N/Z equilibration: Mapping isotopic yields in binary projectile breakups

A. Hannaman, A.B. McIntosh, A. Jedele, A. Rodriguez Manso, K. Hagel, Z. Kohley, and S.J. Yennello

N/Z equilibration in dynamically deformed atomic nuclei formed from heavy ion collisions has been studied to gain new insights into the nuclear equation of state [1,2]. A low-density neck formed between the projectile and target produces a region of neutron-richness due to the density dependence of the asymmetry energy. The evolution of this dynamic system leads to N/Z equilibration between the neutron-rich and neutron-poor regions of the PLF* depicted in Fig 1; these two regions can develop into the "heavy fragment" and "light fragment" in the exit channel.

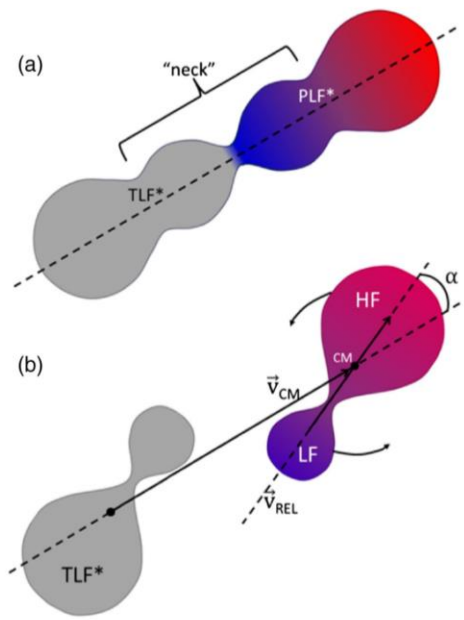

FIG. 1. Illustration from [3] depicting dynamical projectile and target interaction and decay. (a) Deformed PLF* and TLF* during the interaction. (b) At a later time, the PLF* will break after rotating relative to the TLF* (measured by the angle α) forming the heavy fragment (HF) and light fragment (LF). The blue region denotes neutron richness while the red region denotes neutron deficiency.

The rotation angle $\alpha = \mathrm{acos}[\vec{v}_{CM} \cdot \vec{v}_{REL}/(\| \vec{v}_{CM} \| \| \vec{v}_{REL} \|)]$ of the PLF* prior to binary breakup into the HF and LF is used as a measure for probing the equilibration time [3,4]. The velocity vectors used in the calculation of α are the two-fragment center-of-mass velocity $\vec{v}_{CM} = (m_{HF}\vec{v}_{HF} + m_{LF}\vec{v}_{LF})/(m_{LF} + m_{HF})$ and the relative velocity between the HF and LF $\vec{v}_{REL} = \vec{v}_{HF} - \vec{v}_{LF}$. In this work, the isotopic yields of the light fragment are mapped against α to seek a more sensitive probe for equilibration and to discover the contributions and behaviors of each isotope during this process. In this study, a 35 MeV/u beam of ^{70}Zn accelerated by the K500 Cyclotron at Texas A&M University was impinged on a thin ^{70}Zn target and reaction products were measured in NIMROD (Neutron Ion Multidetector for Reaction Oriented Dynamics) [5, 6].

Prior studies show stronger signatures of equilibration when the HF is significantly larger than the LF, therefore the requirement that $Z_{HF} \geq 12$ is used for this analysis [7]. The average composition <N-Z/A> of the LF as a function of α shows characteristic first order kinetics, with neutron richness decreasing as the PLF* undergoes greater rotation prior to breakup [Fig. 2]. The deviation from exponential behavior at α values less than ~15° results from the inability to measure the HF and LF in the same detector as well as the confined phase space that this aligned breakup orientation occupies. Equilibration resulting from the dynamical process depicted in Fig. 1 is observed in the α range of 0° to 90°, with statistical decay dominating past an α of 90° [2].

