

Contribution of Nuclear Potential in Isobaric Pair Fragmentation

Varinderjit Kaur^{1,*}

¹G.S.S.D.G.S. Khalsa College, Patiala-147001, Punjab, India

Abstract. The influence of different components of nuclear interaction potential on the fragmentation of isobaric pairs with varying neutron-to-proton (N/Z) ratios is investigated within the framework of Isospin-dependent Quantum Molecular Dynamics (IQMD) model. Specifically, the effects of Coulomb, momentum-dependent, and symmetry potentials on the production of light charged particles (LCPs) and intermediate mass fragments (IMFs) in isobaric pair collisions are analyzed. To examine system mass dependence, central collisions of five sets of reactions- $^{23}\text{Ne}+^{23}\text{Ne}$, $^{74}\text{Ge}+^{74}\text{Ge}$, $^{102}\text{Ru}+^{102}\text{Ru}$, $^{124}\text{Xe}+^{124}\text{Xe}$, $^{144}\text{Sm}+^{144}\text{Sm}$ are simulated at 50 MeV/nucleon with a fixed N/Z ratio. The results indicate that nuclear interaction potential effects intensify in heavier nuclei as compared to lighter nuclei, primarily due to enhanced Coulomb repulsion and momentum-dependent interactions. To further explore the energy dependence and isospin effects, isobaric pairs of heavier systems ($A_{\text{tot}} = 248$) are investigated by systematically varying the N/Z ratios. The multiplicity of LCPs increases monotonically with energy due to stronger NN scattering, whereas IMFs exhibit the characteristic rise-and-fall trend. Additionally, the spatial distribution of fragment production is correlated with the momentum distribution of same fragments, reflecting the degree of nuclear stopping. This study provides valuable insights into the reaction dynamics of neutron-rich systems and demonstrates that incorporating different components of the nuclear potential is essential for developing a more realistic and comprehensive description of heavy-ion fragmentation.

1 Introduction

The study of heavy ion reactions (HIRs) helps to understand the reaction dynamics by studying the decay of hot and dense nuclear matter formed in the reaction. The intermediate energy ($10 \text{ MeV} \leq E/A \leq 2 \text{ GeV}$) HIRs are rich sources of different phenomena—multi-fragmentation, nuclear flow, fragment flow and nuclear stopping [1, 2]. Several attempts have been made to study multi-fragmentation in symmetric as well as asymmetric reactions by studying the emission of different fragments—light charged particles (LCPs) and intermediate mass fragments (IMFs) [3–5]. Equal attempts have been made on theoretical ground to confront the experimental data for multi-fragmentation [6]. The influence of key model inputs such as in-medium cross-sections, the equation of state and the Gaussian width on the fragmentation has been examined [7]. The different entrance channel parameters such as incident beam energy, impact parameter, and reaction mass asymmetry also influence the reaction dynamics [8]. The role of mass and isospin in fragmentation has been investigated by using four different projectiles at 600 MeV/nucleon, revealing that isospin influences various observable phenomena such as multi-fragmentation, directed transverse flow and thermalization effects [9]. The advancement in radioactive ion beam facilities leads to exploration of neutron rich nuclei which are also important to study many astrophysical happenings.

Many researchers have made efforts in the literature to investigate the mechanism behind HIRs, employing the role of different types of nuclear interaction potentials in the reaction dynamics [10]. The different types of the Skyrme forces have been used in Skyrme energy density formalism to explore the reaction dynamics at low energies [11], while limited efforts exist in the literature to study such effects at the intermediate energies. While the Coulomb potential contributes to fragment formation, its significance reduces progressively with higher incident energies [12]. It has been reported in literature that in addition to density dependent potential, reaction dynamics also depends on the momentum dependent interactions. The momentum dependence of nuclear equation of state plays a significant role in fragment production. The total interaction potential at intermediate energies arises from the combined contribution of the Skyrme, Yukawa, Coulomb, momentum dependent and density dependent symmetry potentials. Each component of nuclear interaction potential impacts distinct reaction features in HIRs within the intermediate energy domain [8]. The influence of different potential components for symmetric and asymmetric reactions has been explored [13], while limited attention has been made to study the collective impact of different components of potential on the spatial and momentum distribution of fragments. In the present work, the influence of different components of nuclear interaction potential on the fragmentation and nuclear stopping of isobaric pair colli-

*e-mail: drvarinderjit@gmail.com

sions is studied within the framework of Isospin dependent Quantum Molecular Dynamics (IQMD) model.

