Observing the Ping-pong Modality of Isospin Degree of Freedom in Cluster Emission from Heavy Ion Reactions

Authors: Yijie Wang, Fenhai Guan, Dawei Si, Sheng Xiao, Boyuan Zhang, Yaopeng Zhang, Baiting Tian, Xianglun Wei, Herun Yang, Peng Ma, Rongjiang Hu, Limin Duan, Fangfang Duan, Qiang Hu, Junbing Ma, Shiwei Xu, Zhen Bai, Yanyun Yang, Jiansong Wang, Wenbo Liu, Wanqing Su, Xiaobao Wei, Chun-Wang Ma, Xinxiang Li, Hongwei Wang, Fangyuan Wang, Yingxun Zhang, Michał Warda, Arthur Dobrowolski, Bożena Nerlo-Pomorska, Krzysztof Pomorski, Li Ou, Zhigang Xiao, Xinyue Diao, Mengting Wan, Yuhao Qin, Zhi Qin, Qianghua Wu, Dong Guo

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Abstract

Two-body correlations of the isotope-resolved light and heavy clusters are measured in 86Kr+ 208Pb reactions at 25 MeV/u. The yield and kinetic variables of the A = 3 isobars, triton and 3He, are analyzed in coincidence with the heavy clusters of 7 ≤ A ≤ 14 emitted at the earlier chance. While the velocity spectra of both triton and 3He exhibit scaling behavior over the type of the heavy clusters, the yield ratios of t/ 3He correlate reversely to the neutron-to-proton ratio N/Z of the latter, showing the ping-pong modality of the N/Z of emitted clusters. The commonality that the N/Z of the residues keeps the initial system value is extended to the cluster emission in heavy ion reactions. The comparison of transport model calculations to the data is discussed.

Full Text

Preamble

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Yijie Wang,[1], * Fenhai Guan,[1] Xinyue Diao,[1] Mengting Wan,[2],[3] Yuhao Qin,[1] Zhi Qin,[1] Qianghua Wu,[1] Dong Guo,[1] Dawei Si,[1] Sheng Xiao,[1] Boyuan Zhang,[1] Yaopeng Zhang,[1] Baiting Tian,[4] Xianglun Wei,[5] Herun Yang,[5] Peng Ma,[5] Rongjiang Hu,[5] Limin Duan,[5] Fangfang Duan,[5] Qiang Hu,[5] Junbing Ma,[5] Shiwei Xu,[5] Zhen Bai,[5] Yanyun Yang,[5] Jiansong Wang,[5],[6] Wenbo Liu,[7] Wanqing Su,[7] Xiaobao Wei,[7] Chun-Wang Ma,[7] Xinxiang Li,[8] Hongwei Wang,[8],[9] Fangyuan Wang,[10] Yingxun Zhang,[10] Michał Warda,[11] Arthur Dobrowolski,[11] Bożena Nerlo-Pomorska,[11] Krzysztof Pomorski,[11] Li Ou,[2],[3], † and Zhigang Xiao[1],[12], ‡

[1]Department of Physics, Tsinghua University, Beijing 100084, China
[2]College of Physics and Technology, Guangxi Normal University, Guilin 541004, China
[3]Guangxi Key Laboratory of Nuclear Physics and Technology, Guangxi Normal University, Guilin 541004, China
[4]College of Physics, Sichuan University, Sichuan, 610065, China
[5]School of Science, Huzhou University, Huzhou, 313000, China
[6]Institute of Particle and Nuclear Physics, Henan Normal University, Xinxiang 453007, China
[7]Shanghai Institute of Applied Physics, Chinese Academy of Science, Shanghai 201800, China
[8]Shanghai Advanced Research Institute, Chinese Academy of Science, Shanghai 201210, China
[9]China Institute of Atomic Energy, Beijing 102413, China
[10]Institute of Physics, Maria Curie Skłodowska University, 20-031 Lublin, Poland
[11]Collaborative Innovation Center of Quantum Matter, Tsinghua University, Beijing 100084, China

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Two-body correlations of isotope-resolved light and heavy clusters are measured in ^{86}Kr+^{208}Pb reactions at 25 MeV/u. The yield and kinetic variables of the A = 3 isobars, triton and ^{3}He, are analyzed in coincidence with heavy clusters of 7 ≤ A ≤ 14 emitted at the earlier chance. While the velocity spectra of both triton and ^{3}He exhibit scaling behavior over the type of heavy clusters, the yield ratios of t/^{3}He correlate reversely to the neutron-to-proton ratio N/Z of the latter, showing the ping-pong modality of the N/Z of emitted clusters. The commonality that the N/Z of the residues keeps the initial system value is extended to cluster emission in heavy ion reactions. The comparison of transport model calculations to the data is discussed.

