Yield ratios and directed flows of light fragments from reactions induced by neutron-rich nuclei at intermediate energy *

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Abstract: The yield ratios of neutron/proton and ^{3}H/^{3}He and the directed flow per nucleon for these projectile-like fragments at large impact parameters are studied for ^{50}Ca + ^{40}Ca and ^{50}Cr + ^{40}Ca for comparison at 50 MeV/u using the isospin-dependent quantum molecular dynamics (IQMD) model. It is found that the yield ratios and the directed flows per nucleon are different for reactions induced by the neutron-rich nucleus ^{50}Ca and the stable isobaric nucleus ^{50}Cr, and depend on the hardness of the EOS. The ratios of neutron/proton and ^{3}H/^{3}He and the difference of directed flow per nucleon of neutron-proton are suggested to be possible observables to investigate the isospin effects.

Keywords: yield ratio, directed flow, neutron-rich nuclei

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1 Introduction

The desire to extend our understanding of nuclear matter at densities, temperature, pressures and neutron-to-proton ratios away from those of ground state nuclei has become a driving force of the nuclear science community. In particular, the emergence of radioactive beam facilities has placed an emphasis on exploring nuclear matter along the isospin degree-of-freedom. The ultimate goal of radioactive heavy-ion collisions is to determine the isospin dependence of the in-medium nuclear effective interactions and the equation of state (EOS) of isospin asymmetric nuclear matter. One has to look for observables which are sensitive to the isospin. Collective flows have been found to be one of the most sensitive observables to the dynamics of heavy-ion collisions [1–10]. The yield ratio of neutron/proton is also a promising candidate that has been identified to explore isospin physics [11–17]. So in this work the yield ratio and the directed flow of light projectile-like fragments for neutron-rich nuclei induced reactions ^{50}Ca + ^{40}Ca at intermediate energy are explored, and the same observables are also investigated for the stable isobaric nuclei induced collisions ^{50}Cr + ^{40}Ca for comparison.

2 Theoretical framework

Intermediate energy heavy-ion collision dynamics is complex, since both mean field and nucleon-nucleon collisions play the competition role. Furthermore, the isospin-dependent role should be also incorporated for asymmetric reaction systems. The isospin-dependent quantum molecular dynamics model (IQMD) has been affiliated with isospin degrees of freedom with mean field and nucleon-nucleon collisions [18–20]. The IQMD model can explicitly represent the many-body state of the system and principally contains correlation effects to all orders and all fluctuations, and can well describe the time evolution of the colliding system. When the spatial distance Δr is smaller than 3.5 fm and the momentum difference Δp between two nucleons is smaller than 300 MeV/c, two nucleons can coalesce into a cluster [18]. With this simple coalescence mechanism, which has been extensively applied in transport theory, different sized clusters can be recognized.

In the model the nuclear mean-field potential is parameterized as [19]

$$U(\rho,\tau_z)=\alpha\left(\frac{\rho}{\rho_0}\right)+\beta\left(\frac{\rho}{\rho_0}\right)^{\gamma}+\frac{1}{2}(1-\tau_z)V_{\rm c} +C_{\rm sym}\frac{(\rho_{\rm n}-\rho_{\rm p})}{\rho_0}\tau_z+U^{\rm Yuk}, \tag{1}$$

where ρ_0 is the normal nuclear matter density (0.16 fm^{-3}), $\rho_{\rm n}$, $\rho_{\rm p}$ and ρ are the neutron, proton and total densities, respectively; and τ_z is the zth component of the isospin degree of freedom, which equals 1

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or −1 for neutrons or protons, respectively. The coefficients α, β and γ are the parameters for the nuclear equation of state. $C_{\rm sym}$ is the symmetry energy strength due to the density difference of neutrons and protons in the nuclear medium, which is important for asymmetry nuclear matter ($C_{\rm sym} = 32\,{\rm MeV}$ is used). $V_{\rm c}$ is the Coulomb potential and $U_{\rm Yuk}$ is the Yukawa (surface) potential. In the present work, we take $\alpha = 124\,{\rm MeV}$, $\beta = 70.5\,{\rm MeV}$ and $\gamma = 2$, which corresponds to the so-called hard EOS with an incompressibility of $K = 380\,{\rm MeV}$, and $\alpha = -356\,{\rm MeV}$, $\beta = 303\,{\rm MeV}$ and $\gamma = 7/6$, which corresponds to the so-called soft EOS with an incompressibility of $K = 200\,{\rm MeV}$.

