The enhancement of neutron rich particle emission from out-of-fission-plane in Fermi energy heavy ion reactions

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The neutron richness of the light charged particles emitted out of the fission plane in heavy ion reactions has been experimentally investigated via the production of $A = 3$ mirror nuclei in ^{86}Kr +$^{\rm nat}$Pb reactions at 25 MeV/u. The energy spectra and angular distributions of triton (t) and ^{3}He in coincidence with two fission fragments are measured with the Compact Spectrometer for Heavy IoN Experiment (CSHINE). The energy spectrum of ^{3}He is observed harder than that of triton in the fission events, in accordance with the phenomena reported as "^{3}He-puzzle" in inclusive measurements. With a data driven energy spectrum peak cut scenario, it is observed that the yield ratio R(t/^{3}He) increases with the angle to the fission plane, showing an enhancement of neutron rich particle emission from out-of-fission-plane. A qualitative comparison with the transport model calculations suggests that this observation may serve as a new probe for the nuclear symmetry energy.

Keywords: Heavy ion reaction, Fast fission, ^{3}He-puzzle, out-of-fission-plane emission, Nuclear symmetry energy

I. INTRODUCTION

Heavy ion reactions (HIR) provide a femtoscopic laboratory for investigating the properties of the nuclear equation of state (nEoS), particularly the nuclear symmetry energy $E_{\rm sym}(\rho)$ [1–6]. The stringent constraint of $E_{\rm sym}(\rho)$ is crucial for both nuclear- and astro-physics, and draws the most attention since the detection of the gravitational waves from the neutron star merging event GW170817 [7–9]. Although great progress has been made via neutron skin thicknesses[10–14], nuclear charge radius[15], flow[16–18] and the detection of isobaric yield ratios in HIRs, like n/p [19], t/^{3}He [20, 21], π^-/π^+ [22–25], K^0/K^+ [26] and Ξ^-/Ξ^0 [27], the $E_{\rm sym}(\rho)$ is still suffering a lot uncertainties [28–32], and the efforts are ongoing to search novel probes to explore the effects of $E_{\rm sym}(\rho)$ in HIRs [33–37].

The nuclear (fast)fission process is a large-amplitude collective motion mode happening in the HIRs. The low-density neutron rich neck region formed in the rupture of two fission fragments provides a good condition for studying $E_{\rm sym}(\rho)$ and dynamic properties in isospin degree of freedom (IDOF)[38–41]. The neck zone has been explored to understand the mechanism of intermediate mass fragment (IMF) formation [42–45], isotopic cluster emission [46–49] and neutron-proton equilibration [50–54]. Because of the density gradient and the isospin migration, the neck zone provides a beneficial environment to study the $E_{\rm sym}(\rho)$ [52, 54]. For more discussions about neck zone, one can refer to the review articles of heavy ion reactions from the experimental [38, 39, 55] and theoretic points of view [56–60].

The emissions of light particles in coincidence with fission fragments is a natural idea for exploring the symmetry energy effect and (fast)fission properties in HIRs [40, 41]. Among the probes using the light charged particles (LCPs), the yield ratio of t/^{3}He, written as R(t/^{3}He), has been particularly identified to probe the enriched feature of isospin dynamics in HIRs. Transport model calculations demonstrate that the R(t/^{3}He) at intermediate-energy HIRs depends on the stiffness of $E_{\rm sym}(\rho)$ [21, 61]. At high-energy HIRs, R(t/^{3}He) depends more sensitively on the value of $E_{\rm sym}(\rho)$ [62] and the specific form of the interaction potential [25, 63], but is less dependent on the slope of $E_{\rm sym}(\rho)$ [64]. In addition, R(t/^{3}He) reflects the isospin dependent nucleon density in the reactions [43, 65, 66]. Experimentally, the yield ratios of various mirror nucleus pairs, including the R(t/^{3}He), led to the discovery of isospin fractionation [67]. It has been suggested that more neutron-rich particles are emitted at mid-

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rapidity, as inferred by the $R(\mathrm{t}/^3\mathrm{He})$, which correlates positively with the charge number of projectile-like fragments[43] but reversely with the center of mass energy [68]. Similarly, in high-energies HIR, the $R(\mathrm{t}/^3\mathrm{He})$ reflects the neutron enrichment of the emission source[43, 69, 70] and isospin mixing during the collision [71]. Recently, the $R(\mathrm{t}/^3\mathrm{He})$ has also been used to study the pick-up mechanism of pre-equilibrium light nucleus production in the pion scattering experiment [72]. Hence, the distribution of $R(\mathrm{t}/^3\mathrm{He})$ relative to the fission plane is a good prob to characterize the properties of fission process and explore the properties of symmetry energy.

