Revisit to experimental search for high-spin isomers in inverse collisions of $^{28}Si+^{12}C$ at 35 MeV/nucleon using FAUST array

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In our previous work of Ref. [1], we reported three possible candidates with estimated cross sections of 30-50μb for toroidal high-spin isomer states at high excitation energies in ^{28}Si in the 7α decay channel, using inverse kinematic collisions of $^{28}Si+^{12}C$ at 35 MeV/nucleon with the NIMROD 4π array.

To verify the results with higher energy resolution and better statistics, the same reaction was studied with the upgraded FAUST array. As reported in Ref.[2], no strong evidence wes observed for such resonances above the 20μb range and precluded smaller peaks as statistical fluctuations. In the 1μb range, however, strong correlations are observed among peaks in the excitation energy distribution of the subsets of 7α events. In Fig.1, the deviation from the average yield and their standard deviations are

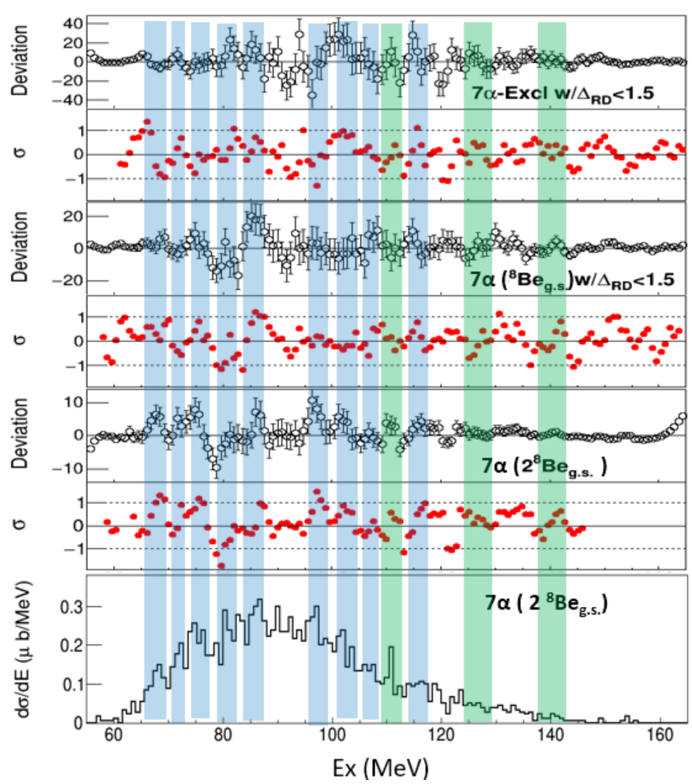

FIG. 1. Candidate resonance peaks. (Top 6) Each two figures from the top shows the deviation from the averaged excitation energy distribution and their statistical standard deviation values (top 2) for exclusive 7α events under a condition of $\Delta_{RD}<1.5$, where events decaying through any cluster formation are excluded, (middle 2) for 7α events decaying through one ^{8}Be(gs) under a condition of $\Delta_{RD}<1.5$, (bottom 2) for 7α events decaying through two-^{8}Be(gs). (Bottom) The excitation energy distribution of 7α events decaying through two-^{8}Be(gs). Blue bars indicates the location of the resonance peaks assigned in this work and green indicates those from Ref.[1]. For a description of the method of calculating the deviations and their standardization, see Ref. [2].

shown for the 7α sub-event sets with a condition of $\Delta_{RD} \leq 1.5$, with decaying trough ^{8}Be(gs) + $\Delta_{RD} \leq 1.5$, and with two ^{8}Be(gs). $\Delta_{RD} \leq 1.5$ condition is set to select events with larger angular momentum. Δ_{RD} is the distance from the rod-disk line in a sphericity-coplanarity plot. As one can see, many peaks are correlated each other at a given excitation energy. Note that events in all three sub-event sets are exclusive from each other.