The nucleon-nucleon (NN) cross section is the experimental parametrization which is isospin dependent. The neutron-proton cross section is about three times larger than the neutron-neutron or proton-proton cross section below 300 MeV/u.

3 Results and discussions

Now we move to the calculations. About 200000 collisions for ^{50}Ca + ^{40}Ca and ^{50}Cr + ^{40}Ca have been simulated with hard EOS and soft EOS at 50 MeV/u with large impact parameter from 4 to 6 fm. In this study, we extract the physical results at 200 fm/c for light projectile-like particles when the system is in freeze-out stage.

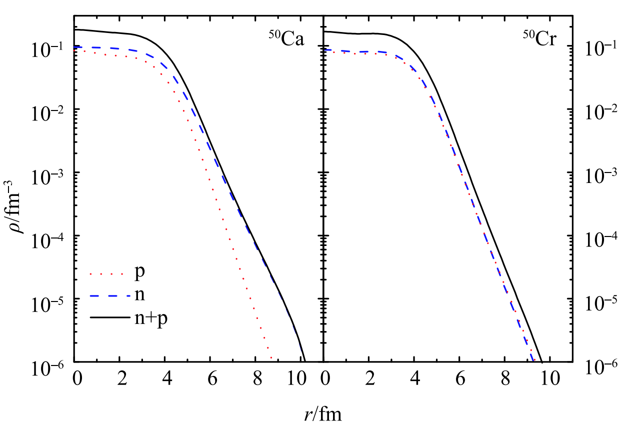

Fig. 1. (color online) Proton (dotted line), neutron (dashed line), and matter (solid line) density distributions in ^{50}Ca and ^{50}Cr calculated using the Skyrme-Hartree-Fock theory.

For the initialization of the nucleons of the target and projectile, the IQMD model distinguishes the proton and neutron from each other. The neutron and the proton density distributions used are determined from the Skyrme-Hartree-Fock (SHF) method, which can give a reasonable density distribution for stable and neutron-rich nuclei [21]. Figure 1 shows the proton, neutron and matter densities calculated for ^{50}Ca (left panel) and ^{50}Cr (right panel) with dotted, dashed and solid lines respectively. There is a clear neutron skin for ^{50}Ca, while there is no skin structure for ^{50}Cr.

Figure 2 shows the rapidity dependence of the yield ratios of neutron to proton (n/p, square) and ^{3}H to ^{3}He (^{3}H/^{3}He, circle) for ^{50}Ca + ^{40}Ca (solid) and ^{50}Cr + ^{40}Ca (open) collisions with hard EOS, respectively. Here rapidity y is the rapidity of a fragment in the center-of-mass (c.m.) frame normalized to the initial projectile rapidity, i.e., $y = y_{\rm c.m.}/y_{\rm proj}$. It shows that the yield ratios of n/p and ^{3}H/^{3}He for the ^{50}Ca + ^{40}Ca system are almost the same, i.e., they increase from about 1.35 with the rapidity and then tend to be saturated to 1.5. But for the ^{50}Cr + ^{40}Ca system, the ratios are lower than those for ^{50}Ca + ^{40}Ca, and the n/p ratio decreases slightly at high rapidity, while the ratio of ^{3}H/^{3}He increase slowly with rapidity all the way. But what we are more interested in is the average ratio of these projectile-like fragments, which can be roughly evaluated from Fig. 2 to be about 1.5 and 1.1 for ^{50}Ca + ^{40}Ca and ^{50}Cr + ^{40}Ca respectively, while the ratios of constituent neutron to proton (N/P) for the two projectile nuclei ^{50}Ca and ^{50}Cr are 1.5 and 1.1 respectively, which coincides with the above yield ratio of projectile-like fragments. It is apparently the result of the coalescence mechanism for fragment formation. So the yield ratios of n/p and ^{3}H/^{3}He can be an observable for neutron-rich nuclei induced reactions. The increasing tendency of the ratios can be understood as follows. The fragments at small and medium rapidities are formed from the inner part of the overlap zone whose N/P ratio is reduced by the target ^{40}Ca, while the projectile-like fragments at high rapidities are formed from the outer part of the overlap zone whose N/P ratio is the same as the projectile, so the yield ratio increase with rapidity. The more protons and fewer neutrons in the outer part of the overlap zone for ^{50}Cr + ^{40}Ca, i.e., the more impulsive Coulomb potential and less attractive mean field, causes the slightly higher proton production at high rapidities, and correspondingly slowly decreasing ratio of n/p. The same ratios of n/p (up triangle) and ^{3}H/^{3}He (down triangle) for ^{50}Ca + ^{40}Ca (solid) and ^{50}Cr + ^{40}Ca (open) with soft EOS are also shown in Fig. 2, which indicates that the ratios for ^{50}Cr + ^{40}Ca with hard EOS and soft EOS are almost equal to each other, but the ratios for ^{50}Ca + ^{40}Ca with soft EOS are a little bigger than these with hard EOS. It is commonly believed that the soft EOS causes higher yields of heavier fragments. Here it seems that the effect of EOS on the light fragment yields from the nearly symmetric nucleus ^{50}Cr are the same, leading to the same yield ratios of n/p and ^{3}H/^{3}He, while it is dependent on the fragment's isospin for the neutron-rich nucleus ^{50}Ca, i.e., the yields of fragments with more neutrons increase more, resulting in higher yield ratios of n/p and ^{3}H/^{3}He.

