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Fragmentation in isotopic and isobaric systems as probe of density dependence of nuclear symmetry energy

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Abstract

We probe the density-dependent behavior of symmetry energy using the yield of various fragments in central collisions of various isotopic and isobaric colliding pairs. We calculate the yields of free nucleons, light charged particles and intermediate mass fragments in neutron-rich colliding systems as well as the ratio of relative yields of above fragments and free nucleons. Our findings reveal that the ratio of relative yield of light charged particles poses better candidate to probe the density dependence of nuclear symmetry energy.

Keywords: Multifragmentation; Symmetry energy

1. Introduction

The study of nuclear symmetry energy has been gaining a lot of interest as it plays a crucial role in determining the nuclear equation of state (EOS) of isospin asymmetric nuclear matter. The nuclear symmetry energy is also important in understanding the dynamics of neutron-rich heavy-ion collisions as well as structure of exotic nuclei [1–5] and many important astrophysical issues such as properties of neutron stars and supernova explosion [6]. The upcoming and existing radioactive-ion beam (RIB) facilities provide a unique opportunity to study the behavior of symmetry energy at sub- and supra-saturation densities in terrestrial laboratory. As

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nuclear symmetry energy is not a directly observable quantity, various probes (or observables) using nuclear reaction and structure studies have been proposed in literature to gain information about it. The comparison of these probes (or observables) with available theoretical predictions provides the sought-after constraints. For example, the observables at sub-saturation densities involve isospin diffusion/transport [7–9], isotopic scaling [10,11], isobaric ratio of various species [12,13], isospin fractionation [7,14], pre-equilibrium single and double neutron-to-proton ratios [8,15–17], N/Z ratio of fragments [18,19], hard photon production [20] etc. Recently, more probes originating from long-time processes such as fusion, fission etc. are also proposed to constrain symmetry energy. For example, fusion cross-sections at low energy exhibited certain sensitivity to symmetry energy [21]. Another measurement done by Heavy Ion Research Facility at Lanzhou (HIRFL) found strong dependence of isotopic composition of fission fragments towards density dependence of nuclear symmetry energy [22]. In addition to reaction studies, various probes in nuclear structure physics such as neutron skin thickness [23], the giant monopole resonance [24], the systematics of the nuclear binding energies [25] etc. have also been used to constrain the nuclear symmetry energy at sub-saturation densities. On the other extreme, high density behavior of symmetry energy has been probed using collective [26,27] and elliptic flows [28], neutron–proton ratios of free nucleons [29,30], triton to ^{3}He ratio [19, 31–33], π^-/π^+ [34–37], K^+/K^0 [38] and Σ^-/Σ^+ ratios [39] as well as η meson production [40] etc. Various studies at sub-saturation density region have concluded a softer form of the symmetry energy [9,16,17,41]. For example, the calculated n/p ratios of free nucleons using various one-body (BUU-type) [15] or many-body (QMD-type) [16] models for soft symmetry energy showed better agreement with data [17]. Similarly, recent study done by Wang et al. [33] also favors softer symmetry energy at sub-saturation density, where ^{3}H/^{3}He ratios calculated using QMD-type model were compared with FOPI measurements [42]. Also, similar conclusions were put forward in various other studies [8,10] where isospin diffusion and isoscaling have been used to investigate the sub-saturation symmetry energy behavior. On the other hand, it is much more challenging to constrain symmetry energy at supra-saturation densities and situation is worse as results are quite diverse and model-dependent. For example, a comparison of pion ratio measurement by the FOPI collaboration [43] with Improved Isospin-dependent Quantum Molecular Dynamics (ImIQMD) model calculations [36] favors stiff symmetry energy, in contrast to soft symmetry energy claimed by Isospin-dependent Boltzmann–Uehling–Uhlenbeck (IBUU) model calculations [35]. In contrast, results reported by Xie et al. [37] using Isospin-dependent Boltzmann–Langevin (IBL) model favor supersoft behavior of symmetry energy in the supra-saturation density region. Therefore, more theoretical studies identifying the observables sensitive to symmetry energy are still going on. From the above literature review, we observed that extraction of nuclear symmetry energy from heavy-ion collisions relies on transport model calculations. At the same time, model-dependent treatment of potential and collision hinders the exact determination of symmetry energy and may yield some discrepancies in the results. Therefore, further studies to locate effective probes (free from transport model limitations) are still going on [41,44–46]. For example, recently nuclear symmetry has been determined from nucleon optical potentials extracted from nucleon–nucleus scattering [45].

As mentioned above, various studies on collective flow and fragmentation explored observables sensitive to nuclear symmetry energy. In one such study, Kohley et al. [5] investigated the transverse flow of intermediate mass fragments in isotopic and isobaric colliding pairs and put forward a observable 'R_{flow}' which depicts the ratio of relative transverse flow (of intermediate mass fragments) of isotopic and isobaric colliding pairs and signifies the comparative role of neutron content and Coulomb interaction in the dynamics of transverse flow. The sensitivity of