

Nuclear temperature of spectator source extracted by neutron spectra in $^{124}\text{Sn}, ^{107}\text{Sn} + ^{120}\text{Sn}$ collisions at 600 MeV/nucleon

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Abstract

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Full Text

Preamble

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Abstract

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Introduction

The study of nuclear properties under extreme conditions has long been a focal point of research [1]. These studies are crucial for understanding astrophysical and nuclear physics-related issues [2–4]. Heavy-ion collisions at intermediate energies are commonly used to investigate the thermodynamic properties of hot nuclei at high temperature and density [5–7]. In particular, hot nuclear systems with excitation energies in the range of 3–8 MeV/A are applied to study the nuclear liquid-gas phase transition [8, 9]. Pochodzalla et al. used Au + Au peripheral collisions to analyze the caloric curve and discovered a plateau in nuclear temperature in the excitation-energy region of 3–8 MeV/A, a phenomenon analogous to the liquid-gas phase transition of water at 373.15 K. This finding is considered significant evidence of the liquid-gas phase transition in nuclei [10].

Isospin effects play a critical role in nuclear fragmentation reactions [11–13]. Research on isospin effects provides a new way to extract information on symmetry energy [14, 15]. Since the application of the caloric curve concept to atomic nuclei, a significant isotopic dependence of the caloric curve or nuclear temperatures has been expected [16, 17]. Related experiments have been explored, such as the comprehensive study of isospin dependence in projectile fragmentation for ^{107}Sn , ^{124}Sn , and $^{124}\text{La} + \text{Sn}$ at 600 MeV/nucleon at the GSI Schwerionen-Synchrotron. In 2009, the A/Z dependence of projectile fragmentation at relativistic energies was studied with the ALADIN forward spectrometer at SIS [18]. It was found that isotopic temperatures for neutron-rich projectiles are slightly larger than those for neutron-poor projectiles. Global fragmentation observables were published, showing weak dependence on the projectile N/Z ratio [19]. Based on the Z distributions of the largest fragment in spectator fragmentation, the deduced pseudocritical points were found to be only weakly dependent on the ratio of the fragmenting spectator source [20].

Recently, the Large-Area-Neutron-Detector LAND has been used to measure neutron emission in projectile fragmentation and explore the N/Z dependence of the identified neutron source [21].

For data interpretation, various models have been developed to study the mechanisms of fragmentation reactions [22]. Statistical models are based on the assumption that fragments produced in a collision arise from a system in thermal equilibrium and have been widely applied to study fragmentation. In 1999, Borderie et al. [23] used a quantum statistical model based on thermodynamic equilibrium to describe the properties of fragment products from the projectile in an Ar+Ni reaction with an incident energy of 95 MeV/A. Similarly, Ogul et al. [19] applied the statistical multifragmentation model to study spectator fragment products and found that the model could effectively describe the distribution of spectator fragmentation products. However, many studies suggest that thermal nuclei produced in peripheral collisions only partially achieve thermodynamic equilibrium.

In 2003, Colin et al. [24] studied the fragmentation process of spectators in heavy-ion collisions in the Fermi energy region using systems of different masses. They found that most spectator fragments did not satisfy thermodynamic equilibrium conditions. Zbiri et al. [25] used Au + Au collisions in the intermediate-energy region to study fragmentation products from both participants and spectators, showing that spectator fragmentation products did not achieve equilibrium in the dynamical degrees of freedom. Furthermore, Russotto et al. [26, 27], using heavy-ion collisions in the Fermi energy region, studied the emission probabilities of intermediate-mass fragments and found that their emission involved both dynamical and statistical mechanisms.

