

*Short note***Isospin effects on squeeze-out flow in heavy-ion collisions**Feng-Shou Zhang^{1,2,4,a}, Lie-Wen Chen^{1,2}, Wen-Fei Li^{1,2}, and Zhi-Yuan Zhu^{1,3}¹ Center of Theoretical Nuclear Physics, National Laboratory of Heavy Ion Accelerator, Lanzhou 730000, China² Institute of Modern Physics, Academia Sinica, P.O. Box 31, Lanzhou 730000, China³ Shanghai Institute of Nuclear Research, Academia Sinica, Shanghai 201800, China⁴ CCAST (World Laboratory), P.O. Box 8730, Beijing 100080, China

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Abstract. The squeeze-out flow in reactions of $^{124}\text{Sn} + ^{124}\text{Sn}$ and $^{124}\text{Ba} + ^{124}\text{Ba}$ at different incident energies for different impact parameters is investigated by means of an isospin-dependent quantum molecular dynamics model. For the first time, it is found that the more neutron-rich system ($^{124}\text{Sn} + ^{124}\text{Sn}$) exhibits weaker squeeze-out flow. This isospin dependence of the squeeze-out flow is shown to mainly result from the isospin dependence of nucleon-nucleon cross-section and the symmetry energy.

PACS. 25.70.-z Low and intermediate energy heavy-ion collisions – 25.75.Ld Collective flow

The recent advance in radioactive nuclear beam (RNB) physics provides people a unique opportunity to investigate isospin effects in heavy-ion collisions (HICs) [1,2]. Isospin effects on directed flow [3–5], radial flow [6] and rotational flow [7] in HIC's at intermediate energies have been explored theoretically and/or experimentally, and it is indicated that the isospin dependence of nuclear collective flow may provide people some important information about the isospin-dependent nuclear EOS, particularly the symmetry energy, and the isospin-dependent in-medium N - N cross-section. The squeeze-out flow [8] is of special interest since it comes from the only direction where the nuclear matter might escape without being hindered by the presence of the cold spectator remnants and thus a less disturbed information on the matter of high density and temperature is expected. Therefore, it is very significant to explore isospin effects on the squeeze-out flow.

In this short note we report results of the first theoretical study on the squeeze-out flow from reactions of $^{124}\text{Sn} + ^{124}\text{Sn}$ and $^{124}\text{Ba} + ^{124}\text{Ba}$ at different energies for different impact parameters within the framework of an isospin-dependent quantum molecular dynamics (IDQMD) model which includes the symmetry energy, Coulomb interaction, isospin-dependent experimental N - N cross-sections, and particularly the isospin-dependent Pauli blocking [5, 9]. In the initialization process of the IDQMD model, the neutron and proton are distinguished from each other and meanwhile the nonphysical rotations in the initialized nuclei have been removed [7]. In the IDQMD model, the

nuclear mean field can be parameterized by

$$U(\rho, \tau_z) = \alpha(\rho/\rho_0) + \beta(\rho/\rho_0)^\gamma + \frac{1}{2}(1 - \tau_z)V_c + C \frac{\rho_n - \rho_p}{\rho} \tau_z + U^{\text{Yuk}}, \quad (1)$$

with ρ_0 the normal nuclear matter density (here is 0.16 fm^{-3}); ρ , ρ_n , and ρ_p are the total, neutron, and proton interaction densities, respectively; τ_z is the z -th component of the isospin degree of freedom, which equals 1 or -1 for neutrons or protons, respectively; C is the symmetry strength; V_c is the Coulomb potential; and U^{Yuk} is the finite range Yukawa (surface) potential which will vanish for infinite nuclear matter. The forms and parameters of eq. (1) can be found in ref. [6]. The IDQMD is different from the so-called IQMD (Isospin-QMD) model [10–12] by the Pauli blocking, the initialization process, and construction of fragment. Both IDQMD model and IQMD model are evolutionary from QMD model [13]. This model has been used recently to explain successfully several phenomena in HIC's at intermediate energies, which depend on the isospin of the reaction system [5–7, 9, 14]. In the present calculations, the so-called soft EOS with an incompressibility of $K = 200 \text{ MeV}$ is used and the symmetry strength $C = 32 \text{ MeV}$ without particular consideration.