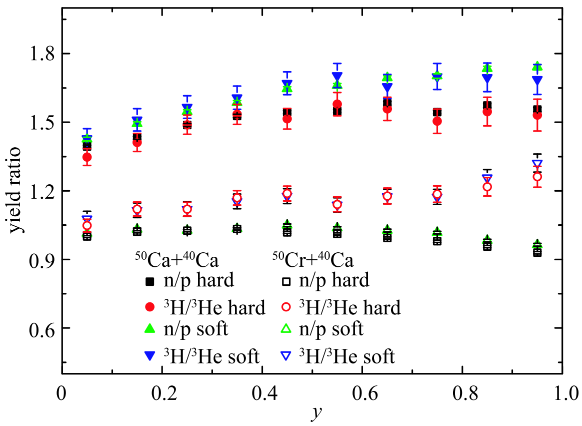

Fig. 2. (color online) The rapidity dependence of the yield ratios of neutron to proton (squares for hard EOS and up triangles for soft EOS) and ^{3}H to ^{3}He (circles for for hard EOS and down triangles for soft EOS). Solid symbols are for ^{50}Ca + ^{40}Ca collisions, and open ones are for ^{50}Cr + ^{40}Ca.

Anisotropic flows are defined as different nth harmonic coefficients v_n of the Fourier expansion for the particle invariant azimuthal distribution,

$$\frac{\mathrm{d}N}{\mathrm{d}\phi} \propto 1+2\sum_{n=1}^{\infty} v_n \cos(n\phi), \tag{2}$$

where ϕ is the azimuthal angle between the transverse momentum of the particle and the reaction plane. The directed flow is the first coefficient as the following expression in terms of single-particle average:

$$v_1 = \langle \cos\phi \rangle = \left\langle \frac{p_x}{p_\mathrm{t}} \right\rangle, \tag{3}$$

where p_t is the transverse momentum ($p_\mathrm{t} = \sqrt{p_x^2+p_y^2}$), and p_x and p_y are, respectively, the projections of particle transverse momentum parallel and perpendicular to the reaction plane. So the directed flow commonly depends on the transverse momentum and the rapidity of the fragment.