Despite of the enormous progress of the studies on the triton (t) and ^{3}He emission, some questions remain unclear and require further studies. For example, when considering the spectra of ^{3}He, there is an anomalous phenomenon that the yield of high energy ^{3}He is relatively larger, compared to that of triton [73–77] or ^{4}He [73, 75–78]. This phenomenon has been called "^{3}He-puzzle" [73, 74, 77]. While the energy spectra are suffering "^{3}He-puzzle", the yield ratio of triton and ^{3}He is sensitive to the neutron-to-proton ratio (N/Z) of the emitting system [53, 70, 79, 80]. The excitation function of $R(\mathrm{t}/^3\mathrm{He})$ measured by the FOPI collaboration [81] can not be reproduced with a single model [62]. More interestingly, the results of the INDRA experiment suggest that the triton and ^{3}He isobars seem to dominate the neutron enrichment of the neck zone [54]. However, the existence of "^{3}He-puzzle" in the coincidence events of LCPs and fission fragments is still an uncertain issue.

Due to the enriched but not-well-understood information carried by triton and ^{3}He coupling to both the isospin transport and the neck emission during fission process in HIRs, we are motivated to explore the emission of these two isobars in coincidence with fission fragments by inspecting the energy spectra and the yield ratio $R(\mathrm{t}/^3\mathrm{He})$ over wide angular range, and to bridge the ratio $R(\mathrm{t}/^3\mathrm{He})$ and the feature of fission process, as well as to infer the slope parameter of $E_{\mathrm{sym}}(\rho)$. In this article, the energy spectra of triton and ^{3}He in coincidence with fission fragments at different angles are measured in the reactions of $^{86}\mathrm{Kr}+^{\mathrm{nat}}\mathrm{Pb}$ at 25 MeV/u. The distributions of $R(\mathrm{t}/^3\mathrm{He})$ with respect to the fission plane and as a function of the laboratory polar angle are analyzed. The comparison of the experimental data to the transport model simulation is discussed. The paper is organized as following. Section II and III present the experimental setup and the description of the transport model, respectively. Section IV is the results and the discussions, and section V is the summary.

II. EXPERIMENTAL SETUP

The experiment was conducted at the Compact Spectrometer for Heavy IoN Experiment (CSHINE) [82, 83], built at the final focal plane of the Radioactive Ion Beam Line at Lanzhou (RIBLL-I) [84]. The ^{86}Kr beam of 25 MeV/u was extracted from the cyclotron of the Heavy Ion Research Facility at Lanzhou (HIRFL) [85], bombarding a natural lead target installed in the scattering chamber with the radius $R \approx 750$ mm. The target thickness is about 1 mg/cm^2. Fig. 1 presents the experimental setup (a) and the spatial coverage of the silicon-strip detector telescopes (SSDTs) and the parallel plate avalanche counters (PPACs) (b).

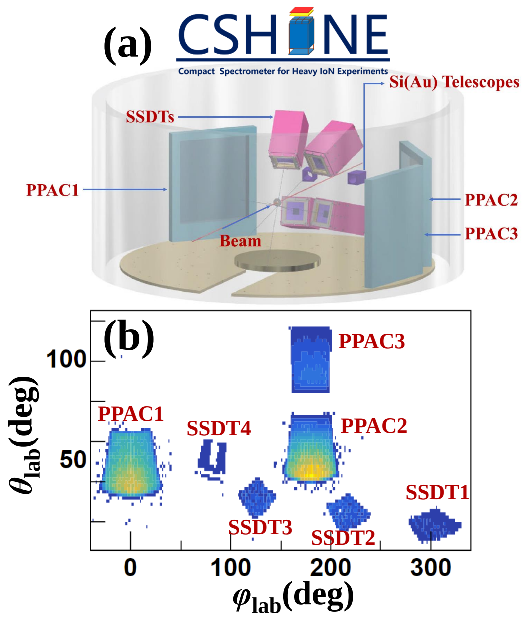

Fig. 1. (Color online) (a) The experimental setup of CSHINE. (b) The spatial coverage of SSDTs and PPACs on $\theta - \varphi$ plane in laboratory reference frame.

The LCPs from the reactions were measured by 4 SSDTs, covering the angular range from 10° to 60° in laboratory. Each SSDT consists of three layers, namely, one single-sided silicon-strip detector (SSSSD) for ΔE_1 and one double-sided silicon strip detector (DSSSD) for ΔE_2, backed by a 3×3 CsI(Tl) crystal hodoscope with the length of 50 mm for the energy deposit E. The granularity of the SSDT is 4×4 mm^2, giving about 1° angular resolution. The energy resolution of the SSDT is better than 2%, and the isotopes up to $Z = 6$ can be identified [36]. Multi hits and signal sharing are carefully treated in the track recognition, and the track recognition efficiency is about 90% [86]. Fig. 2 shows the particle identification of light particles for this analysis. Panel (a) to (d) presents the scattering plot of $\Delta E_2 - E_{\mathrm{CsI}}$ of the four SSDTs. The results show that $Z \leq 3$ LCPs, including triton and ^{3}He, were identified clearly in each SSDT, supporting the reliability of the experimental results.