In the QMD model, the reaction plane is known *a priori* and it is defined as the x - z plane (the z -axis corresponds to the beam direction). The azimuthal angle with respect to the reaction plane can be written as

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$$\phi = \arctan(P_y/P_x), \quad (2)$$

where P_x and P_y are the x - and y -components of nucleon momentum in the center-of-mass (c.m.) system. Many studies have shown that the azimuthal distribution in HICs can be fitted well by the Legendre polynomial up to the second order [15], *i.e.*,

$$dN/d\phi = c(1 + a_1 \cos(\phi) + a_2 \cos(2\phi)). \quad (3)$$

The coefficient a_1 represents the strength of the in-plane directed flow while a positive a_2 reflects the strength of the rotational collective motion (the azimuthal distribution peaks at $\phi = 0^\circ$ and $\pm 180^\circ$, simultaneously) and negative one (the azimuthal distribution peaks at $\phi = \pm 90^\circ$) the out-of-plane squeeze-out. For the mid-rapidity azimuthal distribution, the ratio R_N ,

$$R_N = \frac{dN/d\phi(90^\circ) + dN/d\phi(-90^\circ)}{dN/d\phi(0^\circ) + dN/d\phi(180^\circ)} = \frac{1 - a_2}{1 + a_2}, \quad (4)$$

measures the strength of the squeeze-out flow in a quantitative way. A value $R_N > 1$ corresponds to a preferential out-of-plane emission. It has been shown that R_N depends on the transverse momenta of nucleons [16] and in the present study the normalized nucleon transverse momentum P_t/P_{proj} (where P_t and P_{proj} represent the transverse momenta of nucleon and the projectile momentum in the c.m. system, respectively) is limited to $P_t/P_{\text{proj}} \geq 0.5$ for simplicity. Meanwhile, the mid-rapidity is defined as a narrow region around the c.m. rapidity by applying the condition $-0.25 \leq (y/y_{\text{proj}})_{\text{c.m.}} \leq 0.25$, where $(y/y_{\text{proj}})_{\text{c.m.}}$ is the reduced c.m. rapidity. In addition, it has been shown that R_N depends on the fragment mass [16] and in this work the calculated results are obtained from all nucleons entering the analysis to accumulate the numerical statistics.

Figure 1 displays the IDQMD model prediction of R_N as a function of incident energy for reactions of $^{124}\text{Sn} + ^{124}\text{Sn}$ and $^{124}\text{Ba} + ^{124}\text{Ba}$ at impact parameter $b = 4$ fm. The errors shown are the statistical errors resulting from the Legendre polynomial fits. It is indicated in fig. 1 that the R_N value increases with increment of the incident energy and then saturate or decrease at higher incident energies, which is in agreement with the recent experimental results [17,18]. The reduction of the R_N value at higher incident energies is easy to understand by the shadowing effects of the cold nuclear matter surrounding the participant zone which decreases because the projectile spectators escape faster. A more interesting feature in fig. 1 is that the more neutron-rich system $^{124}\text{Sn} + ^{124}\text{Sn}$ displays systematically smaller R_N values than the system $^{124}\text{Ba} + ^{124}\text{Ba}$, which implies that there exists a strong isospin dependence of the squeeze-out flow, namely, the more neutron-rich system displays weaker squeeze-out flow. Meanwhile, one can find that the isospin dependence of the squeeze-out flow decreases as the incident energy

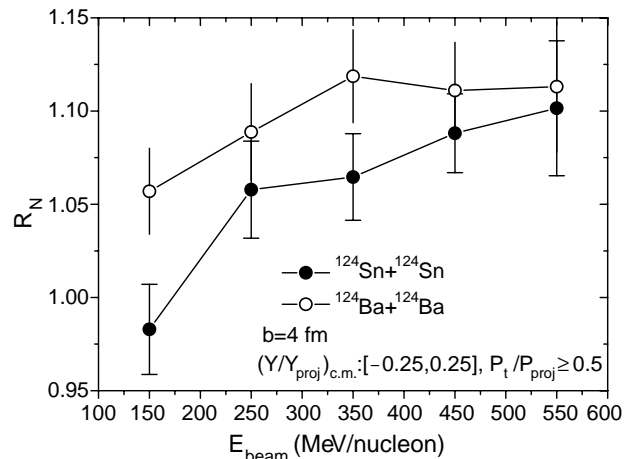


Fig. 1. The IDQMD model predicted R_N as a function of incident energy for reactions of $^{124}\text{Sn} + ^{124}\text{Sn}$ and $^{124}\text{Ba} + ^{124}\text{Ba}$ at impact parameter $b = 4$ fm. The lines are plotted to guide the eye.

