Revisit to the yield ratio of triton and ^{3}He as an indicator of neutron-rich neck emission

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Abstract

The neutron rich neck zone created in heavy ion reaction is experimentally probed by the production of the $A = 3$ isobars. The energy spectra and angular distributions of triton and ^{3}He are measured with the CSHINE detector in ^{86}Kr +^{208}Pb reactions at 25 MeV/u. While the energy spectrum of ^{3}He is harder than that of triton, known as "^{3}He-puzzle", the yield ratio $R(rmt/^{3He})$ presents a robust rising trend with the polar angle in laboratory. Using the fission fragments to reconstruct the fission plane, the enhancement of out-plane $R(rmt/^{3He})$ is confirmed in comparison to the in-plane ratios. Transport model simulations reproduce qualitatively the experimental trends, but the quantitative agreement is not achieved. The results demonstrate that a neutron rich neck zone is formed in the reactions. Further studies are called for to understand the clustering and the isospin dynamics related to neck formation.

Full Text

Preamble

Revisiting the Triton to ^{3}He Yield Ratio as an Indicator of Neutron-Rich Neck Emission

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Abstract

The neutron-rich neck zone created in heavy-ion reactions is experimentally probed through the production of A = 3 isobars. The energy spectra and angular distributions of triton and ^{3}He were measured with the CSHINE detector in ^{86}Kr + ^{208}Pb reactions at 25 MeV/u. While the energy spectrum of ^{3}He is harder than that of triton—a phenomenon known as the "^{3}He-puzzle"—the yield ratio R(t/^{3}He) shows a robust rising trend with polar angle in the laboratory frame. Using fission fragments to reconstruct the fission plane, the enhancement of out-of-plane R(t/^{3}He) is confirmed compared to in-plane ratios. Transport model simulations qualitatively reproduce the experimental trends, but quantitative agreement is not achieved. These results demonstrate that a neutron-rich neck zone is formed in the reactions, and further studies are needed to understand the clustering and isospin dynamics related to neck formation.

Key words: Neutron-rich neck, ^{3}He-puzzle, out-of-plane emission, isospin transport
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Introduction

Heavy-ion reactions (HIR) serve as micro-laboratories for investigating properties of the nuclear equation of state (nEoS), particularly the nuclear symmetry energy Esym( ) [1,2,3,4,5,6]. Accurate constraints on Esym( ) are crucial for both nuclear physics and astrophysics, and have become unprecedentedly important since the detection of gravitational waves from the neutron star merger event GW170817 [7,8,9]. Although great progress has been made through measurements of isobaric yield ratios in HIRs, such as n/p [10], t/^{3}He [11,12], π^-/π^+ [13,14,15,16], K^0/K^+ [17], and Ξ^-/Ξ^0 [18], the Transport Model Evaluation Project (TMEP) has been launched to benchmark methods for allocating uncertainties in model analyses of Esym( ) [19,20,21,22,23], and efforts are ongoing to search for novel probes to explore the effects of Esym( ) in HIRs [24,25,26,27].

The determination of Esym( ) relies on a comprehensive understanding of the underlying dynamic processes in HIRs, particularly those involving the isospin degree of freedom (IDOF) [28]. During the thermal and chemical evolution of the reaction, a low-density neutron-rich neck zone forms as a result of complex dynamics [29,30]. The neck zone has been explored to understand the mechanisms of intermediate-mass fragment formation [31,32,33,34], isotopic cluster emission [35,36,37,38], and neutron-proton equilibration [39,40,41,42,43]. Due to density gradients and isospin migration, the neck zone provides a favorable environment for studying Esym( ) [41,43]. For further discussion of the neck zone, readers may refer to review articles on heavy-ion reactions from both experimental [29,30,44] and theoretical perspectives [45,46,47,48,49].

Among probes using light charged particles (LCPs), the yield ratio of t/^{3}He, denoted as R(t/^{3}He), has been particularly identified as a sensitive probe of isospin dynamics in HIRs. Transport model calculations demonstrate that R(t/^{3}He) in intermediate-energy HIRs depends on the stiffness of Esym( ) [12,50]. At high energies, R(t/^{3}He) depends more sensitively on the value of Esym( ) and the specific form of the interaction potential [16,52], but less on the slope of Esym( ) [53]. Additionally, R(t/^{3}He) reflects the isospin-dependent nucleon density in reactions [54,32,55]. Experimentally, yield ratios of various mirror nucleus pairs, including R(t/^{3}He), led to the discovery of isospin fractionation [56]. It has been suggested that more neutron-rich particles are emitted at midrapidity, as inferred from R(t/^{3}He), which correlates positively with the charge number of projectile-like fragments [32] but inversely with center-of-mass energy [57]. Similarly, in high-energy HIRs, R(t/^{3}He) reflects the neutron enrichment of the emission source [58,32,59] and isospin mixing during collisions [60]. Recently, R(t/^{3}He) has also been used to study the pick-up mechanism of pre-equilibrium light nucleus production in pion scattering experiments [61].