In order to explore the isospin properties of fission process, the fission fragments (FFs) were detected by 3 PPACs, each of which had a sensitive area of 240×280 mm^2 [87, 88]. The perpendicular distance of the PPACs to the target is about 428 mm. The coverage of the PPACs ensures a high efficiency to measure the FFs in coincidence with the LCPs. And the trigger system is established to selected the fission events [89]. The working voltage of the PPACs can suppress the light charged particles significantly, although the specific values of mass and charge for FFs were not accurately determined. According to the previous source test results [82], the detection efficiency is almost 100% for FFs and negligibly low for light

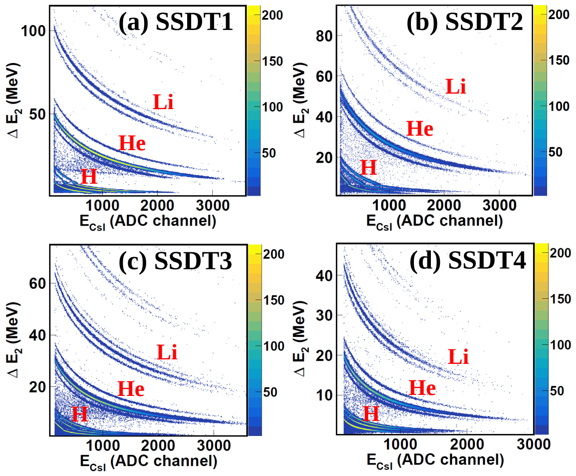

Fig. 2. (Color online) $\Delta E_2 - E_{\mathrm{CsI}}$ plots of the four SSDTs.

particles with the detector condition (HV=460 V) as adopted in the experiment. So, the PPACs can only be fired by heavy fragments, rather than LCPs or IMFs.

Referring to the energy loss calculations only, the projectile-like fragments (PLF) and target-like fragments (TLF) may fire the PPACs as well. However, the geometric coverage of the PPACs in the experiment suppresses the PLF and TLF. Otherwise because PLFs and TLFs are well separated in velocity ($v_{\mathrm{PLF}} \approx 6.8$ cm/ns, $v_{\mathrm{TLF}} \approx 1.2$ cm/ns at small linear momentum transfer or in peripheral reactions), one shall be able to see two components clearly on the velocities of the two coincident fragments recorded in the PPACs. Indeed, the two-component feature is not visible in the velocity scattering plot (see Fig. 11 in [87]), it is safe and reasonable to speculate that the heavy fragments detected with PPACs in the experiment are mainly fission fragments.

III. THEORETICAL MODEL

A hybrid model by the improved quantum molecular dynamics model (ImQMD05) coupled with statistical decay afterburner (GEMINI) was used for theoretical simulation in this work. The ImQMD05 [90] was used to simulate the nucleon transport process in HIRs. And the GEMINI [91, 92] was appended to obtain the final state productions of the reactions. The ImQMD05 model is an improved version from the original quantum molecular dynamics code [93, 94], and is widely used to understand the dynamics of nuclear reactions induced by heavy ions or light nuclei at both low and intermediate energies [40, 41, 95–97]. The mean field part of the ImQMD05 model used here includes the symmetry potential energy part. And the local nuclear potential energy density functional in the ImQMD05 model is written as

$$V_{\mathrm{loc}} = \frac{\alpha}{2}\frac{\rho^2}{\rho_0} + \frac{\beta}{\eta+1}\frac{\rho^{\eta+1}}{\rho_0^{\eta}} + \frac{g_{\mathrm{sur}}}{2\rho_0}(\nabla\rho)^2 + \frac{g_{\mathrm{sur,iso}}}{\rho_0}[\nabla(\rho_{\mathrm{n}}-\rho_{\mathrm{p}})]^2 + g_{\rho\tau}\frac{\rho^{8/3}}{\rho_0^{5/3}} + \frac{C_{\mathrm{s}}}{2}\frac{\rho^{\gamma+1}}{\rho_0^{\gamma}}\delta^2, \quad (1)$$

where ρ, ρ_{n} and ρ_{p} are the density of nucleon, neutron and proton, respectively. $\delta = (\rho_{\mathrm{n}} - \rho_{\mathrm{p}})/(\rho_{\mathrm{n}} + \rho_{\mathrm{p}})$ is the isospin asymmetry degree. The parameters in Eq. (1) except C_{s}, which are listed in Table 1, are obtained directly from Skyrme interaction with MSL0 parameter set [98]. C_{s} is determined by the symmetry potential energy at saturation density. Together with different values of γ, one can get the MSL0-like Skyrme interaction with various density dependent symmetry potential energy. After scanning the impact parameter up to 16.0 fm, the most probable weight of the fission events filtered by experimental conditions is located at 7.0 fm. Hence, the reaction was simulated with impact parameter in the range of $1.0 \leq b \leq 7.0$ fm by a step of $\Delta b = 1.5$ fm. At the end of the dynamical evolution in ImQMD05, setting at 500 fm/c, the minimum spanning tree (MST) algorithm [94, 99] was used to recognize the free nucleons and fragments formed in the evolution. Next, the statistical decay of excited fragments was performed with GEMINI afterburner. At last, the information of final state particles will be obtained.