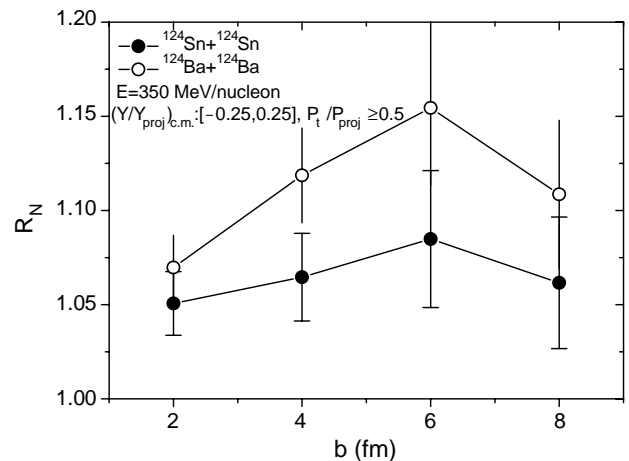


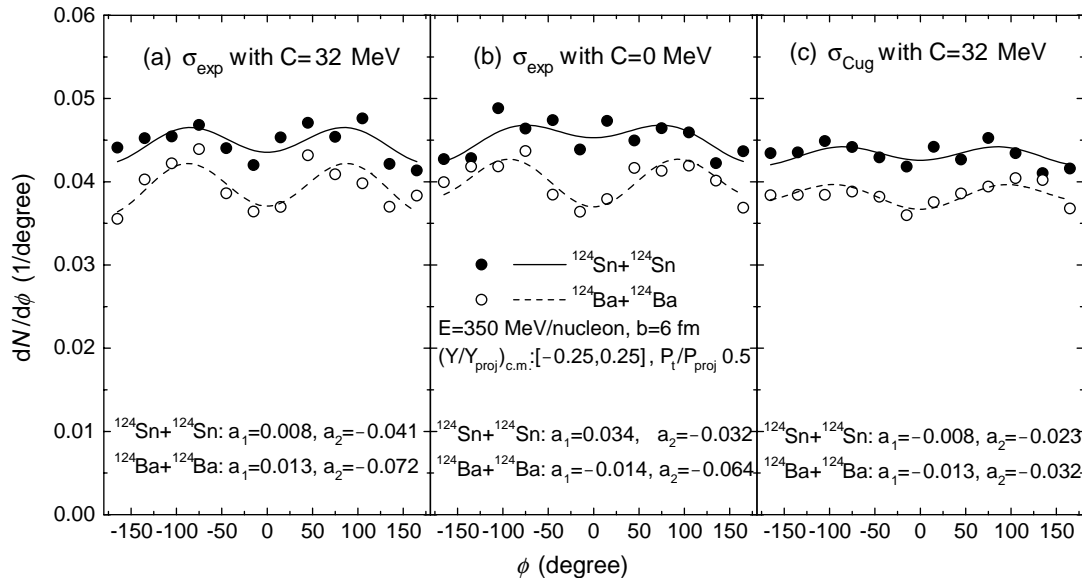
Fig. 2. The IDQMD model predicted R_N as a function of impact parameter for reactions of $^{124}\text{Sn} + ^{124}\text{Sn}$ and $^{124}\text{Ba} + ^{124}\text{Ba}$ at 350 MeV/nucleon. The lines are plotted to guide the eye.

increases, which may be due to the fact that the isospin dependence of the N - N cross-section disappears at higher incident energies.

In order to investigate further the isospin dependence of the squeeze-out flow, we show in fig. 2 the ratio R_N as a function of impact parameter for reactions of $^{124}\text{Sn} + ^{124}\text{Sn}$ and $^{124}\text{Ba} + ^{124}\text{Ba}$ at 350 MeV/nucleon. The errors shown are the statistical errors resulting from the Legendre polynomial fits. Similarly, a strong isospin dependence of the squeeze-out flow is observed once again, namely, the more neutron-rich system $^{124}\text{Sn} + ^{124}\text{Sn}$ displays systematically smaller R_N values than the system $^{124}\text{Ba} + ^{124}\text{Ba}$ at different impact parameters. In particular, this isospin dependence is more pronounced in semi-central collisions. In addition, it is indicated that the largest R_N value is obtained at $b = 6$ fm, *i.e.*, in semi-central collisions, which

Table 1. The R_N values at different situations (see text) for $^{124}\text{Sn} + ^{124}\text{Sn}$ and $^{124}\text{Ba} + ^{124}\text{Ba}$ at 350 MeV/nucleon and $b=6$ fm.

Reaction systems	$C=32$ MeV with σ_{exp}	$C=0$ with σ_{exp}	$C=32$ MeV with σ_{Cug}
$^{124}\text{Sn} + ^{124}\text{Sn}$	1.086 ± 0.036	1.066 ± 0.029	1.047 ± 0.021
$^{124}\text{Ba} + ^{124}\text{Ba}$	1.155 ± 0.041	1.137 ± 0.034	1.066 ± 0.023

**Fig. 3.** The IDQMD model predicted normalized azimuthal distribution for $^{124}\text{Sn} + ^{124}\text{Sn}$ (solid circles) and $^{124}\text{Ba} + ^{124}\text{Ba}$ (open circles) at 350 MeV/nucleon and $b = 6$ fm for mid-rapidity nucleons by using different symmetry energy strength C and parametrizations of N - N cross-sections: $C = 32$ MeV with experimental N - N cross-section σ_{exp} (a), $C = 0$ (no symmetry energy) with σ_{exp} (b), and $C = 32$ MeV with Cugnon's N - N cross-section σ_{Cug} (c). Meanwhile, the results of Legendre polynomial fits according to eq. (3) for $^{124}\text{Sn} + ^{124}\text{Sn}$ (solid line) and $^{124}\text{Ba} + ^{124}\text{Ba}$ (dashed line) as well as the resulting a_1 and a_2 are also included.

is in good agreement with the recent experiment where a maximum of R_N located at about $b = 6$ fm has been evidenced in reaction of Au+Au at 400 MeV/nucleon [17, 18]. This phenomenon can be explained by an expansion shadowing scenario [13] where the expansion of the participant matter is rescattered by the cold target or projectile spectator.

