Investigating resonant state modification with a Coulomb trajectory model

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Heavy-ion collisions in the proper kinematic regime can produce excited projectile-like fragments (PLF*) that will subsequently de-excite via accessible pathways. Heavier and more excited nuclei favor the emission of light charged particles (LCP) and intermediate mass fragments (IMF) [1]; if the emitted component is an excited state IMF (IMF*), it will also de-excite, often by decaying into several LCPs. This de-excitation mechanism is well-understood for isolated decays, i.e., decays occurring without a spectator nucleus, but is otherwise less clear.

Unstable nuclei in isolation decay with well-defined energy distributions parameterized by their intrinsic energy and lifetime; however, when ejected from a de-exciting parent nucleus, these distributions can be modified following interactions with the parent's Coulomb field. The capacity for modification is directly related to the mean lifetime of the unstable ejectile; long-lived states decay unperturbed while shorter-lived states decay in the vicinity of the parent. This alteration is also dependent on the final *Z* compositions of the LCPs, ejection energy from the de-exciting parent, decay orientation, and decay energy of the ejectile. This class of dynamical interactions is known as resonant state modification.

Modification for two-body decays is quantified by the relative energy of decay of the state with respect to the breakup orientation angle, β, defined as the angle between the center-of-mass velocity vector of the children particles in the remnant frame and the relative velocity vector of the children particles (Fig. 1). Previous work investigating resonant state modification demonstrated that it was reproducible through simulation [2], although not beyond first order. It was hypothesized that the discrepancies present between simulation and experiment were consequent of influences from PLF* deformation, thermal fluctuations, and IMF*-PLF nuclear surface stabilization, but iterative incorporation of these failed to mitigate the differences [2].

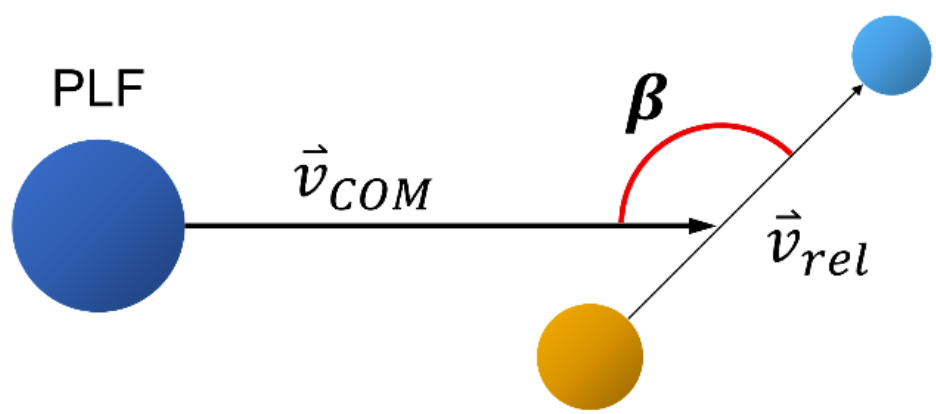

Fig. 1. Depiction of a two-body IMF* decay into two LCPs. For mass-asymmetric decays, β is defined as the angle between the COM velocity vector and the lighter child.

Experimental 35 MeV/nucleon ^{28}Si + ^{12}C collision data were taken with the position-sensitive Forward Array Using Silicon Technology (FAUST) at Texas A&M University; the excellent angular information provided by the array has permitted a more in-depth study of resonant state modification. The analysis method used is detailed in [3] but can be summarized as follows: events are selected based on if desired particles are present and those selected are used in the calculation of relative energy distributions of the children particles gated on regions of β. The means of these distributions are then isolated by uncorrelated background subtraction (mixed event analysis) and Gaussian peak fitting (Fig. 2).