Despite enormous progress in understanding triton and ^{3}He emission, several questions remain unresolved and require further investigation. For example, when considering ^{3}He spectra, an anomalous phenomenon occurs where the yield of high-energy ^{3}He is relatively larger compared to triton [62,63,64,65,66] or ^{4}He [62,67,64,65,66]. This phenomenon has been termed the "^{3}He-puzzle" [62,63,66]. While energy spectra suffer from the "^{3}He-puzzle," the yield ratio of t and ^{3}He remains sensitive to the neutron-to-proton ratio (N/Z) of the emission system [59,68,42,69]. The excitation function of R(t/^{3}He) measured by the FOPI collaboration [70] cannot be reproduced with a single model [51]. More interestingly, INDRA experiment results suggest that t and ^{3}He isobars may dominate the neutron enrichment of the neck zone [43].

Motivated by the rich but not-yet-understood information carried by triton and ^{3}He, which couples to both isospin transport and neck formation in HIRs, we explore the emission of these two isobars by examining their energy spectra and yield ratio R(t/^{3}He) over a wide angular range, and connect this ratio to features of neck emission. In this letter, we present energy spectra of t and ^{3}He at different angles measured in ^{86}Kr + ^{208}Pb reactions at 25 MeV/u. The distributions of R(t/^{3}He) as a function of laboratory polar angle and angle relative to the fission plane are analyzed. Comparisons between experimental data and transport model simulations are discussed. The paper is organized as follows: Sections 2 and 3 present the experimental setup and transport model description, respectively. Section 4 contains the results and discussion, and Section 5 provides a summary.

2 Experimental Setup

The experiment was conducted at the Compact Spectrometer for Heavy IoN Experiment (CSHINE) [71,72], located at the final focal plane of the Radioactive Ion Beam Line at Lanzhou (RIBLL-I) [73]. A ^{86}Kr beam at 25 MeV/u was extracted from the cyclotron of the Heavy Ion Research Facility at Lanzhou (HIRFL) [74] and bombarded a natural lead target installed in a scattering chamber with radius R 750 mm. The target thickness was about 1 mg/cm^2. Light charged particles from the reactions were measured by four silicon-strip detector telescopes (SSDTs), covering the angular range from 10° to 60° in the laboratory. Each SSDT consists of three layers: a single-sided silicon-strip detector (SSSSD) for ΔE_1, a double-sided silicon strip detector (DSSSD) for ΔE_2, and a 3 × 3 CsI(Tl) crystal hodoscope with length 50 mm for energy deposit E. The granularity of the SSDT is 4 × 4 mm^2, providing about 1° angular resolution. The energy resolution of the SSDT is better than 2%, and isotopes up to Z = 6 can be identified. Multi-hit events and signal sharing are carefully treated in track recognition, with an efficiency of about 90% [75].

To tag the reaction geometry, fission fragments (FFs) were detected by three parallel plate avalanche counters (PPACs), each with a sensitive area of 240 × 280 mm^2. The perpendicular distance from the PPACs to the target is about 428 mm. The PPAC coverage ensures high efficiency for measuring LCPs in coincidence with FFs, selecting semi-peripheral collisions. [Figure 1: see original paper] presents the experimental setup (a) and the spatial coverage of the SSDTs and PPACs (b).

3 Theoretical Model

A hybrid model combining the improved quantum molecular dynamics model (ImQMD05) with a statistical decay afterburner (GEMINI) was used for theoretical simulations in this work. ImQMD05 [76] simulates the nucleon transport process in HIRs, and GEMINI [77,78] provides the final-state reaction products. ImQMD05 is an improved version of the original quantum molecular dynamics code [79,80] and is widely used to understand nuclear reaction dynamics through event-by-event analysis in both low- and intermediate-energy HIRs. The mean-field part of the ImQMD05 model used here includes the symmetry potential energy term. The local nuclear potential energy density functional in the ImQMD05 model is written as:

$$V_{\text{loc}} = \alpha + g_{\text{sur,iso}}\eta + 1 + g_{\text{sur}}[\nabla(\rho_n - \rho_p)]^2 + g_{\rho\tau}(\nabla\rho)^2$$

where , , and are the nucleon, neutron, and proton densities, respectively. δ = (-)/(+) is the isospin asymmetry degree. The parameters in the equation except C , which are listed in , are obtained directly from the MSL0 parameter set [81]. C is determined by the symmetry potential energy at saturation density. Together with various γ, one can obtain MSL0-like Skyrme interactions with various density-dependent symmetry potential energies. The reaction was simulated with impact parameters in the range $1.0 \leq$ b ≤ 7.0 fm in steps of Δb = 1.5 fm. At the end of the dynamic evolution in ImQMD, the minimum spanning tree (MST) algorithm [80,82] was used to recognize free nucleons and fragments formed during evolution. Subsequently, the statistical decay of excited fragments was performed with the GEMINI model, yielding the final-state particle information.