On the other hand, dynamical models such as the Isospin-dependent Quantum Molecular Dynamics (IQMD) model focus on the microscopic dynamics of the collision and fragmentation process, considering factors such as nucleon-nucleon interactions and the time evolution of the system [28]. The combination of microscopic dynamics and statistical models allows for a more comprehensive description of the fragmentation process, including the transition from a dynamical to a statistical regime as the system evolves. Recent progress has been made in combining these models to better predict and describe the complex fragmentation patterns observed in peripheral collisions. For instance, in the works by Su et al., the IQMD model is used to study non-equilibrium thermalization and fragmentation, while the statistical code GEMINI is applied to simulate the secondary decay of pre-fragments. Data on intermediate-mass fragments (IMFs) in $^{107,124}\text{Sn}$ and ^{124}La projectile fragmentation have been successfully reproduced by the combined model [29–31].

In this work, the IQMD+GEMINI model is applied to study the properties of neutrons emitted from the spectator source produced in $^{124}\text{Sn}, ^{107}\text{Sn} + ^{120}\text{Sn}$ collisions at 600 MeV/nucleon. The paper is organized as follows. In Sec. II, we briefly describe the method. In Sec. III, we present both results and discussions. Finally, a summary is given in Sec. IV.

II. Theoretical Framework

A. Isospin-dependent quantum molecular dynamics model

The wave function for each nucleon in the IQMD model is represented by a Gaussian wave packet:

$$\phi_i(\mathbf{r}, t) = \frac{1}{(2\pi L)^{3/4}} \exp\left[-\frac{(\mathbf{r} - \mathbf{r}_i(t))^2}{4L}\right] \exp\left[\frac{i\mathbf{p}_i(t) \cdot \mathbf{r}}{\hbar}\right]$$

where \mathbf{r}_i and \mathbf{p}_i are the average position and momentum of the i th nucleon, and L is related to the extension of the wave packet. The phase-space density of the system is given by:

$$f(\mathbf{r}, \mathbf{p}, t) = \frac{1}{(\pi\hbar)^3} \sum_i \exp\left[-\frac{(\mathbf{r} - \mathbf{r}_i(t))^2}{2L}\right] \exp\left[-\frac{(\mathbf{p} - \mathbf{p}_i(t))^2 \cdot 2L}{\hbar^2}\right]$$

The time evolution of the nucleons in the system is governed by Hamiltonian equations of motion:

$$\dot{\mathbf{r}}_i = \nabla_{\mathbf{p}_i} H, \quad \dot{\mathbf{p}}_i = -\nabla_{\mathbf{r}_i} H$$

The Hamiltonian of baryons consists of kinetic energy, Coulomb interaction, and nuclear interaction. The nuclear interaction includes local two-body and three-body interactions, and the symmetry potential. The nuclear potential density is expressed as:

$$V(\rho, \delta) = \alpha \left(\frac{\rho}{\rho_0}\right)^\gamma + \beta \left(\frac{\rho}{\rho_0}\right)^{\gamma+1} + C_{sp} \left(\frac{\rho}{\rho_0}\right)^{\gamma_i} \rho \delta^2$$

where ρ_0 is the normal density. The parameters used in the following work are $\alpha = -356.00$ MeV, $\beta = 303.00$ MeV, $\gamma = 7/6$, $C_{sp} = 38.06$ MeV, and $\gamma_i = 0.75$.

Binary nucleon-nucleon (NN) collisions are included: elastic proton-proton scatterings, elastic neutron-neutron scatterings, elastic neutron-proton scatterings, and inelastic NN collisions. The cross section in free space depends on energy and isospin, and the in-medium factor is also energy-dependent and isospin-dependent. The method of phase space density constraint (PSDC) is taken into account. The Pauli blocking method related to PSDC is necessary after using the PSDC method to compensate for the fermionic nature of nucleons.