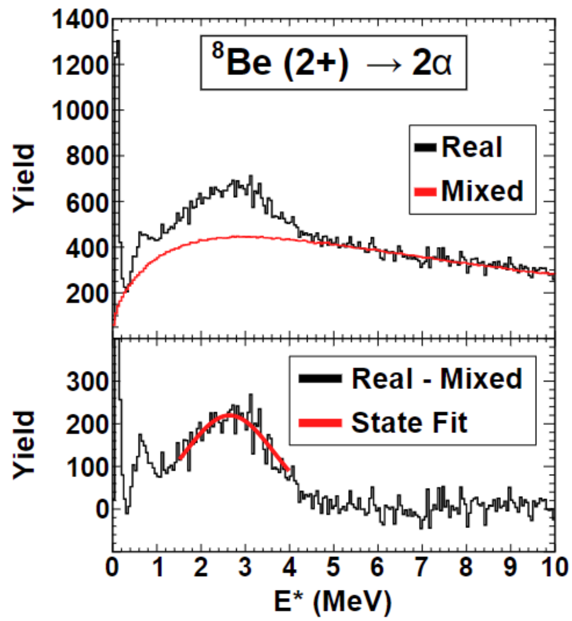

Fig. 2. Method for determining the relative energy mean value, performed here for ^{8}Be (2+) for 20° ≤ β < 25° [3]. (Top) Real (black) and mixed (red) event distributions in MeV. (Bottom) Real - mixed distribution overlaid with Gaussian fit of ^{8}Be (2+) peak (red).

To holistically investigate the phenomenon, a novel C++/ROOT Coulomb trajectory model is being developed to better understand the contribution and interplay of all relevant factors. Like its predecessors, the model simulates nuclei present in an event, performs the IMF* decay, then propagates all particles as legislated by the many-body Coulomb interaction. Properties of the simulation are sampled from corresponding distributions; simulations sample emission velocity from an experimental distribution of a stable isotope of the IMF*, breakup orientation from a sine distribution (assumed to be isotropic), decay time as exponential with parameter $\tau = 1/\Gamma(E)$, and decay energy in accordance with a one-level *R*-matrix description of the resonant state [4]. It is important to note that the decay time is not described by a standard singularly parameterized exponential ((i.e., $P(t) \propto \exp(t \cdot \tau_{literature}^{-1})$);i.e., rather, it is parameterized on an event-by-event basis using the width dependent on the sampled energy, $1/\Gamma(E)$ (Fig. 3).

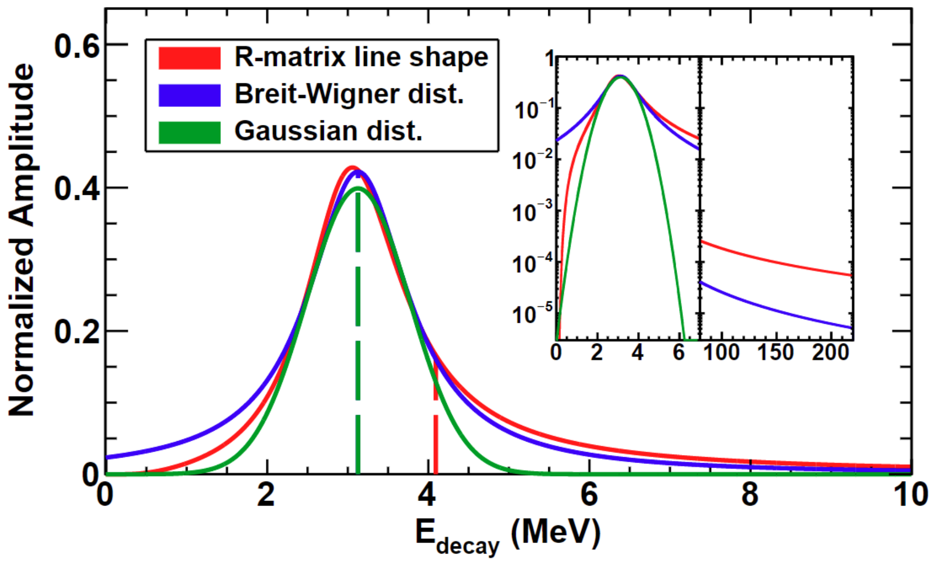

Fig. 3. *R*-matrix line shape for $^{8}Be\ (2^{+}) \rightarrow \alpha + \alpha$ from which the decay energy is sampled compared to a one-level Breit-Wigner and Gaussian description. The inset depicts the low- and high-energy tails of the distributions and how they compare. Decay energy samples are used to parameterize unique exponential curves from which lifetimes of events are sampled.

