CHIN. PHYS. LETT. Vol. 26, No. 11 (2009) 112501

Isospin Effects on Anisotropic Flows in Intermediate Energy Heavy Ion Collisions *

YAN Ting-Zhi(颜廷志)**, HU Si-Ke(胡思科), GUO Wen-Xue(国文学), WANG Sheng-Long(王升龙), XU Jin-Ping(徐津平)

School of Energy Resources and Mechanical Engineering, Northeast Dianli University, Jilin 132012

(Received 8 June 2009)

Anisotropic flows per nucleon (v_1/A, v_2/A, v_3/A and v_4/A) of light fragments up to the mass number 4 as a function of transverse momentum per nucleon are studied for 55 MeV/nucleon ^{58}Fe+^{58}Fe and ^{58}Ni+^{58}Ni at large impact parameters by the isospin-dependent quantum molecular dynamics model. The effects of symmetry energy and nucleon-nucleon cross sections, which are both isospin-dependent on anisotropic flows, are studied in detail. In comparison of the two systems with or without symmetry potential term, the results show that the strength of flows is sensitive to symmetry potential and nucleon-nucleon cross sections, which mainly cause a repulsion effect in this energy region.

PACS: *25.75.Ld, 24.10.−i, 21.60.Ka*

Anisotropic flows are very useful in exploring heavy-ion collision dynamics and many studies of directed flow v_1 and elliptic flow v_2 have been carried out to explore the properties and origin of the collective motion in both nucleonic or partonic levels.[1−11] We have carried out a quantum molecular dynamics model calculation and found that there is a nucleon-number scaling for the elliptic flow of light particles up to the mass number $A = 4$,[12] and a phenomenological scaling of rapidity dependence for anisotropic flows,[13] and found that the strengths of flows are sensitive to the nuclear EOS and the symmetry potential term.[14] In this Letter, we present isospin effects on transverse momentum dependent anisotropic flows for two symmetric collisions ^{58}Fe+^{58}Fe and ^{58}Ni+^{58}Ni at 55 MeV/nucleon and large impact parameters ($b = 5$–8 fm) with different symmetry energy interactions.

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

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

where ϕ is the azimuthal angle between the transverse momentum of the particle and the reaction plane. Anisotropic flows generally depend on both particle transverse momentum and rapidity, and for a given rapidity the anisotropic flows at a transverse momentum of p_t $\left(p_t = \sqrt{p_x^2 + p_y^2}\right)$ can be evaluated according to

$$v_n(p_t) = \langle \cos(n\phi) \rangle, \tag{2}$$

where $\langle \cdot \rangle$ denotes the average over the azimuthal distribution of particles with a transverse momentum of p_t. The anisotropic flows v_n can further be expressed in term of single-particle averages,

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

$$v_2 = \langle \cos(2\phi) \rangle = \left\langle \frac{p_x^2 - p_y^2}{p_t^2} \right\rangle, \tag{4}$$

$$v_3 = \langle \cos(3\phi) \rangle = \left\langle \frac{p_x^3 - 3p_x p_y^2}{p_t^3} \right\rangle, \tag{5}$$

$$v_4 = \langle \cos(4\phi) \rangle = \left\langle \frac{p_x^4 - 6p_x^2 p_y^2 + p_y^4}{p_t^4} \right\rangle, \tag{6}$$

where p_x and p_y are, respectively, projections of particle transverse momentum parallel and perpendicular to the reaction plane.

The intermediate energy heavy-ion collision dynamics are complex since both mean field and nucleon-nucleon collisions are playing the competition role. Furthermore, the isospin-dependent role should also be incorporated for asymmetric reaction systems. The Isospin-dependent quantum molecular dynamics model (IDQMD) has been affiliated with isospin degrees of freedom with a mean field and nucleon-nucleon collision.[15−20] The IDQMD 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 coalescence into a cluster.[15] With this simple coalescence mechanism, which has been extensively applied in transport theory, different size clusters can be recognized.

*Supported by the Doctoral Research Foundation of Northeast Dianli University under Grant No BSJXM-200807.