The transverse momentum per nucleon (p_t/A) dependence of the directed flow per nucleon (v_1/A) for neutron (square) and proton (circle) at projectile-like rapidity ($0<y<1$) from ^{50}Ca + ^{40}Ca (solid symbols) and ^{50}Cr + ^{40}Ca (open symbols) are shown in the upper panel of Fig. 3. It shows that the directed flows per nucleon for all studied particles are negative for the negative in-plane transverse momentum due to the attractive mean field and rotation effect playing a major role at this energy, and the absolute values increase monotonically with transverse momentum per nucleon increasing, and then descend with increasing p_t/A which may be because the particles with high p_t/A are emitted earlier and are blocked relatively strongly by other nucleons [22]. The upper panel also shows that the absolute value of v_1/A for neutrons is bigger than that for protons for the same reaction system, i.e., neutrons have stronger directed flow, which may be because protons have negative Coulomb potential and symmetric potential, in other words, weaker attractive mean field, and so correspondingly smaller directed flow. But for the ^{50}Ca + ^{40}Ca reaction system, neutrons have stronger v_1 while protons have weaker v_1. This could also result from more negative Coulomb potential and symmetric potential for protons and the reverse effect for neutrons for the neutron-rich nucleus ^{50}Ca. What shows in the middle panel is similar to the upper panel but for ^{3}H (up triangle) and ^{3}He (down triangle). It seems that

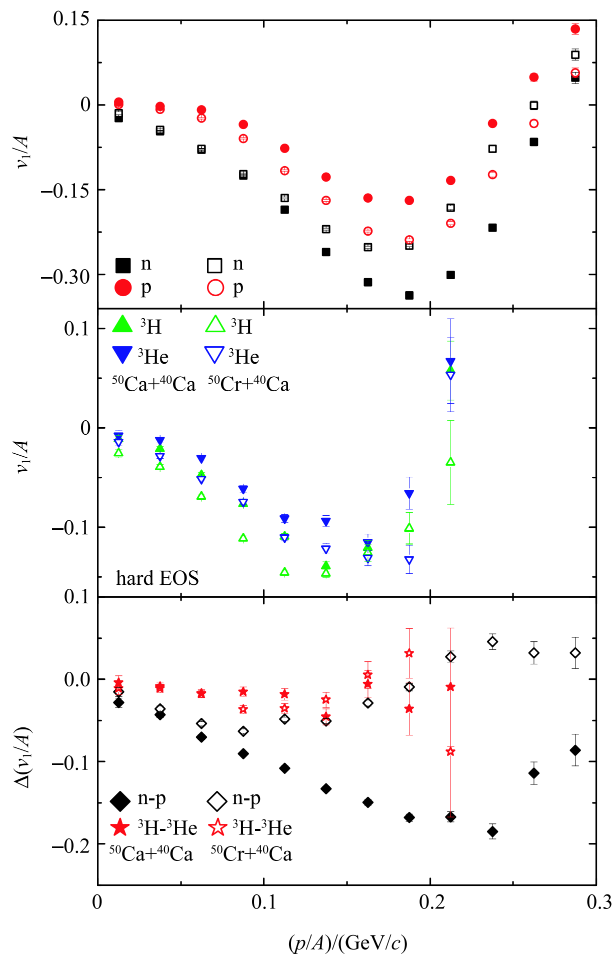

Fig. 3. (color online) Upper and middle panel: Transverse momentum per nucleon (p_t/A) dependence of the directed flow per nucleon (v_1/A) for neutron (square), proton (circle), ^{3}H (up triangle) and ^{3}He (down triangle) at projectile-like rapidity ($0<y<1$). Lower panel: The p_t/A dependence of the differences of v_1/A ($\Delta(v_1/A)$) for neutron-proton (diamond) and ^{3}H-^{3}He (star). The solid and open symbols are for ^{50}Ca + ^{40}Ca and ^{50}Cr + ^{40}Ca with hard EOS respectively.

^{3}H has a stronger v_1/A than ^{3}He for the same system due to its bigger N/P. But contrary to the upper panel, the neutron-rich nucleus ^{50}Ca induced reactions have lower v_1/A for ^{3}H and ^{3}He, which may be because more nucleon-nucleon collisions in the overlap zone of the ^{50}Ca + ^{40}Ca system reduce the v_1/A, and the heavier the fragment, the stronger that effect is. The lower panel shows the p_t/A dependence of the differences of v_1/A ($\Delta(v_1/A)$) for neutron-proton (v_1/A(n)-v_1/A(p)) and ^{3}H-^{3}He ($v_1/A(^3\text{H})$-$v_1/A(^3\text{He})$). It is seen that the absolute difference for neutron-proton from ^{50}Ca + ^{40}Ca is much bigger than that for ^{50}Cr + ^{40}Ca, but the differences for ^{3}H-^{3}He from the two reaction systems are almost same. Figure 4 shows the same correlation as Fig. 5 but using soft EOS, and it is seen that the same particle has a lower absolute value, i.e., less strongly directed flow for simulation with soft EOS because of the lower compression energy to produce the collective flows. But it is still clearly shown that there is a big difference between neutrons and protons from neutron-rich nucleus ^{50}Ca induced reactions.