2 Methodology

The present work is carried within the framework of “Isospin-dependent Quantum Molecular Dynamics” (IQMD) model [14, 15], an updated version of the QMD model, originally proposed by Aichelin and collaborators [16, 17]. In this approach, the isospin degree of freedom is incorporated through the symmetry potential, isospin dependent cross-sections and Coulomb interactions. Within the IQMD formalism, nucleons from the target and projectile interact through two- and three-body Skyrme forces, a surface-dependent Yukawa potential, repulsive Coulomb potential and momentum dependent potential. Moreover, the model employs the explicit charge states of all baryons and mesons, and includes a symmetry potential between neutrons and protons consistent with the Bethe-Weizsacker mass formula. Each nucleon is represented by a Gaussian wave packet characterized by the time dependent parameters $r_i(t)$ and $p_i(t)$:

$$f_i(r, p, t) = \frac{1}{(\pi\hbar)^3} e^{-(r-r_i(t))^2/2L} e^{-(p-p_i(t))^2 2L/\hbar^2} \quad (1)$$

Parameter L related to extension of wave packet in phase space is fixed with $L = 1.08 \text{ fm}^2$. The centroid of each nucleon propagates under classical equations of motion [1]:

$$\frac{d\vec{r}_i}{dt} = \frac{d\langle H \rangle}{d\vec{p}_i}; \quad \frac{d\vec{p}_i}{dt} = -\frac{d\langle H \rangle}{d\vec{r}_i} \quad (2)$$

with

$$\begin{aligned} \langle H \rangle &= \langle T \rangle + \langle V \rangle \\ &= \sum_i \frac{p_i^2}{2m_i} + \sum_i \sum_{j>i} \int f_i(\vec{r}, \vec{p}, t) V^{ij}(\vec{r}, \vec{r}) \\ &\quad \times f_j(\vec{r}, \vec{p}, t) d\vec{r} d\vec{p} \end{aligned} \quad (3)$$

The baryon-baryon potential V^{ij} , in the above relation, reads as:

$$\begin{aligned} V^{ij} &= V_{Skyrme}^{ij} + V_{Yukawa}^{ij} + V_{Coul}^{ij} + V_{sym}^{ij} + V_{MDI}^{ij} \\ &= \left(t_1 \delta(\vec{r}^* - \vec{r}) + t_2 \delta(\vec{r}^* - \vec{r}) \rho^{\gamma-1} \left(\frac{|\vec{r}^* + \vec{r}|}{2} \right) \right) \\ &\quad + t_3 \frac{\exp(-|\vec{r}^* - \vec{r}|/\mu)}{(|\vec{r}^* - \vec{r}|/\mu)} + \frac{Z_i Z_j e^2}{|\vec{r}^* - \vec{r}|} \\ &\quad + t_4 \frac{1}{\rho_0} T_3^i T_3^j \delta(\vec{r}^* - \vec{r}) \\ &\quad + t_5 m^2 [t_6 (\vec{p}^* - \vec{p})^2 + 1] \delta(\vec{r}^* - \vec{r}) \end{aligned} \quad (4)$$