IV. RESULTS AND DISCUSSIONS

A. Characterizing the fission events

We start with the analysis of the orientation of the fission plane with respect to the beam direction. The fission plane is reconstructed by the velocity of two FFs, using $\vec{n}_{\mathrm{FF}} = (\vec{v}_{\mathrm{F}_1} \times \vec{v}_{\mathrm{F}_2})/|\vec{v}_{\mathrm{F}_1}||\vec{v}_{\mathrm{F}_2}|$ to denote the normal vector of the fission plane, as shown in Fig. 3 (a). Defining α_1 as the angle between $\vec{n}_{\mathrm{FF}}$ and the beam direction $\vec{v}_{\mathrm{beam}}$, one can characterize how much the fission plane deviates from the beam. The distribution of $|\cos(\alpha_1)|$ is peaked at 0 with a rather small width $\sigma_{\alpha_1} \approx 6^\circ$, as shown in Fig. 3(b), inferring that the fission plane keeps approximately the memory of the initial angular momentum of the rotating system. With $Z \geq 10$ as the condition to identify FFs for theoretical calculations, the transport model prediction about the distribution of $|\cos(\alpha_1)|$ is in rather agreement with the experiment. The scattering plots of folding angle *vs.* $|\cos(\alpha_1)|$ provide the information of fission and detection geometry. With the detector filter of PPACs on both θ_{lab} and ϕ_{lab} according to the setup, the experimental folding angle in Fig. 3(c) can be approximately described by the model simulation in Fig. 3(d).

The characteristics of this rotating fissioning system was obtained using the experiment data and theoretic simulations. First, to estimate its charge and mass, the linear momentum transfer (LMT) should be estimated experimentally. Assuming a symmetric fission processes, the velocity of the fissioning system (FS) can be simply calculated by

TABLE 1. Parameter set used in the ImQMD05 calculations.

α (MeV)	β (MeV)	η	$g_{\rm sur}$ (MeV fm^2)	$g_{\rm sur,iso}$ (fm^2)	$g_{\rho\tau}$ (MeV)	C_s (MeV)	ρ_0 (fm^{-3})
-254	185	5/3	21.0	-0.82	5.51	36.0	0.160

$$\vec{v}_{\rm FS} = \frac{1}{2}(\vec{v}_{\rm F1} + \vec{v}_{\rm F2}), \quad (2)$$

where $\vec{v}_{\rm F1}$ and $\vec{v}_{\rm F2}$ are the velocities of the two FFs, respectively. The LMT is defined as

$$\mathrm{LMT} = \frac{A_{\rm tar} \cdot v^Z_{\rm FS}}{A_{\rm pro} \cdot (v_{\rm pro} - v^Z_{\rm FS})}, \quad (3)$$

Here the subscripts *pro* and *tar* denotes the projectile and the target, respectively. $v^Z_{\rm FS}$ is the projection of $\vec{v}_{\rm FS}$ on the beam direction. As shown in Fig. 4, the distribution of the LMT derived from the experimental data is peaked in the vicinity of 0.4. The small peak below LMT $<$ 0.2 is contributed by the fission events triggered by PPAC 1 and PPAC 3. Accordingly, the typical charge and mass of the rotating fission system are $Z_{\rm FS} \approx Z_{\rm tar} + Z_{\rm pro} \cdot \mathrm{LMT} = 96$ and $A_{\rm FS} \approx A_{\rm tar} + A_{\rm pro} \cdot \mathrm{LMT} = 242$.

Second, to estimate the angular momentum of the rotating fission system, one needs the most probable impact parameter, which can determined by the event weigh obtained from transport model simulations filtered by experimental conditions. Defining the fission event weight by

$$W_{\rm F} = b\frac{n_{\rm F}}{N_{\rm tot}(b)}, \quad (4)$$

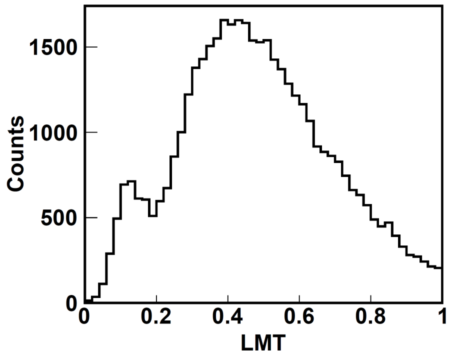

Fig. 4. (Color online) Experimental distribution of LMT.

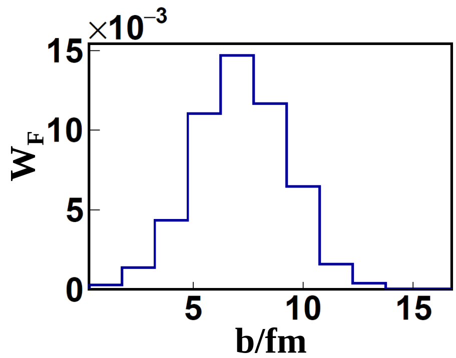

Fig. 5. (Color online) The weight of the fission events as a function of impact parameter b in ImQMD05 simulations.