**To whom correspondence should be addressed. Email: ytz0110@163.com

© 2009 Chinese Physical Society and IOP Publishing Ltd

In the model the nuclear mean-field potential is parameterized as

$$U(\rho,\tau_z)=\alpha\Big(\frac{\rho}{\rho_0}\Big)+\beta\Big(\frac{\rho}{\rho_0}\Big)^{\gamma}+\frac{1}{2}(1-\tau_z)V_c + C_{\rm sym}\frac{(\rho_n-\rho_p)}{\rho_0}\tau_z+U^{\rm Yuk}, \quad (7)$$

where ρ_0 is the normal nuclear matter density ($0.16\,\mathrm{fm}^{-3}$), ρ_n, ρ_p and ρ are the neutron, proton and total densities, respectively; τ_z is zth component of the isospin degree of freedom, which equals 1 or -1 for neutrons or protons, respectively. The coefficients α, β and γ are parameters for 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 (here $C_{\rm sym}=32\,\mathrm{MeV}$ is used to consider the symmetry energy effect or isospin-dependent potential, and $C_{\rm sym}=0$ for the no symmetry energy effect or isospin-independent potential). V_c is the Coulomb potential and $U_{\rm Yuk}$ is Yukawa (surface) potential. In the present work, we take $\alpha=124\,\mathrm{MeV}$, $\beta=70.5\,\mathrm{MeV}$ and $\gamma=2$ which corresponds to the so-called hard EOS with an incompressibility of $K=380\,\mathrm{MeV}$.

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/nucleon.

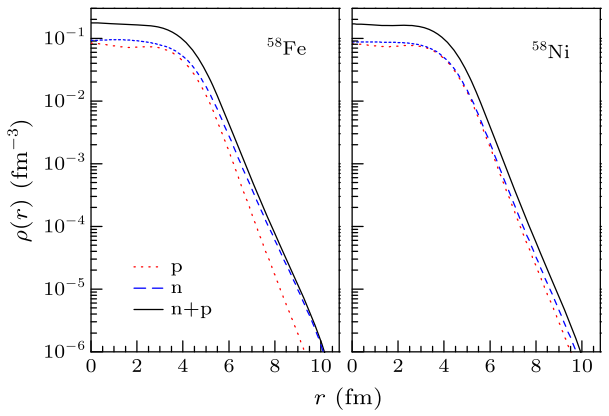

Fig. 1. Neutron (dashed), proton (dotted) and total (n+p) (solid) radial density of initialized nuclei ^{58}Fe and ^{58}Ni.

For the initialization of the nucleons of the target and projectile, the IDQMD model distinguishes the proton and neutron from each other. The neutron and the proton density distributions are determined from the Skyrme–Hartree–Fock (SHF) method, which can give reasonable density distribution for stable and neutron-rich nuclei.[21] One can obtain the radial positions of nucleons in the initial nuclei in terms of the Monte-Carlo method. In the model, the radial density can be written as

$$\rho(r)=\sum_i \frac{1}{(2\pi L)^{3/2}}\exp\Big(-\frac{r^2+r_i^2}{2L}\Big)\frac{L}{2rr_i}. \quad (8)$$

The momentum distribution of nucleons is generated by means of the local Fermi gas approximation. The local Fermi momentum is given by

$$P_F^i(\boldsymbol{r})=\hbar\big[3\pi^2\rho_i(\boldsymbol{r})\big]^{\frac{1}{3}},\ (i=n,p). \quad (9)$$

The stability of the propagation of the initialized nuclei has been checked in detail and can last at least 200 fm/c according to the evolutions of the average binding energies and the rms radii of the initialized nuclei.

Now we move to the calculations. About 110000 events have been simulated for the collision systems ^{58}Fe+^{58}Fe and ^{58}Ni+^{58}Ni at 55 MeV/nucleon and impact parameter from 5 fm to 8 fm with hard EOS and with or without the energy effect (i.e. $C_{\rm sym}=32$ or 0 MeV). The systems tend to freeze-out around 120 fm/c. In this study, we extract the physical results at 200 fm/c for fragments at a rapidity of 0–0.8 among which anisotropic flows do not change much especially for the higher order flows.