Introduction

Since the detection of gravitational waves from the neutron star merging event GW170817 [1–3], it has become more indispensable than ever to unveil the equation of state (EOS) of nuclear matter, which is essential for describing the explosion of celestial objects where heavy elements are created in the universe. Particularly, the EOS of asymmetric nuclear matter, namely the density-dependent nuclear symmetry energy $E_{\mathrm{sym}}(\rho)$, has been a longstanding frontier of common interest bridging nuclear physics and astrophysics. Great progress has been made in constraining $E_{\mathrm{sym}}(\rho)$ using astrophysical observations and terrestrial experiments. However, there remains significant room to reduce the uncertainty [4, 5].

In terrestrial nuclear laboratories, depending on the beam energy, a variety of isobaric yield ratios in heavy ion collisions (HICs), such as n/p, t/^{3}He, π^-/π^+, K^0/K^+, and Ξ^-/Ξ^0 [6–14], have been identified to probe $E_{\mathrm{sym}}(\rho)$ over a wide density range. However, quantitative extraction of $E_{\mathrm{sym}}(\rho)$ is not trivial because of the complicated transport behavior of neutrons and protons in the collisions. To achieve precise results, it is essential to understand how the isospin degree of freedom (IDOF) evolves during the process of HIC [15].

Among the aforementioned isobaric ratios, the ratio of A = 3 isobars, t/^{3}He, has been suggested to probe the enriched features of isospin dynamics in HICs both theoretically [13, 14, 16–22] and experimentally [22–29]. Nevertheless, beyond inspecting one-body quantities at the final stage, it has recently been realized that the temporal evolution of isospin observables carries the fine effect of $E_{\mathrm{sym}}(\rho)$ [30, 31]. Additionally, isospin chronology reveals the particle emission hierarchy by measuring correlation functions of like and unlike particle pairs [32–35].

Furthermore, the complication of clustering emerges. As reported recently, cluster formation on the surface of heavy nuclei depends on the N/Z of the system and couples to the properties of dilute neutron-rich matter [36]. As long as cluster emission is abundant in HICs at intermediate energy, one may naturally ask: how does the IDOF evolve with the presence of cluster emission, and is there any commonality of the relaxation of IDOF arising from the effect of $E_{\mathrm{sym}}(\rho)$ across various nuclear processes?

In this letter, we are motivated to differentiate the fine signal featuring the transport of IDOF related to cluster emission and to identify a novel isospin probe using temporal two-body correlation rather than a single isobaric yield ratio. The thermodynamic and chemical correlation of light and heavy clusters are analyzed in 25 MeV/u ^{86}Kr+^{208}Pb reactions. The anti-correlation of the isobaric ratio t/^{3}He with the N/Z of heavier clusters is reported. Further, the commonality that the N/Z of the initial system undergoing cluster emission is preserved across various nuclear processes is discussed.

Experimental Setup

The experiment was performed with the Compact Spectrometer for Heavy IoN Experiment (CSHINE) [37, 38], installed at the final focal plane of the Radioactive Ion Beam Line at Lanzhou (RIBLL-I) [39]. The ^{86}Kr beam with 25 MeV/u incident energy was delivered by the Heavy Ion Research Facility at Lanzhou (HIRFL) [40], bombarding a natural lead target with a thickness of 1 mg/cm^2.

In the current configuration of CSHINE, light charged particles (LCPs) and intermediate mass fragments (IMFs) are measured by four silicon-strip detector telescopes (SSDTs), while coincident fission fragments (FFs) are measured by three parallel plate avalanche counters (PPACs), each covering a sensitive area of 240×280 mm^2. Each SSDT consists of one single-sided silicon-strip detector (SSSSD) and one double-sided silicon strip detector (DSSSD), backed by a 3 $\times$ 3 CsI(Tl) crystal hodoscope with length of 50 mm. The sensitive area of each SSDT is 64 $\times$ 64 mm^2, and the granularity is 4 $\times$ 4 mm^2, delivering approximately 1° angular resolution. The SSDTs cover the angular range from 10° to 60° in the laboratory system. The energy resolution of the SSDT is better than 2%, and isotopes up to Z = 7 can be identified. For details of the construction of CSHINE, see [37, 38]. Since the event statistics of four-body coincidence (i.e., with two charged particles in SSDTs and two FFs in PPACs) are insufficient, we analyze two-body coincidence events of two fragments in the SSDTs. Multi-hit and signal sharing events are treated with care in track recognition, achieving an overall track recognition efficiency of about 90%. The detailed procedure of track reconstruction can be found in [41].