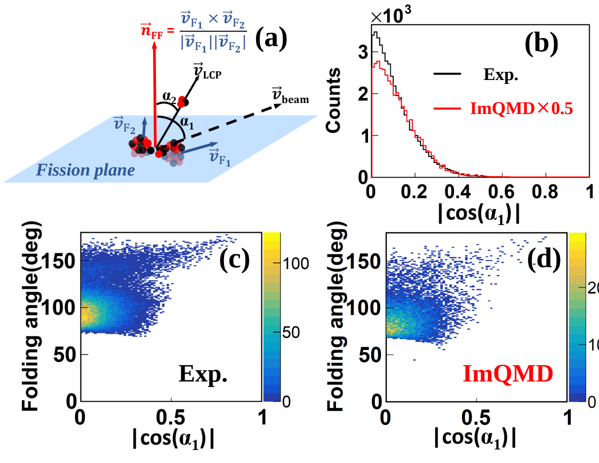

Fig. 3. (Color online) (a) Geometric diagram of fission plane of FFs and LCP emission. (b) Angular distribution between the normal vector $\vec{n}_{\rm FF}$ of the fission plane and the beam direction $\vec{v}_{\rm beam}$. The experimental (c) and simulation (d) results of the folding angle *vs.* $|\cos(\alpha_1)|$ are shown in the bottom panels.

where $n_{\rm F}$ is the number of fission events among $N_{\rm tot}$ events simulated at a given impact parameter b.

Fig. 5 shows the distribution of $W_{\rm F}$, where the most probable impact parameter $b_{\rm m}$ is located in the vicinity of 7 fm.

The distance between the transferred part of the projectile and the mass center of the fissioning system is defined as

$$D = b_{\rm m}\frac{A_{\rm tar}}{A_{\rm tar} + A_{\rm pro} \cdot \mathrm{LMT}}, \quad (5)$$

where $b_{\rm m}$ = 7 fm, $A_{\rm tar}$ = 208, $A_{\rm pro}$ = 86 and LMT = 0.4, respectively.

The angular momentum is written as

$$J = P_{\rm pro} \cdot \mathrm{LMT} \cdot D, \quad (6)$$

where $P_{\rm pro}$ = 18700 MeV/c and $D \approx 6$ fm was derived with LMT = 0.4. Then, the angular momentum of the rotating system is approximately $J \approx 200\ \hbar$.

Third, to estimate the excitation energy of the rotating fission system, the moment of inertia I of a spherical nucleus with the mass M_{FS} is

$$I = \frac{2}{5} M_{\mathrm{FS}} r_{\mathrm{FS}}^2, \quad (7)$$

where $r_{\mathrm{FS}} = 1.4 A_{\mathrm{FS}}^{1/3}$ fm is the radius of the fissioning system. The rotating energy $E_{\mathrm{rot}} = J^2/2I \approx 100$ MeV is approximately obtained. Ignoring the reaction Q value, the excitation energy could be extracted by

$$E^* = E_{\mathrm{kin}}^{\mathrm{i}} - E_{\mathrm{kin}}^{\mathrm{f}} - E_{\mathrm{rot}}, \quad (8)$$

where $E_{\mathrm{kin}}^{\mathrm{i}}$ and $E_{\mathrm{kin}}^{\mathrm{f}}$ are the initial state kinetic energy and the final state kinetic energy, respectively. Approximately, one has $E^* \approx 600$ MeV. The excitation energy is close to the one of the fission system formed in 25 MeV/u Ar+Au at LMT $\approx 80\%$, where the E^* was calculated by the pre-scission α multiplicity [100]. For additional properties of fission systems, such as Viola systematics and angular distribution of the fission axis, please refer to our previously published paper [87].

B. Analysis of the energy spectra of t and ^{3}He

We now present the analysis of the emission of triton and ^{3}He in the (fast)fission events. The energy spectra of LCPs in coincidence with FFs contain thermal and dynamical information of the particles emitted from the fission events. Fig. 6 presents the energy spectra of triton (open circles) and ^{3}He (open triangles) emitted from fission events in different angular ranges corresponding to SSDTs 2 to 4. To reduce the contamination of quasi-projectiles, the data of SSDT1 covering $10-20°$ in the laboratory is not counted here. It is shown that the spectrum of ^{3}He is generally harder than that of triton, leading to a larger average kinetic energy of the former. The difference between triton and ^{3}He is more pronounced at forward angles than at large angles. This observation of "^{3}He-puzzle" is in accordance with the previous inclusive measurements at high beam energies [73, 75–77, 81, 101–104].

TABLE 2. Energy peak position E_{p} of triton and ^{3}He for SSDT 2 to 4.