4 Results and Discussions

We first analyze the energy spectra, which contain thermal and dynamical information about particle emission. [Figure 2: see original paper] presents the energy spectra of triton (solid squares) and ^{3}He (open triangles) in different angular ranges corresponding to SSDTs 2 to 4. To reduce the influence of quasi-projectiles, data from SSDT1 covering 10–20° in the laboratory are not included. The spectrum of ^{3}He is generally harder than that of triton, leading to a larger average kinetic energy for ^{3}He. The difference between triton and ^{3}He is more pronounced at forward angles than at large angles. This observation of the “^{3}He-puzzle” is consistent with previous measurements at high beam energies [83,62,65,84,85,66,64,86,70]. Our experimental results also support that the “^{3}He-puzzle” is more pronounced in heavy systems than in light systems reported in the Fermi energy range [85,86,64].

The "^{3}He-puzzle" has been interpreted through two possible scenarios: sequential decay [63] and coalescence model [67]. In the sequential decay scenario, the difference between ^{3}He and triton is influenced by the Coulomb barrier, as ^{3}He is emitted at an earlier stage with higher temperature to overcome a larger Coulomb barrier than triton [63]. In the coalescence scenario, which was applied to interpret the difference between ^{3}He and α particles [67], ^{3}He is predominantly produced by the coalescence of pre-equilibrium nucleons, resulting in larger mean kinetic energy. These two explanations are qualitatively consistent, suggesting that ^{3}He is predominantly emitted at earlier stages.

The energy spectra calculated by ImQMD05 are presented in [Figure 2: see original paper] with solid and dashed lines for triton and ^{3}He, respectively. It should be noted that transport models typically underestimate cluster yields. To enable clear comparison of spectral shapes, model predictions are scaled to experimental yields using the same correction factor for both triton and ^{3}He in a given angular window. The model calculations qualitatively reproduce the trend of the t and ^{3}He spectra. Switching from triton to ^{3}He, the energy spectra become slightly harder and the energy peak positions shift to higher energies. At large angles, as shown in panels (b) and (c), the simulated descending tails of ^{3}He spectra agree better with data than those of triton, suggesting that high-energy ^{3}He is dominated by dynamic emission. Quantitatively, however, the splitting between triton and ^{3}He in model calculations is less pronounced than in experimental data, particularly at smaller angles. This suggests that the origin and formation of light clusters such as triton and ^{3}He are more complicated than the coalescence approach typically adopted in current transport models. We note that in ImQMD05 calculations, fission events are difficult to simulate due to their long timescale, so events were selected by requiring at least two LCPs firing in SSDTs (M ≥ 2). Examining experimental spectra under the same condition, as shown in the inset of panel (c), does not change these conclusions.

Benefiting from the wide angular coverage of SSDTs in the laboratory reference frame, we analyzed the angular distribution of the isobaric yield ratio t/^{3}He. To avoid possible experimental distortion caused by energy thresholds in each SSDT, we focus on the descending portion to the right of the energy peak. The energy peak positions (E) are listed in . Using the energy condition E $\geq$ E as a lower limit cut suppresses interference from evaporation processes and emphasizes features of dynamic emission.

Figure 3: see original paper presents the angular distribution of R(t/^{3}He) under various conditions as a function of laboratory polar angle b, with the geometric efficiency shown in Figure 3: see original paper. In panel (a), colored square markers represent experimental data from events with one LCP in coincidence with two FFs after applying E cuts. Vertical error bars indicate statistical uncertainties, while colored caps represent systematic uncertainties arising from ± 1 MeV variations in E_p. The angular distribution clearly exhibits a rising trend. Since R(t/^{3}He) is positively correl
versus b over the wide angular range from 20° to 60° reveals a convincing picture of IDOF evolution. Through isospin diffusion and drift mechanisms

[28], neutrons favor transport from the high-density quasi-projectile region to the low-density neck region, whose neutron-rich feature has been predicted by various transport model simulations [87,35,88,89,90,91,37,38,40] and experimentally observed in specific angular windows [31,92,68,34,93,39,94,43] or parallel velocity windows [95,96,68,34,97,98,99,69,100].