B. GEMINI

The output of the IQMD code consists of hot fragments. To obtain cold fragments, emission of light particles ($Z < 3$) from hot fragments is performed by

the statistical code GEMINI [32]. A Monte Carlo technique is employed to follow the decay chains until the excitation energy of the product is zero. The partial decay widths are taken from the Hauser-Feshbach formalism:

$$\Gamma_{J_2}(Z_1, A_1, Z_2, A_2) = \frac{2J_2 + 1}{(2J_0 + 1)(2J_2 + 1)} \int_{|J_0 - J_2|}^{J_0 + J_2} dl \int_0^{E^* - B - E_{rot}} d\varepsilon T_\ell(\varepsilon) \rho_2(E^* - B - E_{rot} - \varepsilon, J_2)$$

where ℓ and ε are the orbital angular momentum and kinetic energy of the emitted particle, E_{rot} is the rotation plus deformation energy of the residual system, ρ_0 and ρ_2 are the level densities of the initial and residual systems, respectively, and T_ℓ is the transmission coefficient.

III. Results and Discussion

A. Properties of projectile spectator

The $107,124\text{Sn} + 120\text{Sn}$ collision at 600 MeV/nucleon is simulated by the IQMD+GEMINI model. Fragments with $Z = 3$ and neutrons are used to extract the fragmenting source. Figure 1 [Figure 1: see original paper] shows the two-dimensional distribution of transverse and longitudinal momentum for $Z = 3$ fragments. Two distinct emission sources are apparent: a target-like source around $p_z = 0$ and a projectile-like source near $p_z = 1200$ MeV/c. The distribution's hot spot center lies at a transverse momentum of 50 MeV/c, corresponding to a transverse kinetic energy of 1.3 MeV. This recoil kinetic energy, influenced by both the emission source recoil and Coulomb repulsion of the fragments, is minor compared to the incident kinetic energy of 600 MeV/nucleon.

The blue line in the figure represents the emission angle of fragments in the laboratory system. The acceptance range of the ALADIN spectrometer covers areas with horizontal angle less than 10.2° and vertical angle less than 4.5° . In Ref. [21], the horizontal and vertical axes are designated as y and x , respectively, with the beam direction defined as z . In the experiment, it is not possible to explicitly identify the collision parameter direction. Instead, the horizontal (y) and vertical (x) directions are defined by the detector orientation. This axis definition differs from theoretical studies, where the beam incidence direction is typically denoted as z' , the collision parameter direction as x' , and the perpendicular direction as y' . However, this discrepancy does not affect our analysis due to the relatively small recoil kinetic energy. Given the small recoil kinetic energy, fragment emission shows axial symmetry along the z -axis. Thus, variations in Cartesian coordinate definitions within the plane perpendicular to z do not impact the dynamic analysis.

The ALADIN spectrometer is designed to detect most fragments from projectile-like sources while excluding most of those from target-like emission sources. The horizontal acceptance angle of 10.2° is large enough to collect most fragments

from projectile-like sources, while the vertical acceptance angle of 4.5° is insufficient. Some $Z = 3$ fragments with emission angles greater than 4.5° are not detected. This issue is more clearly illustrated by the angular distribution shown in Fig. 2 [Figure 2: see original paper], where the blue box represents the acceptance region of the ALADIN spectrometer, extending $\pm 10.2^\circ$ horizontally and $\pm 4.5^\circ$ vertically.

In Ref. [19], it is reported that the ALADIN spectrometer captures 90% of $Z = 3$ fragments. However, our calculations indicate an efficiency of only 74%. This discrepancy is largely due to the recoil effect from the emission source, which impacts the vertical acceptance angle, though the horizontal acceptance angle is sufficiently large. Some fragments escape detection along the horizontal axis. The deviation between experimental and calculated reception efficiencies stems from an overestimation of the emitter temperature in the IQMD+GEMINI model used for simulations. It should be noted that the reception efficiency increases with the mass number of the emission source, eventually approaching 100% for heavier sources. Therefore, this deviation has a minimal effect on the subsequent discussion of the Z_{bound} value.

Figure 3 [Figure 3: see original paper] shows the distribution of neutrons in the plane of transverse momentum p_t versus longitudinal momentum p_z . Neutrons near $p_z = 0$ originate from the target-like system, while those near $p_z = 1200$ MeV/c come from the projectile-like system. A significant number of neutrons are also distributed over a broad range around $p_z = 600$ MeV/c, emitted from participants that acquire substantial transverse momentum due to intense collision dynamics.