	SSDT2	SSDT3	SSDT4
E_{p} of triton (MeV)	45	40	19
E_{p} of ^{3}He (MeV)	62	58	38

The "^{3}He-puzzle" has been interpreted by two possible scenarios: sequential decay [74] and coalescence model [78]. In the sequential decay scenario, the difference between ^{3}He and triton is influenced by the Coulomb barrier, for which ^{3}He is emitted at an earlier stage with high temperature to overcome

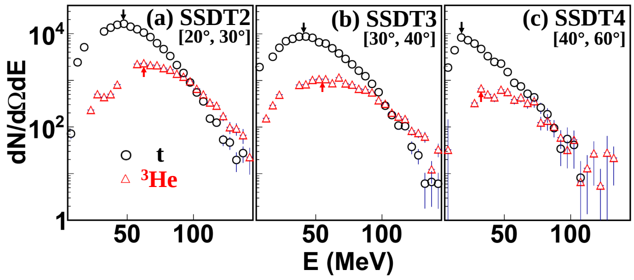

Fig. 6. (Color online) The experimental energy spectra of triton (circle) and ^{3}He (triangle) in $20° \le \theta_{\mathrm{lab}} \le 60°$ covered by SSDT2 to SSDT4 in coincidence with two FFs. The arrows represent the peak position of each experimental energy spectrum.

the Coulomb barrier higher than that of triton [74]. In coalescence scenario, which was applied to interpret the difference between ^{3}He and α particles [78], the former is dominantly produced by the coalescence of preequilibrium nucleons, delivering larger mean kinetic energy. These two explanations are qualitatively in agreement, supporting that ^{3}He is predominantly emitted at earlier stage. Our experimental results show that the "^{3}He-puzzle" exists in the events tagged by fission. It suggests that the puzzle exists in both inclusive and fission events.

C. Out-of-plane emission and the effect of $E_{\mathrm{sym}}(\rho)$

Benefiting from the wide angular coverage of the SSDTs and PPACs in laboratory reference frame, the angular behavior of the particle emission can be analyzed. To compare the yields of particles with different energy spectrum behaviors and avoid the influence of the possible experimental distortion caused by the energy threshold in each SSDTs, a data adaptive energy spectrum peak cut scenario is applying. We focus on the descending part on the high energy side of the energy peak. The energy peak positions (E_{p}) are listed in Table 2. Meanwhile, using the energy condition $E \ge E_{\mathrm{p}}$ as the low limit cut, one can suppress the interference of the evaporation process and emphasize the feature of the dynamic emission.

The angular distribution of $R(\mathrm{t}/^3\mathrm{He})$ as a function of the polar angle in laboratory θ_{lab} is generated with events of one LCP in coincidence with two FFs, as shown in Fig. 7. The same energy threshold, geometry and folding angle cuts are applied to both experimental and simulation results. It is shown that for the wide angular range, the distribution exhibits a rising trend. This feature is consistent with the moving source picture, where the neutron richness of particle emission increases from the projectile-like source to the medium velocity source corresponding to the neck, as predicted by various transport model simulations [40, 41, 46, 48, 49, 51, 105–109], and experimentally observed in a specific angular window [42, 45, 50, 54, 79, 110–112] or a parallel velocity window [45, 79, 80, 113–118].

In order to see the symmetry energy effect, a soft ($\gamma = 0.5$) and a stiff ($\gamma = 1.0$) symmetry energy are adopted in the ImQMD05 simulations. These two γ values correspond to slope parameter of $E_{\rm sym}(\rho)$ with L = 51 and 77 MeV at ρ_0, respectively. Although the predicted value of $R(\mathrm{t}/^3\mathrm{He})$ is far off to the experiment, the rising trend of $R(\mathrm{t}/^3\mathrm{He})$ as a function of $\theta_{\rm lab}$ was reproduced by model simulations in both γ cases. In order to quantify the increasing rate, the function of $f(x) = e^{(p_0+p_1x)}$ is applied to fit the data and the model predictions, respectively. The parameter p_1 describes the increasing rate of $R(\mathrm{t}/^3\mathrm{He})$ to $\theta_{\rm lab}$. As shown in Fig. 7, the rising trend depends on γ. Visibly, a softer $E_{\rm sym}(\rho)$ causes a relative larger increasing rate. When comparing the fitting results between experiment and model in Table 3, the value of experimental p_1 is marginally located between γ = 0.5 and 1.0. Nevertheless, the large uncertainty here reduces the sensitivity and hinder to make a convincing constraint of $E_{\rm sym}(\rho)$.