Here Z_i and Z_j represent the charges of i^{th} and j^{th} baryon respectively. The parameters μ and t_1, \dots, t_6 are chosen to reproduce the real part of the nucleonic optical potential. The Skyrme interaction forms the basic component of potential, reflecting the underlying nuclear matter density. The Yukawa term is added to better describe the nuclear surface features and plays an important role in the

fragment formation. The Coulomb potential comes into picture in case of charged particles and thus, contribute towards the repulsive interaction between protons. Because these interactions are absent for neutrons, this potential has sometimes also been treated as a part of isospin effects, which differentiate the protons from neutrons. Similarly, the influence of momentum-dependent potential is well established during the early stages of a collision, when relative momentum between projectile and target nucleons is large [18]. The nuclear symmetry potential also becomes important in reactions involving isospin asymmetric (neutron-proton) systems. Hence, each component of the nuclear interaction potential contributes meaningfully to fragment production and nuclear stopping at intermediate energies.

3 Results and Discussions

The study simulated several thousand events for five symmetric nuclear systems $^{23}\text{Ne}+^{23}\text{Ne}$, $^{74}\text{Ge}+^{74}\text{Ge}$, $^{102}\text{Ru}+^{102}\text{Ru}$, $^{124}\text{Xe}+^{124}\text{Xe}$, $^{144}\text{Sm}+^{144}\text{Sm}$ -each having an N/Z ratio of 1.3. The simulations were performed for central collisions ($b = 0 \text{ fm}$) at a fixed incident energy of 50 MeV/nucleon to examine the influence of different components of nuclear potential. The acronym SYC means Skyrme+Yukawa+Coulomb, SYCM means Skyrme+Yukawa+Coulomb+momentum dependent and SYCMS means Skyrme+Yukawa+Coulomb+momentum dependent+symmetry potential. To evaluate the contribution of various components of nuclear interaction potential to different observables, one can begin with the basic SYC potential and then repeat the simulations by progressively adding the remaining interaction terms. Fig.1 shows the variation in the multiplicities of light charged particles (LCPs) and intermediate mass fragments (IMFs) with system mass for different potential sets. The contribution of individual potential terms becomes increasingly evident for heavier systems. As the system mass increases, the larger proton content enhances Coulomb repulsion, which in turn increases fragment production. Introducing the momentum-dependent potential (SYCM) and the symmetry potential (SYCMS) enhances compression and thermalization, leading to noticeable changes in fragment yields. Moreover, larger colliding nuclei deposit more energy, undergoing stronger compression and higher production of fragments. Because these effects are less pronounced in light mass systems, the heavier isobaric pairs are selected with total mass $A_{tot}=248$ units to clearly demonstrate the impact of different potential components in the fragment production.

Furthermore, two heavier isobaric pairs of system $^{124}\text{La}+^{124}\text{La}$ (neutron deficient) and $^{124}\text{Ag}+^{124}\text{Ag}$ (neutron rich) with N/Z = 1.1 and 1.6 respectively are selected to examine the energy dependence of multiplicity of LCPs and IMFs for different components of nuclear potential as shown in Fig.2. For both systems, LCPs production grows with incident beam energy due to the enhanced violence of the collision, while IMFs exhibit the characteristic rise-and- fall trend [7]. The SYC potential yields comparatively lower multiplicities. With the

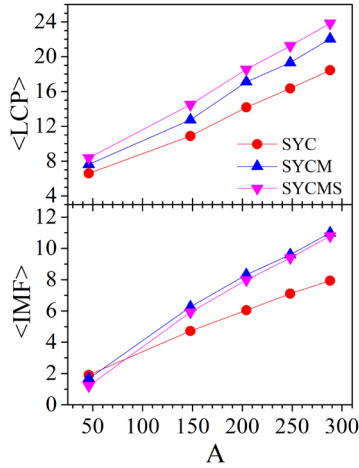


Figure 1: The system size dependence of multiplicity of LCPs and IMFs for $^{23}\text{Ne}+^{23}\text{Ne}$, $^{74}\text{Ge}+^{74}\text{Ge}$, $^{102}\text{Ru}+^{102}\text{Ru}$, $^{124}\text{Xe}+^{124}\text{Xe}$, $^{144}\text{Sm}+^{144}\text{Sm}$ (with fixed $N/Z=1.3$) for central collisions at $E=50$ MeV/nucleon for different components of interaction potential