Neutrons can be emitted throughout the entire heavy-ion collision process, from the pre-equilibrium stage (characterized by violent two-body collisions), to the high-temperature stage of multiple fragmentation, and finally to the lower-temperature stage of secondary decay. In contrast, the $Z = 3$ fragments (shown in Fig. 1) primarily originate from the multiple fragmentation stage. This results in a wider kinetic energy distribution for neutrons compared to the $Z = 3$ fragments.

The blue line in the figure represents the neutron emission angle. As shown in Ref. [21], the maximum horizontal acceptance angle of LAND is 8.72° , and the maximum vertical acceptance angle is 4.09° . It is clear that LAND can effectively exclude most neutrons from both target-like and participant systems.

Figure 4 [Figure 4: see original paper] shows the angular distribution of neutrons in the detector's receiving plane. The blue box represents LAND's acceptance region. The center of the neutron distribution is at the origin, and the distribution is circular. LAND covers the angular range $0 < \theta_x < 8.72^\circ$ and $-4.09^\circ < \theta_y < 4.09^\circ$. The detector does not cover the region where $\theta_x > 0^\circ$. However, due to the symmetry of the system, this limitation does not adversely affect the results. In Ref. [21], a neutron emission source with a temperature of 4 MeV was studied, and it was found that LAND's acceptance for neutrons is

42.4%. However, the model calculations show that LAND's acceptance is lower than this value for neutrons emitted by spectator sources in the reaction.

The energy spectrum of neutrons with emission angles less than 2° has been measured in Ref. [21]. The calculated energy spectrum from the IQMD+GEMINI model is compared with experimental data in Figure 5 [Figure 5: see original paper]. The dashed line in the figure represents the incident energy of 600 MeV/u. Both experimental and calculated spectra show a peak in the differential cross section at 600 MeV/u, indicating that neutrons emitted at angles less than 2° primarily originate from projectile-like emission sources, with minimal recoil effect.

The experimental energy spectra for the ^{124}Sn and ^{107}Sn systems have similar shapes, but the cross section for the ^{124}Sn system is slightly larger than that for ^{107}Sn . For the ^{124}Sn system, the peak value is 21.7 mb/MeV, while for the ^{107}Sn system, the peak value is 4.3 mb/MeV. The calculations capture the overall shape and system dependence of the experimental energy spectrum: the peak occurs at 600 MeV, and the peak for the ^{124}Sn system is larger than for the ^{107}Sn system. However, the energy spectrum predicted by the model is somewhat narrower than the experimental spectrum.

The GEANT4 toolkit was used in Ref. [21] to simulate a ^{124}Sn beam at 600 MeV/u incident on a 0.5 mm thick Sn target, calculating neutron multiplicity as a function of Z_{bound} , as shown by the dots in Fig. 6 [Figure 6: see original paper]. The GEANT4 simulations employ the Bertini cascade model. In the calculations, neutrons emitted from secondary de-excitations of target fragments were excluded by applying the condition $E_{\text{lab}} > 100$ MeV. Following this criterion, we obtained the neutron multiplicity as a function of Z_{bound} from the IQMD+GEMINI model, represented by the blue curve in Fig. 6.

In the range $20 < Z_{\text{bound}} < 45$, the IQMD+GEMINI model and the Bertini cascade model yield closely matching results. Differences appear, however, in peripheral and central collision regions. For peripheral collisions, the neutron multiplicity predicted by the Bertini cascade model is lower than that predicted by the IQMD+GEMINI model. At $Z_{\text{bound}} = 50$, the cascade model gives a neutron multiplicity of 4, while the IQMD+GEMINI model predicts 11. This discrepancy reflects differences in the predicted isotopic distribution of Sn fragments: the IQMD+GEMINI model suggests more neutron-deficient isotopes. If only quasi-projectile fragments are considered, the maximum Z_{bound} should be 50. However, the cascade model shows calculations even for $Z_{\text{bound}} > 50$, possibly due to the method for selecting quasi-projectile fragments.