[Figure 1: see original paper] summarizes the data used in the current analysis. Panel (a) presents the scattering plot of $\Delta E_2 - E\_\{CsI\}$ of SSDT1, showing that all isotopes can be clearly identified up to Z = 6. Panel (b) presents the PID plots for all isotopes on $\Delta E_2 - E\_\{CsI\}$ summed over SSDT 1 to 4 after the tracking procedure [41]. Panels (c) and (d) present the phase space distribution of triton and ^{3}He stopped in the CsI(Tl) hodoscope, respectively.

Results and Discussions

To observe temporally correlated emissions of charged particles, we investigate two-body events in the SSDTs, with one being a light charged particle, $F_L(Z_L, A_L)$, and the other being a heavy fragment, $F_H(Z_H, A_H)$, with $7 \leq A_H \leq 14$, where the subscripts L and H denote light and heavy, respectively. Here F_L is chosen as one of the mirror nuclei, triton or ^{3}He. According to earlier studies using correlation function methods, heavy fragments are emitted with a shorter average time constant in this energy region [42]. Thus, it is reasonable to assume that F_H is emitted earlier than F_L in our study. To eliminate influence from low-energy statistical decay, we count only high-energy particles—specifically, only F_L stopped in the CsI(Tl) hodoscope are analyzed.

We first examine the thermodynamic correlation. [Figure 2: see original paper] (a) and (b) present the velocity spectra of triton (a) and ^{3}He (b) in coincidence with various heavy fragments F_H. The shape and range of the velocity distributions of triton and ^{3}He exhibit insignificant dependence on the type of F_H, although the coincident yield differs. Normalizing the yields to the black histograms corresponding to coincidence with ^{7}Li, one sees that all spectra exhibit scaling behavior, as shown in the insets in (a) and (b). Further, the mean velocity $\langle v \rangle$ of triton and ^{3}He are presented in (c) and (d), varying with the type of F_H. The shaded band represents the standard deviation σ_v of each individual velocity distribution. Solid and open symbols denote F_H with larger and smaller neutron richness, respectively. Clearly, both $\langle v \rangle$ and σ_v are nearly constant, showing insignificant dependence on the N/Z of the heavy fragments. This suggests that the light particles experience the same dynamic process, regardless of whether the heavy clusters are rich or deficient in neutrons.

Surprisingly, the IDOF features behave differently. [Figure 3: see original paper] (a) presents the yield ratio of t/^{3}He, written as $R(t/^3\text{He})$, as a function of the mass of F_H. Again, solid (open) symbols correspond to the more (less) neutron-rich F_H at a given mass. Here the heavy cluster ^{8}Be is reconstructed by two correlated α particles. The ratio $R(t/^3\text{He})$ splits into two groups, with the exception of the F_H pair with A = 12 where the effect is blurred by large uncertainty. A ping-pong motion modality of the N/Z in cluster emission is suggested: after a neutron-rich heavy fragment (solid) is emitted, $R(t/^3\text{He})$ is smaller, indicating that a less neutron-rich F_L follows. Conversely, if F_H is less neutron-rich (open), $R(t/^3\text{He})$ is larger, indicating that F_L is on average more neutron-rich. The ping-pong behavior of the N/Z of the two clusters demonstrates that the isospin content of F_L depends on the N/Z of F_H emitted earlier. This tendency is further presented in panel (b), where $R(t/^3\text{He})$ is plotted as a function of the relative neutron richness of F_H defined by $\delta_{I_H} = (N_H - Z_H)/A_H$. The solid line is the least-square linear fit to the data points. A non-zero negative slope k is confirmed at the 5.3σ confidence level, evidencing that the isospin compositions of F_H and F_L are anti-correlated.

Model-independently, the anti-correlation between the N/Z of F_L and F_H infers how the IDOF evolves toward equilibrium during the decay of the highly excited system formed in ^{86}Kr+^{208}Pb reactions. If more (less) neutrons are carried away by the heavy cluster at an earlier stage, the following light cluster carries fewer (more) neutrons. This suggests that the neutron richness of the emitted clusters is balanced near a certain value, so that the remaining system—possibly destined to become an emission residue or fission fragment—possesses a certain N/Z close to that of the initial system, as discussed below.