Preliminary results from the model for $^{8}Be\ (2^{+})$ are promising; further than simply replicating the experimentally observed trend of increasing relative energy with increasingly transverse breakup, the agreement between model and simulation within standard error is comprehensive across β (Fig. 4). In addition to changing various sampling distributions to investigate dependence, the starting position configuration of the remnant and unstable ejectile and that of the children particles were also varied. Initial simulations probing position dependence began with surface-surface configurations in which the nuclei, modeled as point particles, were separated by a distance $d = r_1 + r_2$ where each *r* is one nuclear radius (calculated as $r = r_0A^{1/3}$ where $r_0 = 1.25\ fm$). Introducing additional offsets acted to move the particles away from each other. Regarding $^{8}Be\ (2^{+})$, the inclusion of offsets for both the ejection and breakup configurations appeared to improve experiment and simulation agreement (Fig. 4).

While these results are promising, $^{8}Be\ (2^{+})$ is both mass- and charge-symmetric and decomposes into children particles that have a high detection efficiency in FAUST. To further characterize resonant state modification, investigating behavior of mass- and charge-asymmetric resonant states and states that decay into harder-to-detect products is necessary. An ideal candidate for such investigation is the $^{5}Li\ (3/2-) \rightarrow p + \alpha$ channel; this system, aside from being a resonant state modification candidate, satisfies *both* requirements by being both mass- and charge-asymmetric and by decaying into alphas and protons, the latter being harder to detect in FAUST.

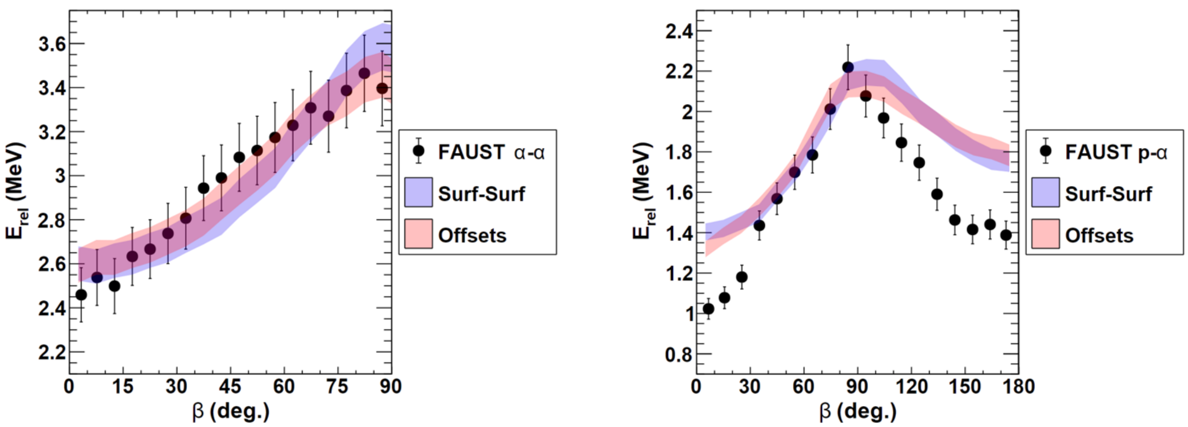

Fig. 4. Relative energy of decay versus breakup angle β for ^{8}Be (left) and ^{5}Li (right); experimental and simulated data use a remnant of Z = 10 and 8 ≤ Z ≤ 11, respectively. Touching spheres configuration is given as the blue curve and position offsets of 4 fm and 2 fm for ejectile-remnant and children, respectively, is given as the red curve. The inclusion of offsets has a non-negligible impact on the results.

Preliminary results from the model for ^{5}Li (3/2^{-}) are also promising, but they do expose shortcomings with the current formulation of the model. As with ^{8}Be (2^{+}), simulations reproduce the experimentally observed relationship between the relative energy and breakup orientation; however, orientations nearer parallel emissions systematically over predict the mean relative energy (Fig. 4). This effect is more pronounced for breakups near 180°, in which the proton emitted in the decay is more forward in the center of mass, versus near 0°, in which it is more backward; it was first believed that this was due to protons in the former orientation having a higher lab frame energy on average than protons in other orientations resulting in comparably less detection efficiency with the filter, but it was later surmised that this effect alone would act to *decrease* the mean relative energy. Subsequent hypotheses focus instead on "double filtering"; converting to the lab frame after simulating in the system center of mass relies on experimental data which implicitly incorporates geometric and particle acceptance. Regarding changes to initial position configurations, the inclusion of offsets in a similar fashion to ^{8}Be (2^{+}) had an effect of similar magnitude, although the change was neither wholly favorable or unfavorable.

