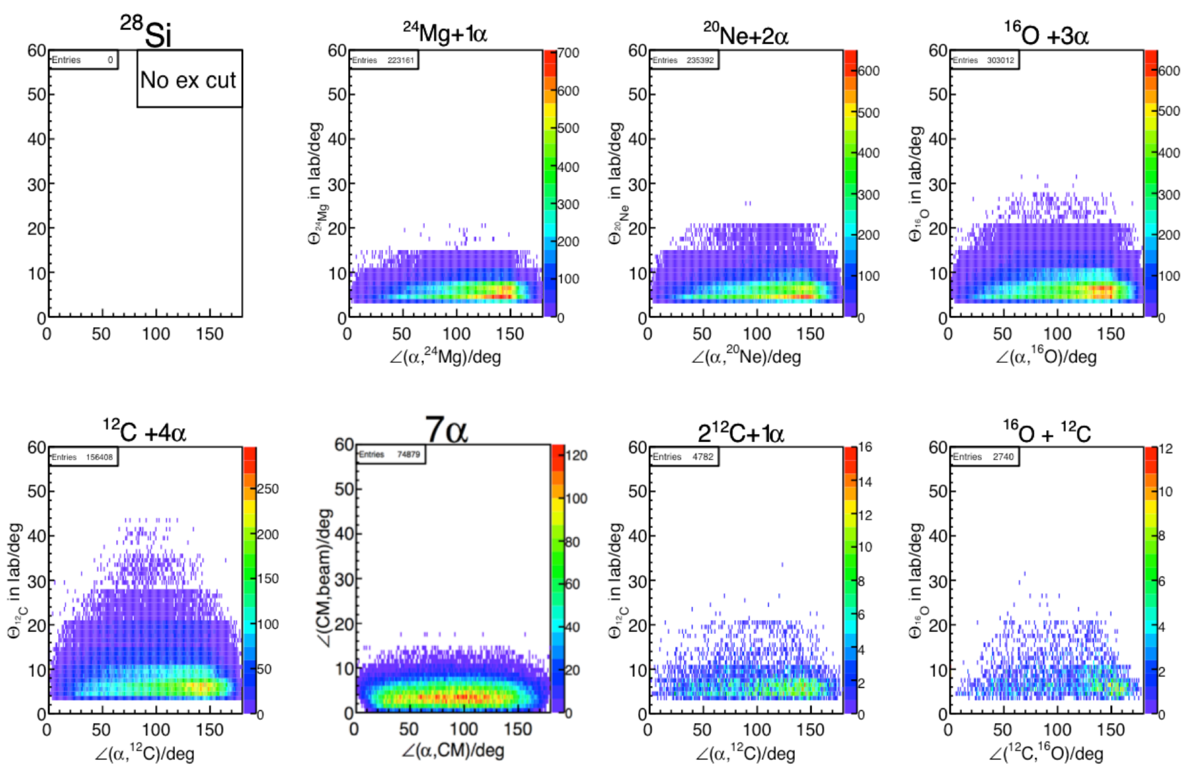

FIG. 2. The emission angle between α and heavier fragment for the α-like decay channels. For the 7 α channel, the angle is calculated between center-of-mass velocity and the velocity of α particles.

be emitted backward relative to the large fragment, indicating they mainly come from the neck region. This means absence of complete equilibrium of the α-like emission source.