To show this effect clearly, [Figure 4: see original paper] presents the N-Z correlation of the remaining nuclei, obtained by subtracting F_L and F_H from the initial system. The N/Z = 1.497 relationship is indicated by the red dashed line, and the asterisk denotes the location of the ^{86}Kr+^{208}Pb system. The remaining system is situated in the vicinity of the dashed line, indicating that the average N/Z of the remaining system is the same as the initial value of ^{86}Kr+^{208}Pb. Here we can only count the two clusters measured, including A = 3 isobars and the heavy clusters. Because of the anti-correlation demonstrated in [Figure 3: see original paper], it is reasonable to assume the undetected decay particles have a similar N/Z to the detected products and thus do not drag the distribution center away from the dashed line.

Interestingly, cluster radioactivity observed in various super-heavy nuclei [43–

45] shows similar behavior, as illustrated by the circles in the plot. The cluster decay channels are taken from [44]. The daughters (blue) are distributed near the same N/Z line as the parent nuclei (black). Moreover, if one inspects the fission of heavy nuclei—for instance, the neutron-induced fission of ^{235}U plotted in the inset—the N/Z of the fission fragments follows the same N/Z value as the parent nucleus ^{235}U [46]. Because of the presence of $E_{\text{sym}}(\rho)$, which finally contributes to the Q-value, it is seemingly common that the N/Z of the daughters inherits that of the parents in fission and cluster decay of heavy nuclei. Our experiment extends this commonality to cluster emission from the highly excited system formed in heavy ion reactions.

To understand the isospin transport behavior, the reaction process is simulated using the improved isospin-dependent quantum molecular dynamics model (ImQMD05) [47] followed by a statistical decay afterburner GEMINI [48, 49]. The local nuclear potential energy density functional in the ImQMD05 model is written as:

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

where ρ, ρ_n, ρ_p are the nucleon, neutron, and proton densities, $\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p)$ is the isospin asymmetry, and ρ_0 is the saturation density. The parameters are determined by Skyrme interaction with parameter set MSL0 [50] except for $C_s = 36.0$ MeV and the variable γ relevant to $E_{\text{sym}}(\rho)$. The density behavior of $E_{\text{sym}}(\rho)$ can be mimicked by varying γ.

The calculations cover the impact parameter range of $1 \leq b \leq 7$ fm. The same cuts on phase space are adopted as in the experiment. To avoid ambiguity in the correlation, we exclude events containing more than one F_H with the same N_H and A_H, but set no cut on the multiplicity of F_L.

[Figure 5: see original paper] presents the $R(t/^3\text{He})$ ratio as a function of δ_{I_H} for different $E_{\text{sym}}(\rho)$ with $\gamma = 0.4$ (super-soft), 0.5 (soft), and 2.0 (super-stiff), respectively. The simulated ratios depend slightly on b but significantly on the stiffness of $E_{\text{sym}}(\rho)$, as shown in panels (a–c). Panels (d–f) present the b-averaged results. The dashed lines are linear fits, and the experimental trend is replotted as solid lines for comparison. Interestingly, the anti-correlation between $R(t/^3\text{He})$ and δ_{I_H} is qualitatively reproduced with a soft $E_{\text{sym}}(\rho)$ ($\gamma = 0.5$). However, super-stiff and super-soft $E_{\text{sym}}(\rho)$ are disfavored by significant deviation from the experimental trend. Since discrepancies, particularly in the slope, still exist between data and simulations, we do not quantify $E_{\text{sym}}(\rho)$ here. The modeling of clustering in transport theory requires further effort, even for A = 3 clusters, although $R(t/^3\text{He})$ has been proposed to probe $E_{\text{sym}}(\rho)$ in heavy ion reactions.

Summary

The A = 3 isobars are measured in coincidence with heavy clusters of $7 \leq A \leq 14$ in 25 MeV/u ^{86}Kr+^{208}Pb reactions. While the velocity spectra of triton and ^{3}He show scaling behavior over the type of heavy cluster, the yield ratio $R(t/^3\mathrm{He})$ exhibits evident anti-correlation with the N/Z of the heavy clusters, suggesting a ping-pong modality of the N/Z of emitted clusters. The commonality that the remaining system inherits the N/Z of the initial system—which has been reported in cluster decay and fission of super-heavy nuclei—is extended to cluster emission from HIC at Fermi energies. In addition to the yield ratio of t/^{3}He, the anti-correlation between the N/Z of the two clusters provides a new avenue to test transport theory in terms of cluster formation and isospin dynamics, and to eventually achieve accurate constraint of $E_{\mathrm{sym}}(\rho)$ using heavy ion reactions.

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- Electronic address: yj-wang15@tsinghua.org.cn
  † Electronic address: liou@gxnu.edu.cn
  ‡ Electronic address: xiaozg@tsinghua.edu.cn

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Note: Figure translations are in progress. See original paper for figures.