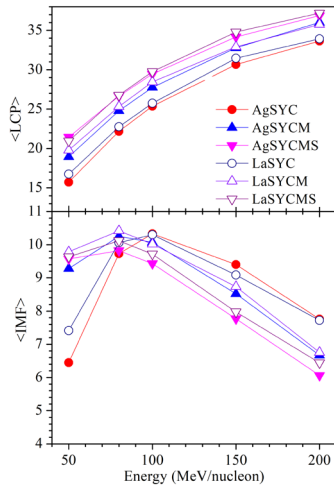


Figure 2: The variation of multiplicity of LCPs and IMFs at $b=0$ fm with energy for different components of interaction potentials for $^{124}\text{La}+^{124}\text{La}$ and $^{124}\text{Ag}+^{124}\text{Ag}$ isobaric pairs of heavier masses.

addition of momentum dependent potential and symmetry potential, the multiplicity of LCPs increases because of repulsive nature of these potentials. At low energies of 50 MeV/nucleon, the comparative role of potentials in both isobaric pairs is clearly visible while at higher energies it decreases and vanishes at $E=200$ MeV/nucleon. At high energies, system becomes too violent, nucleon nucleon collisions dominate, causing the system to vaporize into free nucleons and IMFs. At $E = 100$ MeV/nucleon, the trend for IMF multiplicities reverses for the various potentials. This reversal results from the additional repulsion generated by the momentum-dependent and

symmetry terms, which suppresses IMF formation.

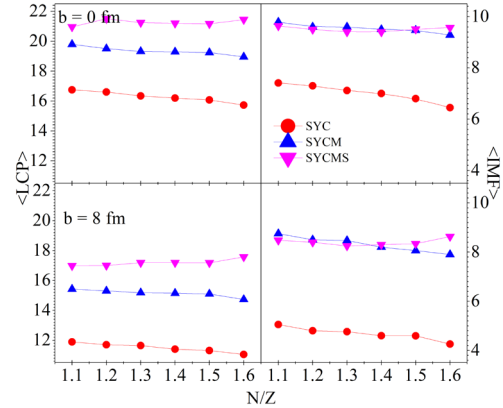


Figure 3: The isospin dependence of multiplicity of light charged particles, intermediate mass fragments for $^{124}\text{La}+^{124}\text{La}$ ($N/Z=1.1$), $^{124}\text{Ba}+^{124}\text{Ba}$ ($N/Z=1.2$), $^{124}\text{Xe}+^{124}\text{Xe}$ ($N/Z=1.3$), $^{124}\text{Sb}+^{124}\text{Sb}$ ($N/Z=1.4$), $^{124}\text{Sn}+^{124}\text{Sn}$ ($N/Z=1.5$) and $^{124}\text{Ag}+^{124}\text{Ag}$ ($N/Z=1.6$) for $b=0$ fm (upper panel) and $b=8$ fm (lower panel) at $E=50$ MeV/nucleon for different components of nuclear interaction potential.

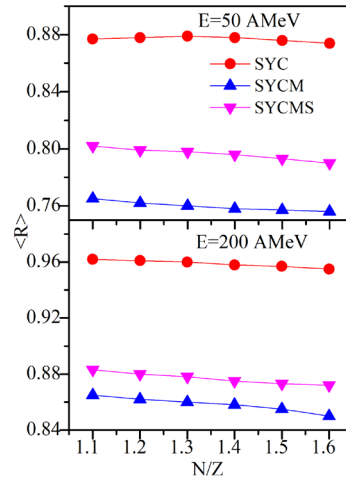


Figure 4: Isospin dependence of anisotropic ratio for Isobaric pairs with N/Z ratio varying from 1.1 to 1.6 at 50 MeV/nucleon (upper panel) and 200 MeV/nucleon (lower panel) for different components of nuclear interaction potential.