In order to explore the configuration of the possible toroid formed in the dynamical stage, we utilize a shape analysis technique to diagnose the source shape in momentum space [7]. Shape analysis is a popular method to study emission patterns of sources, dynamical aspects of multifragmentation and collective flows of particles in relativistic heavy ion collisions. A tensor constructed on the momenta can be written as: $T_{ij} = \sum_{\nu=1}^{N} p_i^{\nu} p_j^{\nu}$, where N is the total nucleon number, p_i^{ν} is the momentum component of ν^{th} nucleon in the center-of-mass and i refers to the Cartesian coordinate. The tensor can be diagonalized to reduce the event shape to an ellipsoid. The eigenvalues of the tensor: λ_1, λ_2, and λ_3, normalized by: $\lambda_1 + \lambda_2 + \lambda_3 = 1$ and ordered according to: $\lambda_1 \le \lambda_2 \le \lambda_3$, can quantitatively give shape information of the events. The sphericity is defined as: $S = \frac{3}{2}(1 - \lambda_3)$, and coplanarity is defined as: $S = \frac{\sqrt{3}}{2}(\lambda_2 - \lambda_1)$. In the sphericity-coplanarity plane, the ideal rod, disk and sphere events exactly locate at the three vertexes of the triangle: (0,0) (3/4, $\sqrt{3}/4$), and (1,0), respectively. A schematic figure of shape analysis is shown by Fig. 3.

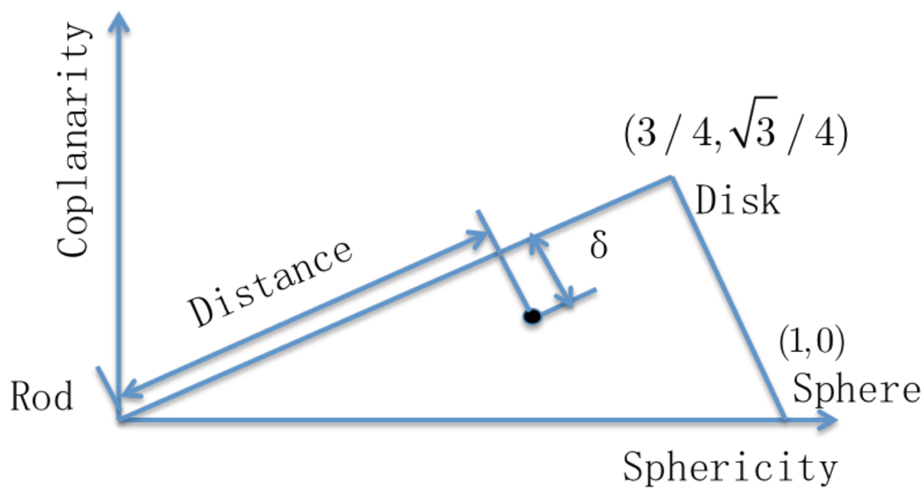

FIG. 3. A schematic figure illustrating the shape analysis method, where the δ and distance definitions are used in Fig. 5.

The results of the shape analysis are shown in Fig. 4. events. Two fragments will always have a rod shape in momentum space while three fragments can form a plane or rod shape. We can see there are always some events located around the disk point, which may be the toroidal candidates, especially for the 7 α channel.