The robustness of the increasing trend of $R(t/^3He)$ with b can be further verified by varying conditions. Using detector thresholds as lower limit cuts instead of E cuts (i.e., v $\geq 0.09c$ and $v_3He \geq 0.15c$, as in [27]) yields a similarly increasing ratio, plotted as the diagonal hatched band in Figure 3: see original paper. More interestingly, removing the coincidence with two fission fragments and using data triggered by a minimum LCP multiplicity M firing the SSDTs (M ≥ 2 in experiment), shown by open circles, preserves the increasing trend but yields markedly smaller absolute values. Since SSDT2 has a much higher threshold due to thicker ΔE_1 and ΔE_2 detectors than SSDT3, only the latter is counted for ratios without E cuts.

The enhancement shown by the hatched band compared to open circles in Figure 3: see original paper indicates that neck emission is related to impact parameter. In our experiment, the linear momentum transfer (LMT) derived from the folding angle of two fission fragments averages LMT $= 0.35$, corresponding to an average impact parameter b 7 fm from simple geometric considerations—indicating semi-peripheral reactions. In contrast, inclusive events triggered by M ≥ 2 have much weaker b-dependence. Thus, due to overlap between the outer neutron skin of projectile and target, the neutron richness of the neck zone formed in semi-peripheral events tagged by fission fragments (diagonal hatched band) is more pronounced than in LCP-triggered events (open circles). It has been noted that the neutron-rich neck zone forms from dynamical effects in semi-peripheral reactions [45,88,39]. The difference between results with and without fission tagging suggests that neck emission occurs before full isospin equilibrium is achieved.

The rising trend of $R(t/^3He)$ is also qualitatively reproduced by transport model calculations using ImQMD05, shown by the solid curve with dot-filled area in Figure 3: see original paper. The dot-filled area represents results with b varying from 1.0 to 7.0 fm, while the solid curve shows b-averaged values. The symmetry energy parameter is $\gamma = 0.5$. Trigger and cut conditions are the same as for the open circles. The calculations confirm the increasing trend but underestimate the rate of increase compared to data points. Again, the failure to quantitatively reproduce the data suggests complications in the clustering mechanism in heavy-ion collisions at Fermi energies.

Finally, neutron-rich neck emission can be confirmed through the ratio $R(t/^3He)$ in and out of the fission plane, as illustrated in Figure 4: see original paper. The fission plane is reconstructed from the velocities of two FFs using the normal vector n FF $= (v\ F1 \times v\ F2)/|v\ F1||v\ F2|$. Defining α_1 as the angle between n FF and the beam direction v beam , the α_1 distribution characterizes how much the fission plane deviates from the beam axis. As shown in Figure 4: see original paper, $|\cos(\alpha_1)|$ peaks at 0 with a small width σ_1 6°, indicating that the fission plane approximately retains memory of the initial angular momentum of the rotating system.

Based on this inference, Figure 4: see original paper presents the angular distribution of R(t/^{3}He) relative to the fission plane. The abscissa α_2 is the relative angle between n FF and the velocity of coincident triton or ^{3}He v LCP , with $|\cos(\alpha_2)| = 0$ (1) corresponding to in-plane (out-of-plane) emission. The same E cuts as in [Figure 3: see original paper] are applied to calculate R(t/^{3}He). The increasing trend of R(t/^{3}He) with $|\cos(\alpha_2)|$ indicates enhanced out-of-plane emission. In a simple picture, particles emitted from the neck region favor out-of-plane directions at α_2 0° or $\cos(\alpha_2)$ 1 because emission in the fission plane can be blocked by the two heavy fragments. Conversely, particles emitted from both bodies of the dinuclear system, which subsequently rupture into quasi-projectile and quasi-target, tend to populate in-plane directions at α_2 90° due to centrifugal motion. This picture consistently supports the formation of a neutron-rich neck in the reactions.

5 Summary

The energy spectra and angular distributions of triton and ^{3}He ranging from 20° to 60° in the laboratory, measured in coincidence with fission fragments, are analyzed for 25 MeV/u ^{86}Kr + ^{208}Pb reactions. The energy spectra of ^{3}He are generally harder than those of triton, with the effect more pronounced at small angles. The yield ratio R(t/^{3}He) exhibits an increasing trend with b, evidencing evolution of the isospin and density gradient from the quasi-projectile to the mid-velocity neck region. ImQMD simulations achieve qualitative description of the energy spectra and angular distributions of t and ^{3}He, supporting the dynamic emission of these isobars from the neck. However, the failure to achieve quantitative reproduction, which cannot be remedied by filter conditions in the analysis, indicates a more complicated clustering mechanism than the current coalescence picture in transport models and calls for further systematic investigation. Moreover, the ratio R(t/^{3}He) increases with angle relative to the fission plane, consistent with enhanced out-of-plane emission of neutron-rich particles from the neck. The distribution properties of triton and ^{3}He provide an effective means to understand isospin dynamics related to neck formation and serve as a fine probe to constrain Esym( ) in heavy-ion reactions.

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