The effect of nuclear reaction dynamics on isoscaling properties

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Isoscaling is a method that seeks to extract information about the asymmetry energy in the nuclear equation of state by comparing integrated yields of isotopes from two reaction systems that differ only in their isospin makeup according to the exponential scaling law $R_{21} = Y_2(N,Z)/Y_1(N,Z) = Cexp(\alpha N + \beta Z)$, where Y_2 is the yield from the more neutron-rich system and Y_1 is the yield from the less neutron-rich system while C, α, and β are fit parameters [1]. This methodology is typically applied under statistical and thermal equilibrium assumptions. However, molecular dynamics model studies have shown that isoscaling accurately describes fragment yields early in the reaction process where dynamical processes occur [2]. We have reported on an investigation as to how well isoscaling describes dynamically produced fragments in an experimental setting [3]. Further, by using the orientation of binary projectile-like fragment (PLF*) decays, we were able to distinguish between fragments primarily produced dynamically and statistically, showing how isoscaling properties change as a function of the mechanism of fragment production [3].

The systems used in this study were symmetric collisions of ^{70}Zn + ^{70}Zn and ^{64}Zn + ^{64}Zn [4]. In both systems, the beam was accelerated to 35 MeV/u by the K500 Cyclotron at Texas A&M University and was impinged on a thin target [4]. Reaction products were measured in NIMROD (Neutron Ion Multidetector for Reaction Oriented Dynamics) [5, 6]. The angle of PLF* rotation $\theta_{prox} = \text{acos}\,[\vec{v}_{CM} \cdot \vec{v}_{REL}/(\| \vec{v}_{CM} \| \| \vec{v}_{REL} \|)]$ after separation from the target-like fragment (TLF*) and prior to binary breakup into the HF and LF is depicted in Fig. 1(b). The velocity vectors used in the calculation of θ_{prox} 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 $\vec{v}_{REL} = \vec{v}_{HF} - \vec{v}_{LF}$. The LF yield distribution in Fig 1(c) shows excess yield at low θ_{prox} due to the dynamical process described favoring PLF* breakup aligned with the PLF*-TLF* separation axis.

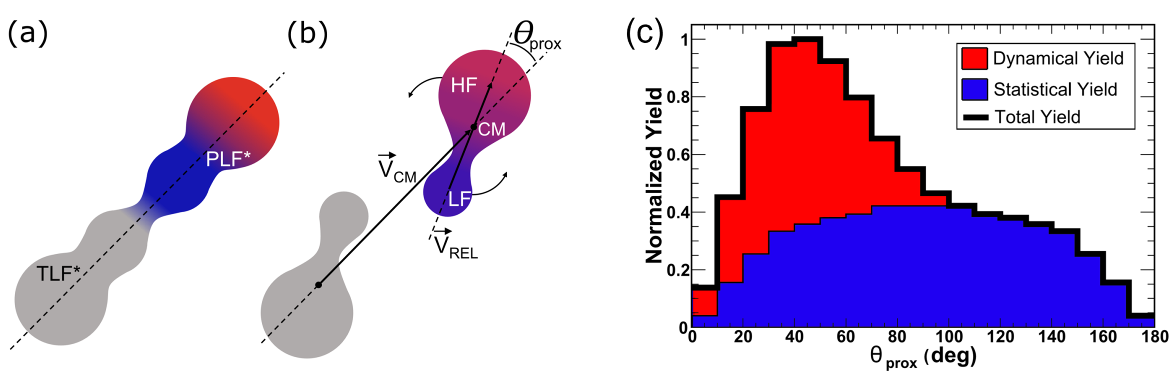

Fig. 1. Illustration depicting dynamical projectile and target interaction and decay. (a) Deformed PLF* and TLF* during the interaction. (b) At a later time, the PLF* will break after rotating relative to the TLF* (measured by the angle α) forming a heavy fragment (HF) and light fragment (LF) in the exit channel. The blue region denotes neutron richness while the red region denotes neutron deficiency. (c) The dynamical (red) and statistical (blue) fragment production yield distribution for the LF with $\boldsymbol{Z_L}$ = 6 in events with a measured $\boldsymbol{Z_H} \geq$ 12 as a function of $\boldsymbol{\theta_{prox}}$.