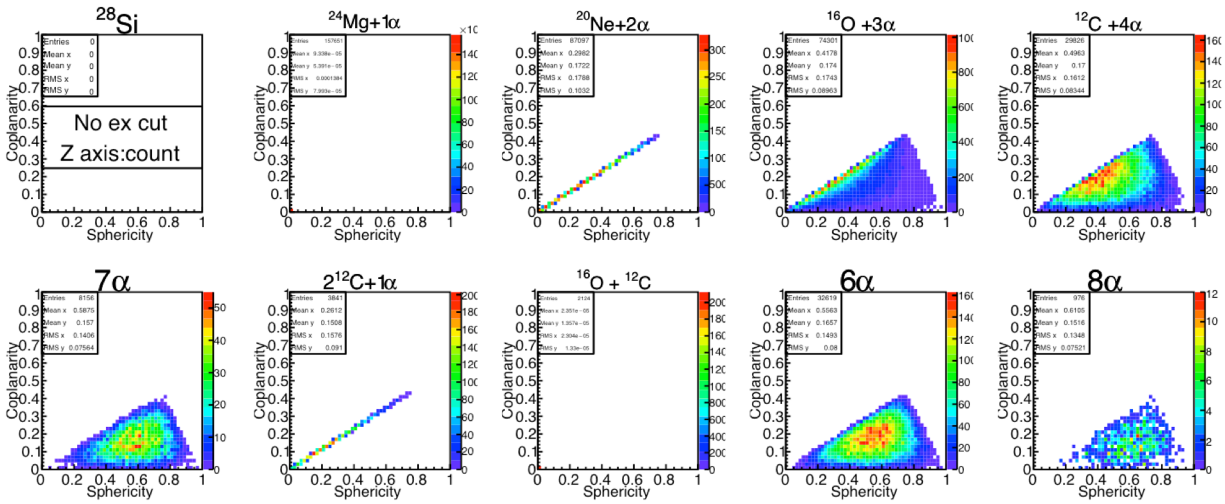

FIG. 4. Shape analysis of sources decaying by Almass.

We extract the excitation energy of source decaying by Almass by scanning around the rod-disk line. The extracted excitation energy is shown in Fig. 5, with cut labeled: $\delta \in [0,0.05]$ and $distance \in [0.4,0.6]$, where the δ and distance are defined in Fig. 3. For our most interesting channel: 7 α, there are several peaks near the 143.18 MeV energy predicted by Staszczak and Wong's [3]. They predicted this to be a 44 $\hbar$ ^{28}Si isomer corresponding to a toroidal configuration. The 6 α and 8 α channels are included for comparison. For the 6 α channel, there are no obvious peaks. For the 8 α channel, at least one α would have to come from the target-like fragment (TLF). The statistics are low and this suggests that the 7 α we analyzed may be relatively free of contributions from decay of the target-like fragment (TLF).

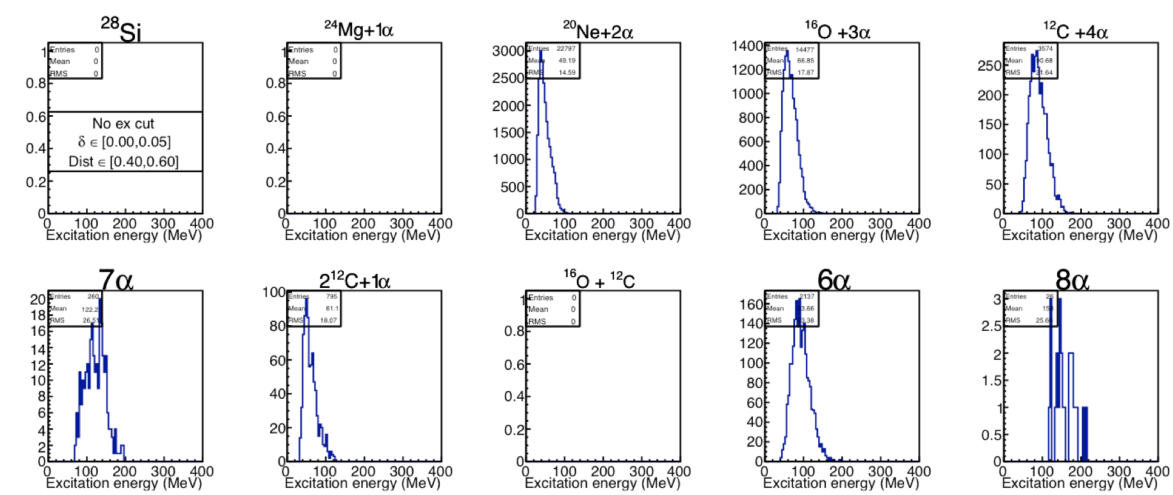

FIG. 5. Excitation energy of Almass source with cut on sphericity-coplanarity plane.

A determination of the angular momentum of Almass source is necessary to pin down the toroidal candidate. Such a determination is difficult. Antisymmetrized molecular dynamics (AMD) simulations are in progress.

Similar results are seen for the $^{28}S+^{28}Si$, and $^{28}Si+^{181}Ta$ systems at 35MeV/u. However, the statistics for the $^{28}Si+^{181}Ta$ reaction is much lower than for the other two systems.

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