In the interest of comparing the results for this work with those of previous, simulations using various sampling methods for the emission and breakup energies of ^{8}Be (2^{+}) were performed to determine where the largest discrepancies arise; this information is consolidated in Fig. 5. It can be seen that simple changes in the sampling methods have significant impacts on the simulated relative energy versus β distributions.

Future work investigating resonant state modification intends to continue exploring the "double-filtering" effect associated with ^{5}Li (3/2-) and to develop handling methods. Additionally, as used to justify the study of ^{5}Li, the continued exploration of resonant candidates with varying mass- and charge-asymmetries and intrinsic lifetimes is needed to fully characterize RSM. Current states of interest beyond what is shown here include ^{7}Li (1+) → $t + \alpha$ (Γ = 0.093 MeV) and ^{7}Be (7/2-) → $h + \alpha$ (Γ = 0.175 MeV) which aid specifically in the exploration of longer-lived states and sensitivities to modification. Although not shown, results for these are also very good and indicate that the bulk dynamical behavior for these systems is captured by the model.

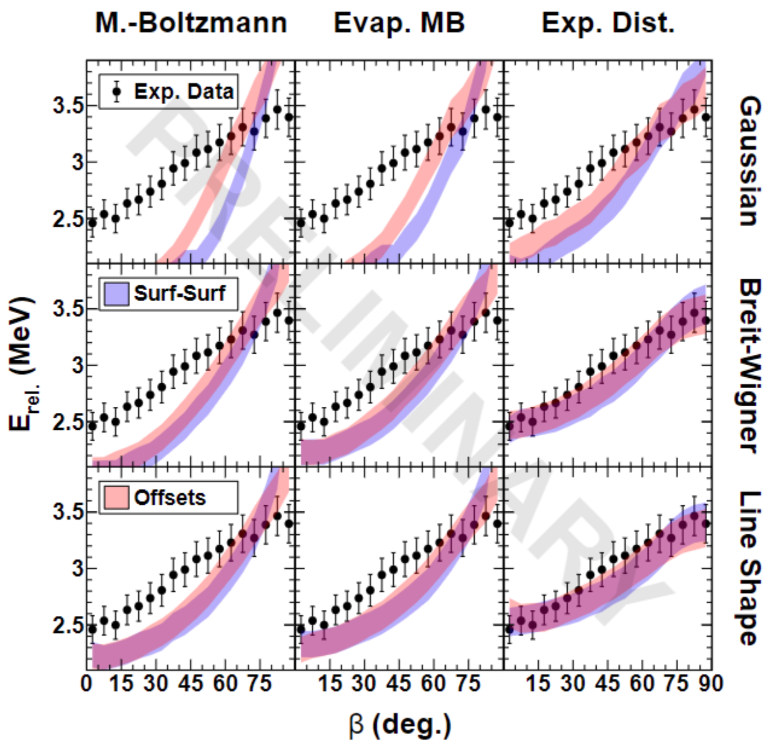

Fig. 5. Results for ^{8}Be (2+) simulations based on the sampling method for emission and decay energies. Emission energies are organized based on column and decay energies based on row. As can be seen, both the emission and decay energy distributions have a discernible effect on the accuracy of the simulation in comparison to experiment.

[1] R. Ghetti, *et. al.*, Nucl. Phys. **A765**, 307 (2006).
[2] A.B. McIntosh *et. al.*, Phys. Rev. Lett., **99**, 132701 (2007).
[3] A. Hannaman, *Progress in Research*, Cyclotron Institute, Texas A&M University (2021-2022) p. II-8.
[4] A.M. Lane and R.G. Thomas, Rev. Mod. Phys. **30**, 257 (1958).