Utilizing a shape analysis method [3], simulated event sets are generated in two steps to characterize these candidate resonance peaks, focusing on their physical shapes and angular momentum. In the first step, different shapes of 7α initial nuclei are generated using EQMD [4]. More than 5M ^{28}Si 7α initial nuclei are generated. Fluctuation in their cooling process generates different shapes. In order to determine their physical shape, a shape analysis method in their coordinate space is utilized. About 80% of the generated initial nuclei have a disk shape. 15% are categorized as spherical. 1% are in a rod shape. The nuclei with a toroidal shape are made from the disk shape nuclei, by excluding nuclei which has α (or αs) within a radius of 1.5fm from the Z axis (XY is the disk plane). Similarly, tube-shaped nuclei (non-linear chain) are made from the rod-shape nuclei excluding those with α(s) within a distance 1.5fm from the Z-axis. Less than a few % remains in the latter two treatments. All shapes are made symmetric around the Z-axis.

The second step is to give kinetic energy to α's in the simulated event set with a given shape at a given excitation energy. Note that α's in the initial nuclei made by EQMD do not have any kinetic energy. For a resonance at the excitation energy E_x, the available energy for the kinetic energy is given by $E_{av} = E_x - Q$. This kinetic energy is divided into two parts, thermal energy and rotational energy. They are distributed among 7α's in two steps.

(1) Thermal energy E_{th} for simulated event sets is set from 1 MeV to E_{av} in every 1 MeV energy step. For each E_{th}, the rotation energy E_{rot} is given by $E_{rot} = E_{av} - E_{th}$. To add the kinetic energy to 7α, their momentum increases gradually using random vector in a small step (0.1 MeV/c) till the thermal energy of 7α reaches to E_{th}. In order to make a clear separation between the thermal and rotation energies, the total angular momentum L is required $|L| < 2$ at the end of this procedure.

(2) Rotational energy is given by rotating the whole 7α system around the Z axis, adjusting L_z to get E_{rot}. For a given E_{rot}, L_z becomes different for different shapes, since their moments of inertia are different.

Each set of the simulated events is compared to the events under a candidate peak to determine their shape and L_z one by one. Three observables are used for this purpose, α kinetic energy E_α, distance Δ_{RD} from the rod-disk line and distance from disk-sphere line Δ_{DS} from the momentum shape analysis. Δ_{RD} is closely related to L_z. Smaller Δ_{RD} corresponds to larger L_z . Δ_{DS} relates to the shape. Spherical shapes show smaller values and rod shape gives larger values. The shape and L_z from the simulated data set at the best χ^2 fit are assigned to each candidate resonance peak.

In Fig.2 an example of the χ^2 fit is shown for the candidate resonance at Ex=87.5 MeV. Here a tube shape is used instead of rod, which results a better fit than that of a rod in all cases. On the left, the fit results at the minimum χ^2 value are shown. E_α, Δ_{RD}, Δ_{DS} and L_z spectra are plotted from left to right and those for sphere, disk, tube and toroid are plotted from the top to the bottom. On the right, χ^2 values are plotted as a function of E_{th}. In this example the preference of the tube shape is observed. Note that