It is important to investigate the influence of the symmetry energy and isospin-dependent N - N cross-section on the squeeze-out flow since the isospin dependence of the squeeze-out flow may result from the competition among several mechanisms in the isospin-dependent reaction dynamics, such as the symmetry energy, isospin-dependent N - N cross-sections, and so on.

Using different symmetry energy strength C and parametrizations of N - N cross-sections, we show in fig. 3 the IDQMD model predicted normalized azimuthal distribution from $^{124}\text{Sn} + ^{124}\text{Sn}$ (solid circles) and $^{124}\text{Ba} + ^{124}\text{Ba}$ (open circles) at 350 MeV/nucleon and $b = 6$ fm for mid-rapidity nucleons. Meanwhile, the results of Legendre polynomial fits according to eq. (3) for $^{124}\text{Sn} + ^{124}\text{Sn}$ (solid line) and $^{124}\text{Ba} + ^{124}\text{Ba}$ (dashed line) as well as the resulting a_1 and a_2 are also included in fig. 3. For the results shown in fig. 3 (a) we use $C = 32$ MeV and experimental N - N cross-section σ_{exp} which is isospin dependent.

In fig. 3 (b) we use $C = 0$ (no symmetry energy) and σ_{exp} . The case of using $C = 32$ MeV and Cugnon's N - N cross-section σ_{Cug} which is isospin independent, is plotted in fig. 3 (c).

One can see from fig. 3 that for the azimuthal distribution there exist minima at $\phi = 0^\circ$ and $\pm 180^\circ$ (*i.e.*, in the in-plane P_x -direction) and maxima at $\phi = \pm 90^\circ$ (*i.e.*, in out-of-plane P_y -direction, which is perpendicular to the reaction plane). These features imply that at mid-rapidity more nucleons are squeezed out perpendicular to the reaction plane than in the reaction plane. In order to see more clearly the isospin effects on the squeeze-out flow, we give in table 1 the R_N values extracted from a_2 in fig. 3 for different cases. The errors shown are the statistical errors resulting from the Legendre polynomial fits. One can see from table 1 that both the symmetry energy and the isospin-dependent N - N cross-section enhance the strength of the squeeze-out flow but the latter enhances it more strongly. Particularly, it is indicated that the influence of σ_{exp} on system $^{124}\text{Ba} + ^{124}\text{Ba}$ is stronger than that on the system $^{124}\text{Sn} + ^{124}\text{Sn}$, which is easy to understand since the neutron-proton cross-section is about three times larger than the neutron-neutron or proton-proton cross-section for σ_{exp} at energy of about 350 MeV/nucleon, which results in more N - N collisions

for $^{124}\text{Ba} + ^{124}\text{Ba}$. On the other hand, the symmetry energy is generally repulsive and the change of symmetry strength C might modify the equation of state and thus the squeeze-out flow. From above analysis, one can conclude that the isospin dependence of the squeeze-out flow seems to mainly result from the isospin dependence of N - N cross-section and the symmetry potential has less influence on it. In above calculations, only the free-space N - N cross-sections are adopted and the in-medium effect is only simulated by the Pauli blocking. However, the in-medium N - N cross-sections and their isospin dependence might be strongly density dependent [19, 20]. The isospin dependence of the squeeze-out flow may provide a unique opportunity to study the isospin dependent in-medium N - N cross-sections.

In summary, by using the IDQMD model, we studied for the first time the out-of-plane squeeze-out flow in reactions of $^{124}\text{Sn} + ^{124}\text{Sn}$ and $^{124}\text{Ba} + ^{124}\text{Ba}$. A strong isospin dependence of squeeze-out flow has been found, namely, the more neutron-rich system exhibits weaker squeeze-out flow, which is shown to mainly result from the isospin dependence of N - N cross-section and the symmetry energy. Meanwhile, it is indicated that the squeeze-out flow depends strongly on the impact parameter and incident energy. Our study proposes that one can investigate the isospin-dependent reaction dynamics by studying the isospin effects on the azimuthal distribution and suggests that the isospin dependence of the squeeze-out flow could be as a probe of the isospin-dependent in-medium N - N cross-section.

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