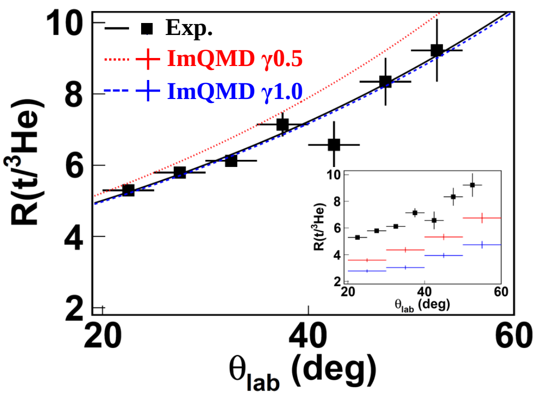

Fig. 7. (Color online) The ratio $R(\mathrm{t}/^3\mathrm{He})$ as a function of $\theta_{\rm lab}$. The black solid squares and black line represent the experiment data and fitting result with $E \geq E_{\rm p}$ cuts in coincidence with fission events. The red and blue cross markers represent the ImQMD05 calculations data of γ = 0.5 and 1.0 in the inset. The red dot and blue dash lines are the fitting results of γ = 0.5 and 1.0 which is normalized with experimental fitting result of p_0.

TABLE 3. Fitting results of the ratio $R(\mathrm{t}/^3\mathrm{He})$ as a function of $\theta_{\rm lab}$ using $f(x) = e^{(p_0+p_1x)}$

	p_0	p_1
Experiment	1.25±0.06	0.018±0.002
γ=0.5	0.75±0.08	0.021±0.002
γ=1.0	0.54±0.09	0.018±0.002

It is then motivated to go a further step to find a novel probe, of which the fission event topology is better controlled and the sensitivity on $E_{\rm sym}(\rho)$ can be enhanced. Fig. 8 presents the angular distribution of $R(\mathrm{t}/^3\mathrm{He})$ with respect to the fission plane. The α_2 on the abscissa is the relative angle between $\vec{n}_{\rm FF}$ and the velocity of the coincident triton or ^{3}He $\vec{v}_{\rm LCP}$ as shown in Fig. 3 (a), with $|\cos(\alpha_2)| = 0\,(1)$ corresponding to in-plane (out-of-plane) emission. Again, the same cuts are applied for both experimental and theoretical results. The increasing trend of $R(\mathrm{t}/^3\mathrm{He})$ with $|\cos(\alpha_2)|$ indicates that the neutron rich particles emitted from out-of-fission-plane is enhanced. This phenomenon is the consequence of the competition between the isospin migration and the centrifugal motion of the particles in the rotating fission system. When the reaction system is viewed as a rotating emission source, particles emitted near the fission plane are subjected to stronger centrifugal potential during the emission process, weakening the difference between neutrons and protons under the isovector potential. From the in-plane to out-of-plane, more neutron rich particles are emitted due to the effect of isospin fractionation [67], indicating that the effect of the isovector potential becomes more significant compared to centrifugal potential. This observation gives us the chance to explore the properties of isospin transport and the density dependence of $E_{\rm sym}(\rho)$ in (fast)fission reactions.

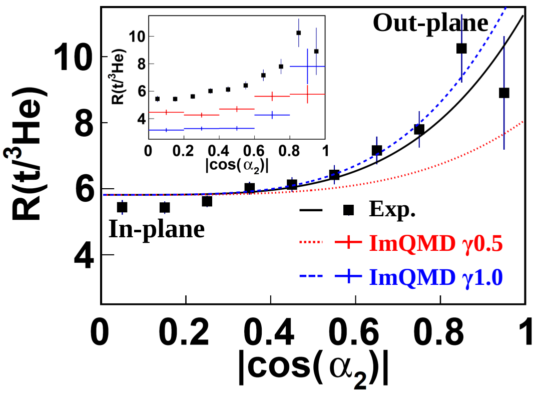

Fig. 8. (Color online) The ratio $R(\mathrm{t}/^3\mathrm{He})$ as a function of $|\cos(\alpha_2)|$. The black solid squares and black line represent the experiment data and fitting result. The red and blue cross markers represent the theoretical calculations data of γ = 0.5 and 1.0 in the inset. The red dot and blue dash lines are the fitting results of γ = 0.5 and 1.0 which is normalized with experimental fitting result of p_0

TABLE 4. Fitting results of $R(\mathrm{t}/^3\mathrm{He})$ as a function of $|\cos(\alpha_2)|$ using $f(x) = p_0 + p_1x^4$.