Since the role of potentials is clearly visible at low energies, the study is further extended by systematically varying N/Z ratio from 1.1 to 1.6 for six different isobaric pairs (with $A_{tot}=248$ units) at 50 MeV/nucleon to include the effects of isospin. Fig.3 shows variation of multiplicity of LCPs and IMFs with N/Z ratio for $^{124}\text{La}+^{124}\text{La}$ ($N/Z=1.1$), $^{124}\text{Ba}+^{124}\text{Ba}$ ($N/Z=1.2$), $^{124}\text{Xe}+^{124}\text{Xe}$ ($N/Z=1.3$), $^{124}\text{Sb}+^{124}\text{Sb}$ ($N/Z=1.4$), $^{124}\text{Sn}+^{124}\text{Sn}$ ($N/Z=1.5$) and $^{124}\text{Ag}+^{124}\text{Ag}$ ($N/Z=1.6$).

All the reactions are simulated for central and peripheral collisions for different sets of nuclear interaction potential. It is observed that SYC potentials give least multiplicity of LCPs and IMFs for both impact parameters. The addition of momentum dependent potential (SYCM) and symmetry potential (SYCMS) leads to enhancement in the multiplicity of LCPs and IMFs due to their repulsive nature. With increase of isospin ratio of isobaric pair, the role of Coulomb potential (SYC) and momentum dependent potential (SYCM) decreases due to decrease of proton content, while the symmetry potential (SYCMS) contribution increases due to increased difference in neutron and proton content. For peripheral collisions, the number of LCPs and IMFs decreases due to decrease of participant region.

To further examine the momentum distribution of the fragments, nuclear stopping has been analyzed using the anisotropy ratio (R), which is defined as

$$R = \frac{2 [\sum_i |p_{\perp}(i)|]}{\pi [\sum_i |p_{\parallel}(i)|]} \quad (5)$$

where the summation runs over all nucleons. The transverse and longitudinal momenta are given as

$$p_{\perp}(i) = \sqrt{p_x^2 + p_y^2}; p_{\parallel}(i) = p_z(i) \quad (6)$$

For a complete stopping, R should be close to unity. Fig.4 further strengthen our findings by illustrating the variation of anisotropy ratio with N/Z ranging from 1.1 to 1.6 for different isobaric pairs at $b = 0$ fm. The results are presented for two incident energies- 50 MeV/nucleon (upper panel) and $E = 200$ MeV/nucleon (lower panel) considering different components of interaction potential. The anisotropy ratio shows only a weak dependence on N/Z , indicating that nuclear stopping remains nearly constant with increasing N/Z ratio. The SYC potential yields the highest values of stopping due to the absence of the momentum-dependent term, which otherwise reduces nucleon–nucleon collisions and hence dissipation. The inclusion of the momentum-dependent interaction in SYCM lowers the stopping power, while the addition of the symmetry potential in SYCMS partially restores it, particularly for neutron-rich systems. The overall trend, remains consistent across both energies, confirming that the momentum-dependent and symmetry energy terms play competing roles in determining the degree of nuclear stopping.

4 Conclusion

The present investigation within the IQMD framework highlights the crucial role of various components of nuclear interaction potential in governing the fragmentation behavior of isobaric systems with varying N/Z ratios. The analysis of central collisions over a wide mass range reveals that the impact of these interaction potentials becomes increasingly significant for heavier nuclei, where enhanced Coulomb repulsion and momentum dependent

effects strongly influence fragment emission. The observed increase in LCPs multiplicity with energy, coupled with the rise-and-fall pattern of IMFs, reflects the interplay between NN scattering and nuclear compressibility. Moreover, the correlation between spatial and momentum distributions of the emitted fragments provides deeper insight into the degree of nuclear stopping and equilibrium achieved during the reaction. Overall, the study yields a more realistic and comprehensive understanding of heavy-ion fragmentation by incorporating multiple components of the nuclear interaction potential.

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