In this work, focus was placed on isoscaling the LF with $4 \leq Z_L \leq 8$ in events containing a $Z_H \geq 12$. The isoscaling parameters α and $|\beta|$ obtained from fitting the isotopic yield ratios of the dynamically and statistically produced fragments as a function of θ_{prox} are shown in Fig 2.

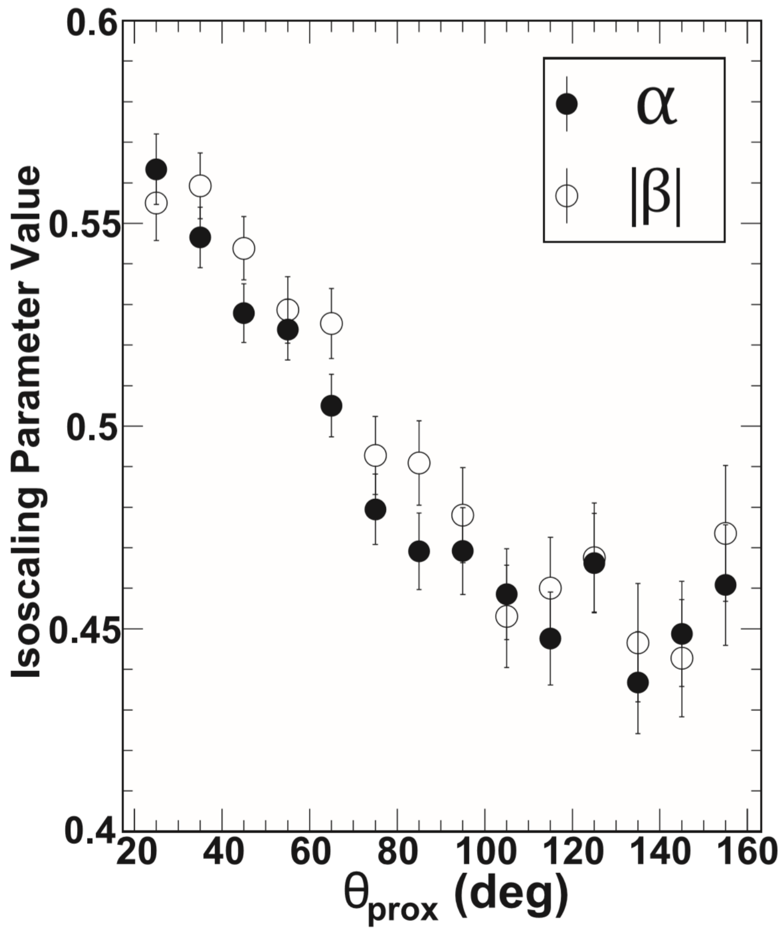

Fig. 2. Isoscaling parameters α and |β| as a function of $\boldsymbol{\theta_{prox}}$ for the total dynamical and statistical yield of $\mathbf{4} \leq \boldsymbol{Z_L} \leq \mathbf{8}$. Error bars contain statistical error from the fitting of R_{21} values.

The value of α is largest at θ_{prox} = 25° with a value of 0.563 ± 0.009 and decreases to an average value of 0.460 ± 0.008 in the statistical region of 80° < θ_{prox} < 160°. This decrease in α and |β|can be understood by the dynamics of the reaction mechanism. θ_{prox} functions as a clock for the extent of N-Z equilibration as described in prior work [7,8]. Smaller angles of θ_{prox} correspond to fragments originating from a largely unequilibrated system. Large values of α indicate that the difference in the mean of the mass distributions for the two systems is great relative to the width. The mass distributions are less aligned for dynamically produced fragments and are more aligned for statistically produced fragments. This directly supports the argument that neutrons are initially attracted to the low-density neck formed in the dynamic interaction, with this attraction being greater for the more neutron-rich system, and relaxing over time as the density gradient allows it to. The validity of the isoscaling model to dynamically produced fragments is a nontrivial result. Moreover, other transport model studies have shown similar isoscaling characteristics explicitly as a function of time [2].

The typical method of invoking statistical and thermodynamic equilibrium assumptions for the extraction of the asymmetry energy are difficult to apply to these results, as the system is evolving dynamically, and significant density gradients exist. However, dynamical transport models can produce data sets that can be treated in the same way as experimental data. These models can use different asymmetry energy inputs for comparison to this experimental result to determine which asymmetry energy is closest to reality. A more detailed description of these results can be found in the publication [3].

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