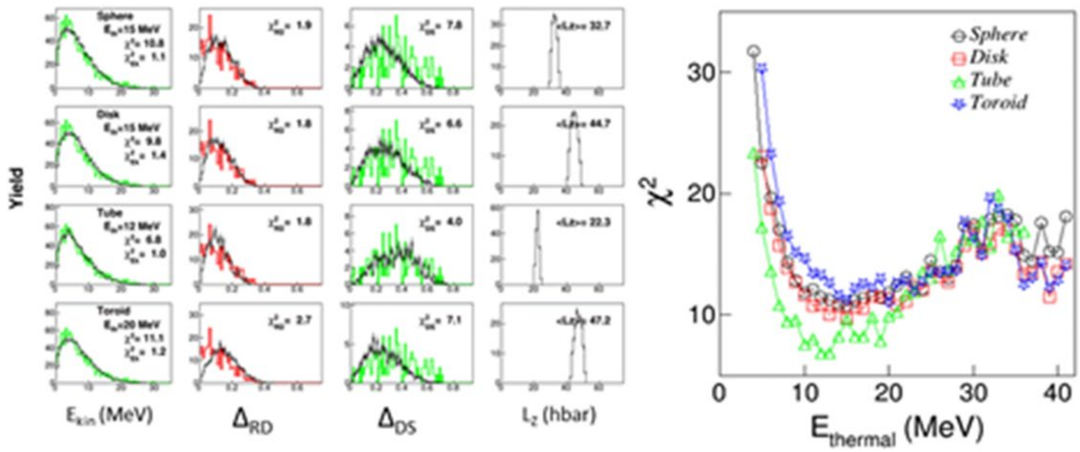

FIG. 2. An example of the χ2 fit for the candidate resonance at 87.5 MeV. (left) Colored spectra are from the experiment and black ones from the simulation. $\chi2 = \chi2_{Ek} + \chi2_{\Delta RD} + \chi2_{\Delta DS}$. <Lz> is the extracted average angular momentum. (right) χ2 value distribution as a function of Eth for different shapes.

this preference mainly originates from the shape of Δ_{DS} in the third column. The best χ^2 fit search is made for all candidate peaks. For the first four candidate peaks from the lowest up to 85.5 MeV, no preference for the shape is observed, indicating their angular momentum is small (L_z<20). In such cases the momenta are distributed randomly, resulting a distribution around the center in the momentum shape independent of the shapes. However those at higher excitation energy at E_x > 87.5 MeV, similar preferences of the tube shape are observed and L_z value is determined for each candidate resonant peak. This fact is consistent with the possibility that the candidate resonances are high-spin isomer states. They are summarized in Fig.3. The extracted L_z values show a good agreement with those of the theoretically

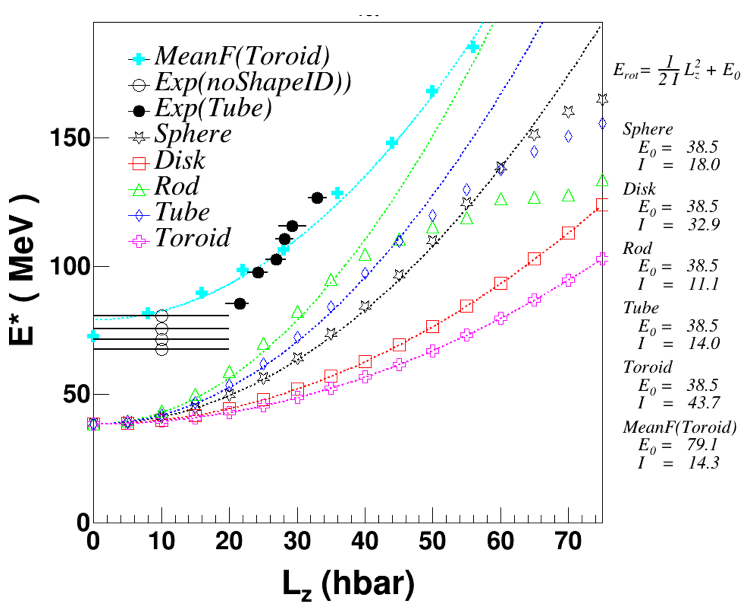

FIG. 3. Summary plot. Experimentally determined resonances are shown by open and closed circles. Open circles represent those with no shape assignment and tentatively L_z < 20 is given. Closed circles represent the preference of a tube shape with extracted L_z value. Light blue symbols are results from the mean filed calculation of Ref.[5]. Other symbols are yrast line for each given shape. Fit function E_{gs} and the moments of inertia are listed on the right.

predicted by Ren et al. in their mean field calculation [5], although their calculations are made for toroidal shapes, not for tube shapes.

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