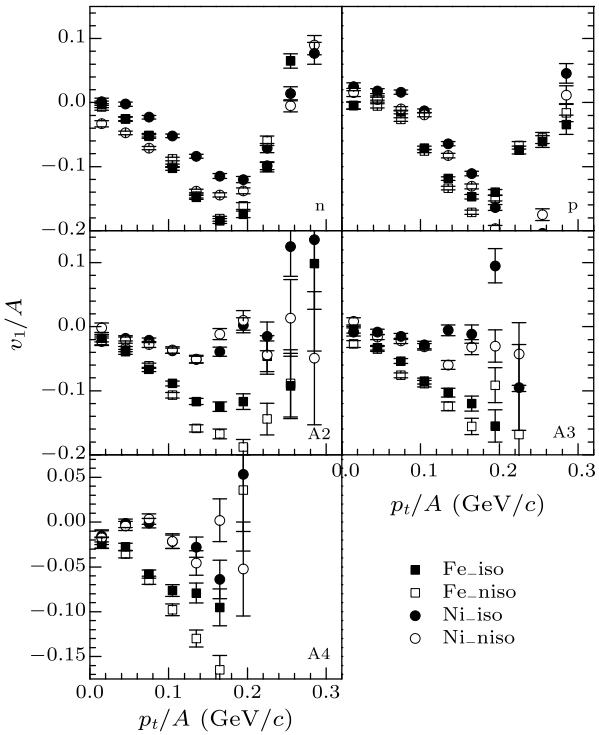

Fig. 2. Directed flows per nucleon as a function of transverse momentum (p_t) per nucleon for light particles at a rapidity of 0–0.8 simulated for ^{58}Fe+^{58}Fe and ^{58}Ni+^{58}Ni systems. Solid and open squares represent the ^{58}Fe+^{58}Fe system with hard EOS and with or without the symmetry energy term respectively, and solid and open circles are for the ^{58}Ni+^{58}Ni system with hard EOS and with or without the symmetry energy term, respectively.

Figure 1 shows the neutron (dashed line), proton

(dotted line) and total (n+p) (solid line) radial density of the initial nuclei ^{58}Fe and ^{58}Ni. It is clear that the total radial densities are nearly the same for the two nuclei. However, the neutron and proton radial densities are not identical, and the difference between them is much larger for ^{58}Fe than that for ^{58}Ni.

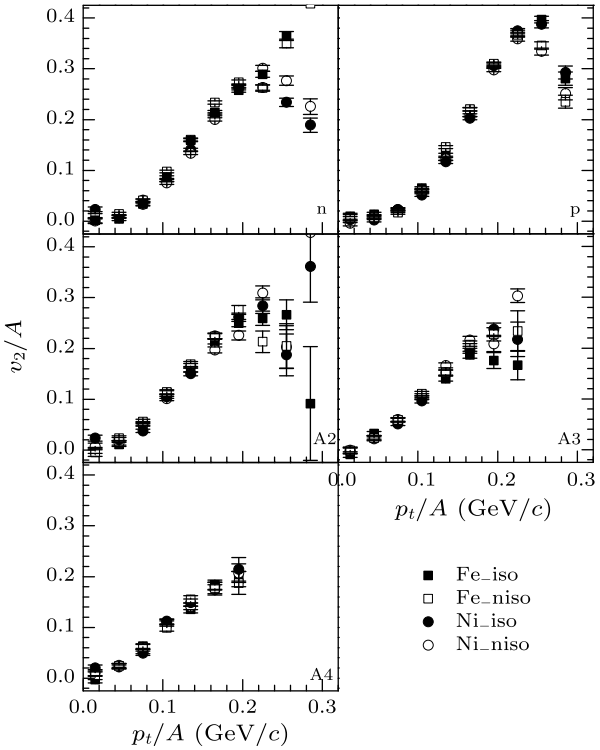

Fig. 3. Elliptic flows per nucleon as a function of transverse momentum per nucleon for light particles at a rapidity of 0–0.8 simulated for the ^{58}Fe+^{58}Fe and ^{58}Ni+^{58}Ni systems. The meanings of the symbols are the same as Fig. 2.