	p_0	p_1
Experiment	5.8±0.2	5.5±1.6
γ=0.5	4.5±0.1	2.3±1.1
γ=1.0	3.0±0.1	6.8±1.8

Similarly, to describe the increasing trend of the angular distribution of $|\cos(\alpha_2)|$, the function of $f(x) = p_0 + p_1x^4$ is used to fit data and the simulations. Again, p_0 is far off to the experiment due to the clustering difficulty of transport model, but the parameter p_1 can be used to describe the increasing rate of the ratio with out-of-plane angle. In Fig. 8, the fitting curves exhibit a different increasing behavior between γ = 0.5 and 1.0, indicating that the enhancement of neutron rich particle emission out of fission plane is sensitive to the form of $E_{\rm sym}(\rho)$. Inspecting the increasing curves and the values of p_1 as listed in Table 4, one finds that the experimental increasing rate situates between the theoretical prediction with γ = 0.5 and 1.0, in accordance with the conclusion of our previous work [36], where a totally different probe was used. The comparison seems to exclude very soft (γ <0.5) and very stiff (γ >1.0) candidates of symmetry energy. The results indicate that the ratio $R(\mathrm{t}/^3\mathrm{He})$ as a function of $|\cos(\alpha_2)|$ seems to be a sensitive probe for density dependent symmetry energy, especially in the larger $|\cos(\alpha_2)|$ range, which is very close to the boundary of the current detector coverage. Hence, more events in the larger $|\cos(\alpha_2)|$ range are preferentially requested in the further experiments. Data analysis of a new measurement of ^{86}Kr+^{124}Sn at 25 MeV/u is ongoing [119].

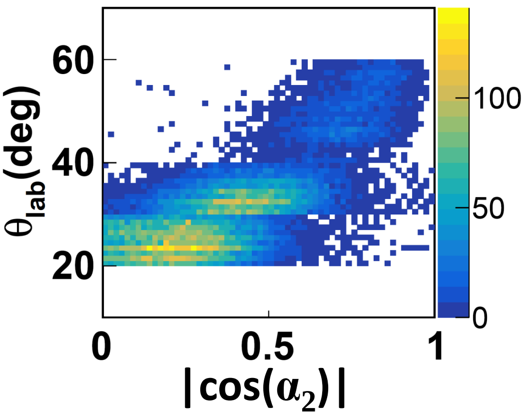

Fig. 9. (Color online) The scattering plot between $|\cos(\alpha_2)|$ and laboratory angle with the experiment events of triton in coincidence with two fission fragments.

Fig. 9 shows in addition the relationship between $|\cos(\alpha_2)|$ and θ_{lab} with the experiment events of triton in coincidence with two fission fragments. Visibly, there is a weak positive correlation between $|\cos(\alpha_2)|$ and θ_{lab}. The origin of the correlation is partly due to the fact that the azimuth coverage of the PPAC is quite limited. With such weak correlation, one infers that the two distributions shown in Fig. 7 and Fig. 8 have their own implications. Namely, the distribution of $R(\mathrm{t}/^3\mathrm{He})$ as a function of θ_{lab} indicates that the low density and neutron rich medium velocity emission source (neck) is formed, while the distribution of $R(\mathrm{t}/^3\mathrm{He})$ as a function of $|\cos(\alpha_2)|$ characterizes the fine out-of-plane properties of the isospin transport in a fissioning process. Upon comparing the results presented in Table 3 and Table 4, it becomes evident that the enhancement of $R(\mathrm{t}/^3\mathrm{He})$ *vs.* $|\cos(\alpha_2)|$, particularly at larger out-of-plane angles, appears to be a more sensitive probe for studying nuclear symmetry energy than the polar angular distribution of $R(\mathrm{t}/^3\mathrm{He})$. In another word, in the properly characterized fission events, the effect of $E_{\mathrm{sym}}(\rho)$ can be magnified, supporting the previous predictions by transport model simulations [40].

Currently we do not attempt to make a fine tuning and constraint of γ parameter in the simulations, since the absolute value of $R(\mathrm{t}/^3\mathrm{He})$ is not yet well reproduced, as indicated by Fig. 7 and 8. Further studies are required in transport model in order to elucidate the origin and the formation mechanism of light clusters including triton and ^{3}He. Recently, the yield of light clusters is better reproduced by introducing Mott effect in transport model [120]. Meanwhile, the cooling process of the rotating fissioning system with similar E^* and J is of high interest. We are going to make further calculations on particle emission from a rotating system with inclusion of deuteron, triton and ^{3}He apart of neutron, proton and α particles, as done in [121]. The emission of other particles than A=3 isobars may bring significant effect to the featured distribution of the latter in the cooling process of the fissioning system.

V. SUMMARY

The energy spectra and angular distributions of triton and ^{3}He ranging from 20° to 60° in the laboratory in coincidence with fission fragments are analyzed in 25 MeV/u ^{86}Kr +$^{\mathrm{nat}}$Pb reactions. It is shown that the energy spectra of ^{3}He are generally harder than triton even in the fission events, and the effect is more pronounced at small angles. Applying a data driven energy spectrum peak cut scenario, the rising trend of angular distribution of $R(\mathrm{t}/^3\mathrm{He})$ is observed in the coincident events of one LCP and two FFs, which is consistent with previous inclusive observations. The yield ratio $R(\mathrm{t}/^3\mathrm{He})$ exhibits an enhancement as a function of $|\cos(\alpha_2)|$, evidencing more neutron rich particles emitted from out-of-fission-plane. With a qualitative comparison with ImQMD05 simulations, the enhancement of neutron rich particle emission from out-of-fission-plane seems to be a novel probe for nuclear symmetry energy. More measurements at large out-of-fission-plane angles and further theoretic investigations are required for a stringent constraint of $E_{\mathrm{sym}}(\rho)$.

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