Analysis techniques for investigating decay pathways in excited light nuclei

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Light nuclei are known to exhibit clusterization when excited. This clusterization of these nuclei is often correlated to how they decay through the emission of alpha particles and what subsequent nuclei are formed. The quintessential example of this is the Hoyle state in ^{12}C, which is known to dominantly decay through sequential emission of alpha particles [1], forming the unbound ground state of ^{8}Be in the process.

These light nuclei and their decay pathways have been studied in some detail over the past few decades but there are still many open questions. The techniques used to study ^{12}C can be explored in recent data collected from a variety of nuclei with the Forward Array Using Silicon Technology (FAUST) detector array [2] at Texas A&M University.

FAUST allows for precise measurements of momentum and particle type with reasonably large angular coverage (~1.5° - ~45°). The array consists of 68 ΔE-E telescopes assembled from a thin (300 um) Si detector, backed by a thick CsI(Tl) detector. The Si detector has resistive surfaces on both faces allowing for precise incident position to be ascertained event-by-event. Over several experiments, data were collected at 35 MeV/u for the following beams all on natural carbon: ^{16}O, ^{20}Ne, ^{24}Mg, ^{28}Si, ^{32}S, and ^{36}Ar. The normal kinematic system ^{12}C + ^{28}Si was also studied.

There are several analyses which can be performed on this dataset, the foundation of which is the ability to reconstruct decay pathways of the excited states of the nuclei through their initial excitation energies and those of their constituent particles. If one can assign decay pathways, one can study branching ratios and angular correlations of the decay products which aids the understanding of the clusterization of nuclei.

As an example to the statistical power these data hold, one can look at the excitation of ^{12}C in ^{12}C + ^{28}Si @ 35 MeV/u. In events where three alpha particles are measured, their relative energy to the 3-alpha center of mass can be determined and associated with an excitation in ^{12}C by the following equation:

$$E^* = \sum_i K_{i,c.m.} - Q_{rxn}$$

The resulting spectra is shown in the first following figure in black points. Several features are immediately apparent. From left to right, the Hoyle state appears at 7.654 MeV, and the next excited state in ^{12}C (a 3^- state) appears just above 9 MeV. Above this, many more states appear, each of which can be compared to literature. One can also look at the energy spectra of every combination of two alpha particles in the events which had three, resulting in Fig. 2.

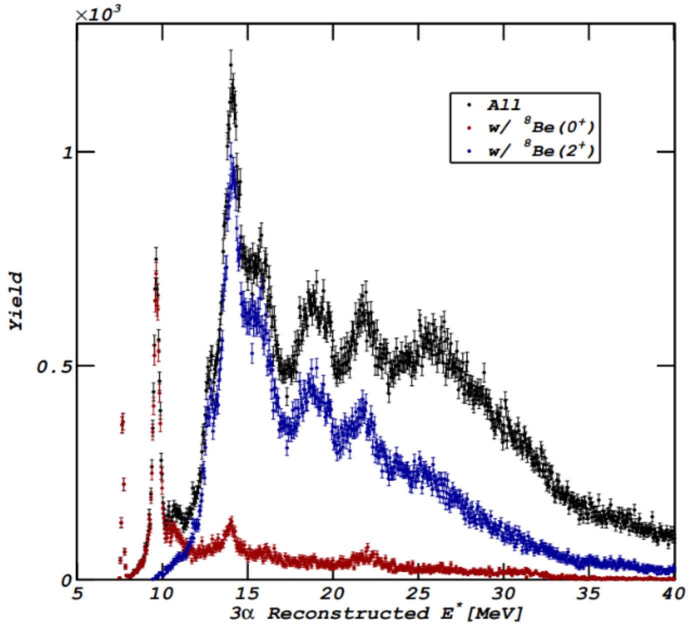

FIG.1. Alpha reconstructed energy, gated on nothing (black), events with a measured Be-8(gs) (red) and gated on states with a measured Be-8(2+) (blue).

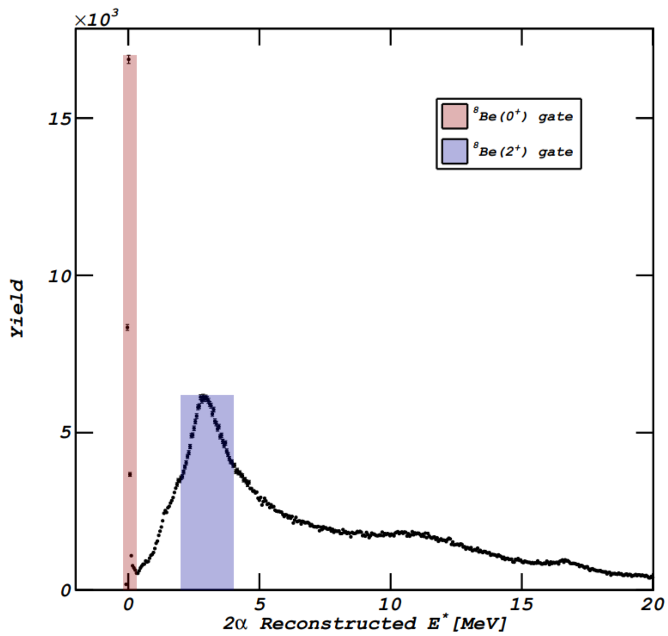

FIG. 2. Alpha reconstructed excitation energy showing gates on different states.

When ^{12}C decays via alpha emission, the remaining residue is an ^{8}Be which promptly decays by second alpha emission. The second spectrum shows which states are populated as an intermediate step from the ^{12}C decays; the very narrow ground state and the much broader 2^{+} first excited state in ^{8}Be are shown in red and blue, respectively. It is therefore possible to gate on three alpha events where one alpha-

alpha pair in the breakup possesses an E* within either shaded region; these gated spectra are shown in the first plot as the red and blue data, respectively. Immediately, one can see that the Hoyle state virtually always decays through the ^{8}Be ground state, as does the ^{12}C 3^- state. However, as the ^{12}C excitation energy increases, the relative contribution from the 2^+ state in ^{8}Be also increases. This technique demonstrates good agreement to reported data and is flexible to study other decay pathways of larger and more complex decay mechanisms in other nuclei going forward.

[1] https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.119.132501
[2] https://doi.org/10.1016/j.nima.2023.168130.