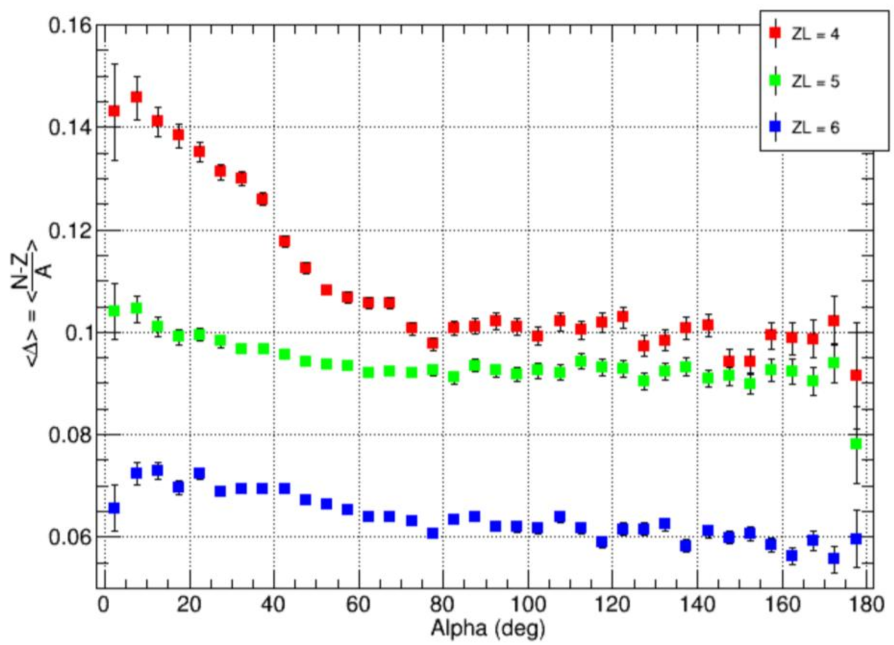

FIG. 2. The average composition <N-Z/A> of the LF for Z = (4,5,6) as a function of the α angle for events allowing all values of Z_{HF} above 12. Error bars are statistical.

When these LF composition curves are decomposed into their constituent isotopic fractional yields, some interesting features become apparent [Fig. 3]. Generally, the most neutron rich and neutron poor isotopes have the largest relative change in fractional yield made apparent by the logarithmic scale; however, these changes contribute little to the average composition due to their low yield. The strong rare isotope sensitivity in this analytical framework reflects the enhanced sensitivity of rare isotope yields across varying compositions of colliding systems [8]. Additionally, while most isotopes exhibit exponential behavior that asymptotically levels off akin to the average composition equilibration curves in Fig. 2, the more abundant N = Z + 1 isotopes decline across the entire α range and are better fit linearly. Further analysis and interpretation of isotopic yields is ongoing.

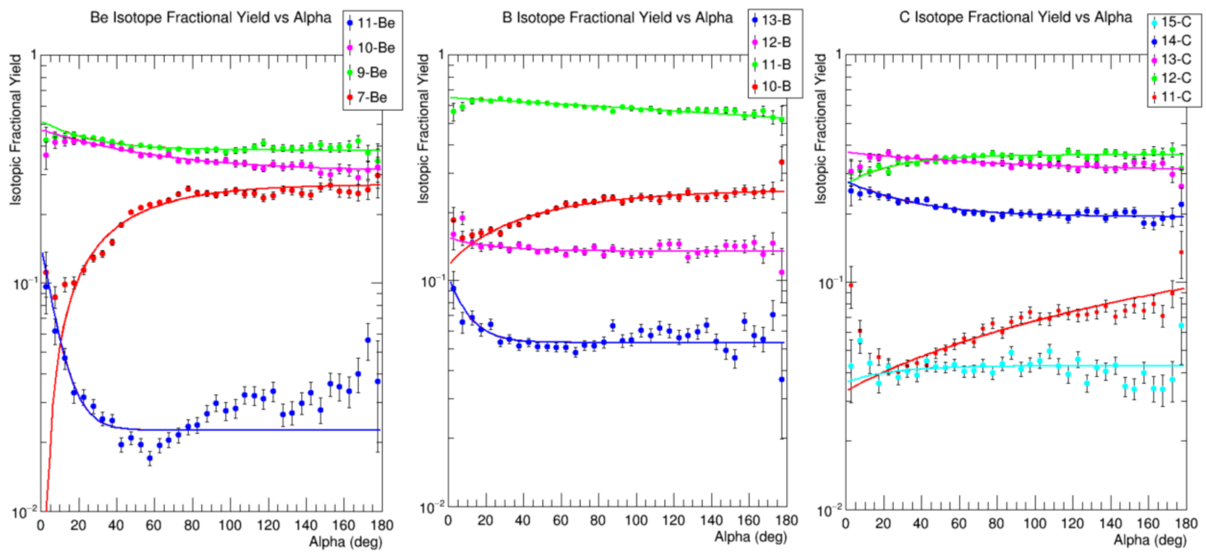

FIG. 3. The average composition <N-Z/A> of the LF for Z = 4,5,6 on log scale plotted as a function of the α angle for events allowing all values of Z_{HF} above 12 (exponential fit parameters exclude data points below 15° α and serve to guide the eye).

[1] S. Hudan *et al.*, Phys. Rev. C **86**, 021603(R) (2012).

[2] A. Rodriguez Manso *et al.*, Phys. Rev. C **95**, 044604 (2017).

[3] A. Jedele *et al.*, Phys. Rev. Lett. **118**, 062501 (2017).

[4] K. Brown *et al.*, Phys. Rev. C **87**, 061601 (2013).

[5] S. Wuenschel *et al.*, Nucl. Instrum. Methods Phys. Res. **A604**, 578 (2009).

[6] Z. Kohley *et al.*, Phys. Rev. C **82**, 064601 (2010).

[7] A.B. McIntosh *et al.*, Phys. Rev. C **81**, 034603 (2010).

[8] E. Ramakrishnan *et al.*, Phys. Rev. C **57**, 1803 (1998).