In central collisions, neutron multiplicity steadily increases as Z_{bound} decreases. For instance, at $Z_{\text{bound}} = 2$, the cascade model predicts a neutron multiplicity near 80, while the IQMD+GEMINI model suggests a higher count, reaching 91 free neutrons. Notably, using $E_{\text{lab}} > 100$ MeV to filter for neutrons from projectile fragmentation is not the optimal method. As shown in Fig. 3, the single-nucleon momentum of the projectile is approximately 1200 MeV/c in the

experimental frame. Applying a longitudinal momentum filter of $p_z > 600$ MeV/c more effectively selects neutrons originating from projectile fragmentation.

The neutron multiplicity filtered by $p_z > 600$ MeV/c is depicted by the red curve in Fig. 6. This criterion selects fewer neutrons than the $E_{\text{lab}} > 100$ MeV threshold. At $Z_{\text{bound}} = 2$, neutron multiplicity reaches 59, indicating that for central collisions, 59 of the 70 neutrons in the ^{124}Sn projectile are released as free neutrons, while the remaining 11 are emitted as deuterons or tritons.

In fact, the neutrons selected using the condition $p_z > 600$ MeV/c do not originate from a single equilibrated thermal source. During the early stages of projectile-target collisions, neutrons are emitted from one side of the projectile due to intense collisions. These neutrons are associated with the participant zone and exhibit a higher temperature. After the violent collision process ends, part of the projectile is sheared off, leaving an excited remnant (i.e., the spectator source), which de-excites through nucleon emission and multi-fragmentation. By isolating this subset of neutrons, the momentum distribution can provide insights into the spectator source characteristics. In Ref. [21], the condition $1000 \text{ MeV/c} < p_z < 1500 \text{ MeV/c}$ is used to select neutrons originating from the spectator source. We used the same method to extract neutrons from the spectator source. Figure 7 [Figure 7: see original paper] shows the experimental and theoretical neutron multiplicity as a function of Z_{bound} . Experimental data indicate that as Z_{bound} increases, neutron multiplicity first rises and then falls. This trend is similar to the variation in intermediate-mass fragment (IMF) multiplicity with Z_{bound} . For events around $Z_{\text{bound}} \approx 30$, the spectator source primarily undergoes multifragmentation during de-excitation, leading to emission of a larger number of neutrons. In contrast, for events with smaller or larger Z_{bound} , the spectator source is either smaller or has lower excitation energy, resulting in fewer emitted neutrons.

Comparing results for the ^{124}Sn and ^{107}Sn projectiles reveals that ^{124}Sn leads to a neutron-rich spectator, producing higher neutron multiplicity. Conversely, ^{107}Sn results in a neutron-deficient spectator, yielding lower neutron multiplicity. However, the difference in neutron multiplicity between the two systems is approximately 4, which is smaller than the neutron number difference of 17 between ^{124}Sn and ^{107}Sn . This suggests that during the violent collision stage, before formation of the equilibrated spectator source, the excess neutrons in ^{124}Sn are largely emitted, causing the neutron multiplicities of the spectator sources in both systems to converge.

Comparing IQMD+GEMINI model calculations with experimental data shows a high degree of consistency. Combined with multiplicity observables reported in the literature, we can conclude that the IQMD+GEMINI model accurately captures the primary features of collision dynamics in $^{124}\text{Sn} + ^{120}\text{Sn}$ reactions. This provides a reliable foundation for subsequent analysis of the spectator source temperature.