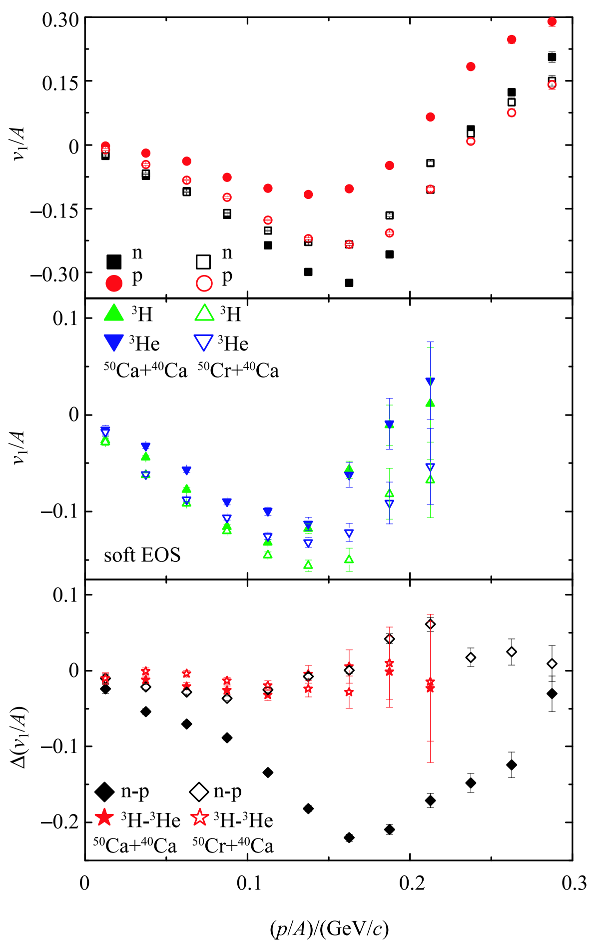

Fig. 4. (color online) Same as Fig. 3 but for ^{50}Ca + ^{40}Ca and ^{50}Cr + ^{40}Ca with soft EOS.

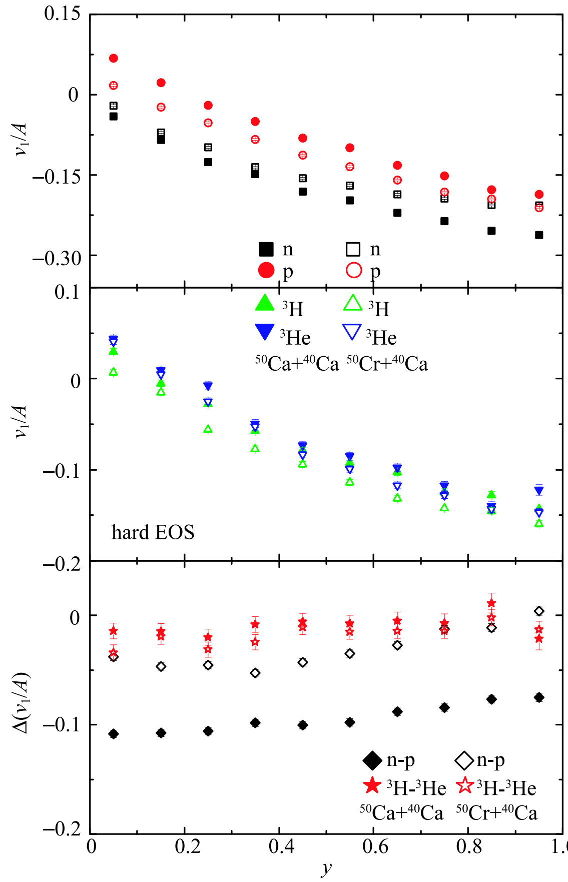

Fig. 5. (color online) Same as Fig. 3 but for rapidity dependence.