We adopted the same method and calculated the transverse momentum distribution of these neutrons, as shown in Fig. 8 [Figure 8: see original paper]. The full circles represent experimental data. The (blue) open circles and (red) open squares are the calculated distributions of p_y and p_x , respectively. The neutron density distribution in the p_y vs p_x plane is assumed to follow a classical Maxwellian function added to a constant background pedestal:

$$\frac{\partial^2 N}{\partial p_x \partial p_y} = C_1 \exp\left(-\frac{p_x^2}{2mT_x^2} - \frac{p_y^2}{2mT_y^2}\right) + C_2$$

where m is the neutron mass, C_1 and C_2 are fitting parameters, and T_x and T_y are temperature parameters. To find the temperature parameter, the distribution of p_x (or p_y) is fitted. The fit of experimental data with a Gaussian distribution corresponding to $T_x = 2.04$ MeV superimposed on a constant background is represented by the dotted line. The cases for the calculated p_x and p_y distributions are shown as (blue) curve and (red) dash. The corresponding temperature parameters are $T_x = 3.37$ MeV and $T_y = 3.31$ MeV, which are significantly higher than the experimental value.

The variation of temperature with Z_{bound} , extracted from momentum distributions, is shown in Fig. 9 [Figure 9: see original paper]. Experimental data are represented by open circles and open triangles, while IQMD+GEMINI model calculations are shown as curves and short dashed lines.

The temperature displays a weak isospin effect, where the temperature of the ^{124}Sn system is slightly higher than that of the ^{107}Sn system. This result is consistent with findings in Ref. [18], and the specific reasons will not be elaborated here.

A key issue in the figure is why the temperatures extracted from neutron momentum distributions calculated by the IQMD+GEMINI model are overall higher than experimental data. The figure shows that as Z_{bound} increases from 5 to 45, the temperature extracted from experimental data decreases from 5 MeV to 3 MeV, while the temperature calculated by the IQMD+GEMINI model decreases from 15 MeV to 4 MeV.

First, for the $^{124}\text{Sn} + ^{120}\text{Sn}$ system at 600 MeV/u, the IQMD+GEMINI model has relatively low systematic uncertainty. In Ref. [29], the IQMD+GEMINI model was applied to study the dynamical features of this reaction and successfully reproduced observables such as intermediate-mass fragment multiplicity. In Ref. [31], it was applied to explore fluctuation characteristics in this reaction.

Second, in the region $Z_{\text{bound}} > 25$, the IQMD+GEMINI model results are consistent with those from the SMM model (shown as stars). Ref. [21] demonstrates that the SMM model cannot fully reproduce experimentally measured neutron multiplicity. In the $Z_{\text{bound}} < 25$ region, the SMM model underestimates neutron multiplicity.

Finally, compared to THeLi (shown as full circles), the temperature parameter extracted from product momentum distributions should be higher. Based on the above analysis, we speculate that the emission source temperature measured in Ref. [21], based on neutron momentum distributions, may have systematic errors that require further investigation.

IV. Conclusion

In summary, the $^{107,124}\text{Sn} + ^{120}\text{Sn}$ collisions at 600 MeV/nucleon are studied using the IQMD+GEMINI model. The two-dimensional distributions of transverse and longitudinal momentum for fragments with $Z = 3$ and neutrons are used to identify emission sources. It is shown that only target-like and projectile-like emission sources are apparent for the $Z = 3$ fragments, but the contribution of the participant source is considerable for neutrons. The recoil kinetic energy of the projectile-like source is minor compared to its kinetic energy near 600 MeV/nucleon.

Calculations of the differential cross section, multiplicity, and transverse momentum distribution of neutrons from the projectile-like source are compared with data from Ref. [21]. The calculations show a high degree of consistency with the differential cross section and multiplicity data as functions of the bound charge. For the transverse momentum distribution, the calculations capture the Gaussian shape, but the calculated distribution width is larger than the experimental case.

The temperatures of the projectile-like source are extracted by fitting the transverse momentum distributions using classical Maxwellian functions. The temperature displays a weak isospin effect, where the temperature of the ^{124}Sn system is slightly higher than that of the ^{107}Sn system. This result is consistent with findings in Ref. [18]. The temperatures extracted from calculations are overall higher than experimental data but are consistent with those from the SMM model taken from Ref. [21] and the isotopic temperature THeLi taken from Ref. [18].

It is speculated that the emission source temperature extracted based on neutron momentum distributions may have systematic errors that require further investigation.

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