Figure 5 is similar to Fig. 3, but for rapidity dependence integrated for all p_t. It shows that the integrated directed flows of all studied fragments in the projectile-like zone are mostly negative, and decrease with rapidity, in other words, fragments with higher rapidity have stronger directed flow. It is easily understood that the characteristics of the absolute values of the integrated v_1/A for different fragments are also the same as the differential v_1/A, i.e., neutrons and ^{3}H have bigger v_1/A than protons and ^{3}He in the same collision system respectively, and neutrons have bigger v_1/A in neutron-rich nucleus ^{50}Ca induced reactions than in stable nucleus ^{50}Cr induced reactions, but protons, ^{3}H and ^{3}He show the opposite behaviour. It is seen in the lower panel of Fig. 5 that $\Delta(v_1/A)$ of ^{3}H-^{3}He for the two systems are almost same at a constant, and $\Delta(v_1/A)$ of neutron-proton increase slightly with the rapidity, while the value for ^{50}Ca + ^{40}Ca is much bigger than that for ^{50}Cr + ^{40}Ca. So the $\Delta(v_1/A)$ of neutron-proton can also reflect the isospin effect. Figure 6 is similar to Fig. 5 but for the two collision systems with soft EOS. It shows that reactions with soft EOS produce smaller integrated directed flow of the same fragment, and there is also a big $\Delta(v_1/A)$ of neutron-proton from ^{50}Ca induced reactions.

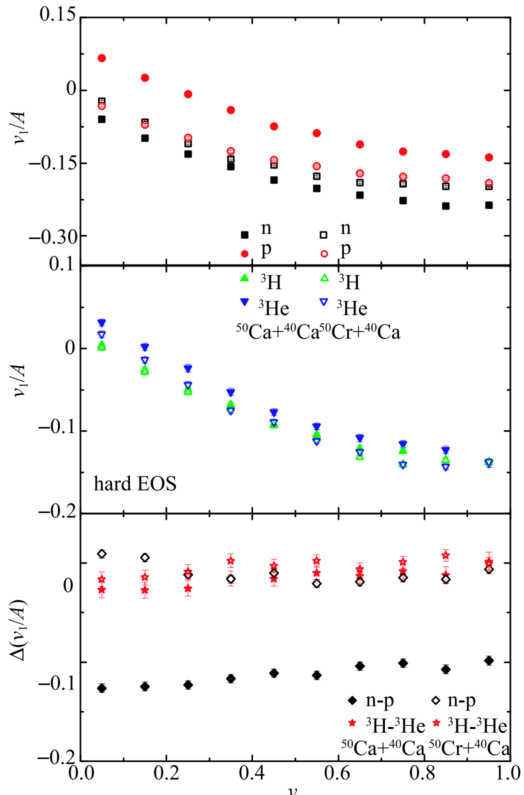

Fig. 6. (color online) Same as Fig. 4 but for rapidity dependence.

4 Summary

We have investigated the directed flow per nucleon of projectile-like neutrons, protons, ^{3}H and ^{3}He at large collision parameters for simulations of ^{50}Ca + ^{40}Ca and ^{50}Cr + ^{40}Ca at 50 MeV/u by the IQMD model with hard or soft EOS. The yield ratios and the differences of v_1/A for neutron-proton and ^{3}H-^{3}He for the two systems were also studied. It is shown that the the yield ratios of projectile-like n/p and ^{3}H-^{3}He can reveal the ratio of constituent neutrons and protons of the projectile nuclei, and they depend on the hardness of EOS, especially for asymmetric projectiles. The values of the directed flow per nucleon of the studied projectile-like fragments are different for the two isobaric nuclei induced reactions, especially those of neutrons and protons. The differences of v_1/A were plotted, showing that the absolute values of the difference of ^{3}H-^{3}He are almost same, while the difference of neutron-proton from ^{50}Ca + ^{40}Ca is much bigger than that from ^{50}Cr + ^{40}Ca and also slightly depends on the hardness of EOS. So the difference of v_1/A of neutron-proton is suggested to be an isospin observable for neutron-rich nuclei. Further experimental and theoretical investigations at intermediate energy are expected to be made.

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