Figure 2 shows the transverse momentum per nucleon dependence of directed flows per nucleon for light fragments (neutron, proton, fragments of $A = 2$, $A = 3$ and $A = 4$) at rapidity (here rapidity y is the rapidity of the fragment in the center of the momentum frame which is normalized to the initial projectile rapidity) from 0 to 0.8 for the two collision systems ^{58}Fe+^{58}Fe and ^{58}Ni+^{58}Ni with or without the symmetry energy effect. It shows that the directed flow is negative for light particles in the 0–0.8 rapidity range and decreases monotonously with increasing p_t/A at low and middle p_t/A. That is probably because the directed flow is mainly driven by the attractive mean field in this energy region[22] and it reflects that particles with higher transverse momentum tend to be strongly emitted within in-plane. It also shows that at the same value of p_t/A, the absolute value of the directed flow per nucleon is mainly larger for EOS without the symmetry energy term than the one for EOS with the symmetry energy term, which is similar to the result of Ref. [14], i.e., the stiffer the EOS, the smaller the flow. It is larger for the ^{58}Fe+^{58}Fe system than that for the ^{58}Ni+^{58}Ni system. The ^{58}Ni+^{58}Ni system has more protons, so the coulomb potential is larger for the ^{58}Ni+^{58}Ni system, whereas the density difference of neutron and proton is larger for the ^{58}Fe+^{58}Fe system, i.e., the symmetry energy term is larger for the ^{58}Fe+^{58}Fe system. Thus it is hard to say which system has the stiffer EOS. The NN cross section may be another influence factor on the value of flows. There are more neutrons in the overlap volume at the same impact parameter for the ^{58}Fe+^{58}Fe system, and the neutron-proton cross section is about three times larger than the neutron-neutron or proton-proton cross section, so there are more NN collisions and more of a Coulomb repulsion effect in the overlap volume for the ^{58}Ni+^{58}Ni system, i.e., p_x mainly driven by the attractive mean field is smaller for the ^{58}Ni+^{58}Ni system. Therefore, the absolute value of the directed flow per nucleon is larger at the same p_t/A for the ^{58}Fe+^{58}Fe system than that for the ^{58}Ni+^{58}Ni system.

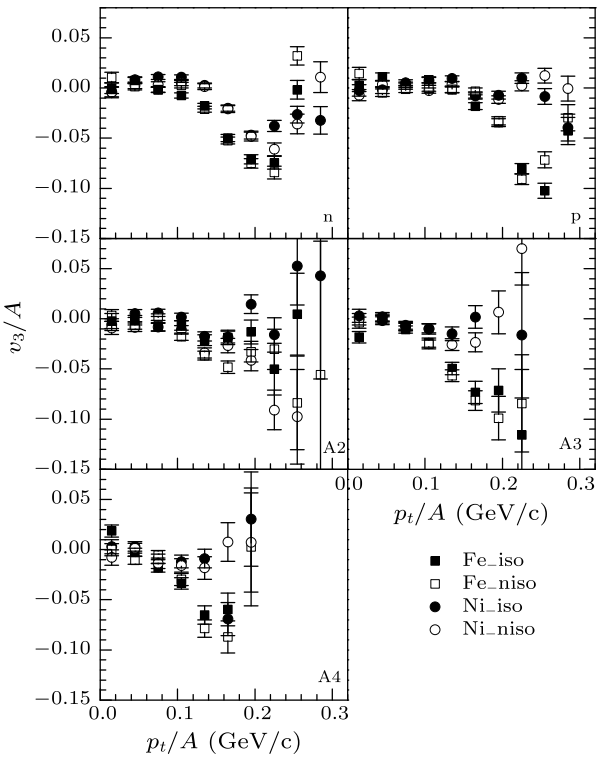

Fig. 4. The same as Fig. 2 but for v_3/A versus p_t/A.

Figure 3 is similar to Fig. 2 but for the elliptic flow per nucleon. It shows that the elliptic flows per nucleon for light fragments are positive and increase with the increasing p_t/A. In intermediate energy domain, collective rotation is one of the main mechanisms to induce the positive elliptic flow.[23–25] It also reflects that particles with a higher transverse momentum per nucleon tend to be strongly emitted within in-plane. Similar to directed flow, the elliptic flow per nucleon is approximately larger for EOS without the symmetry

energy term than the one for EOS with the symmetry energy term at the same p_t/A for the two systems respectively. It is also larger for the ^{58}Fe+^{58}Fe system than that for ^{58}Ni+^{58}Ni system. That may be caused by the factors of a larger NN cross section which drive smaller $|p_x|$ and more of a Coulomb repulsion effect which drives larger $|p_y|$ at the same p_t in the early initial almond anisotropy of the geometrical overlap zone for the ^{58}Ni+^{58}Ni system. However, the difference of elliptic flow per nucleon for light fragments between the two systems is not so large as that of the directed flow especially for $A = 3$ and $A = 4$ particles.

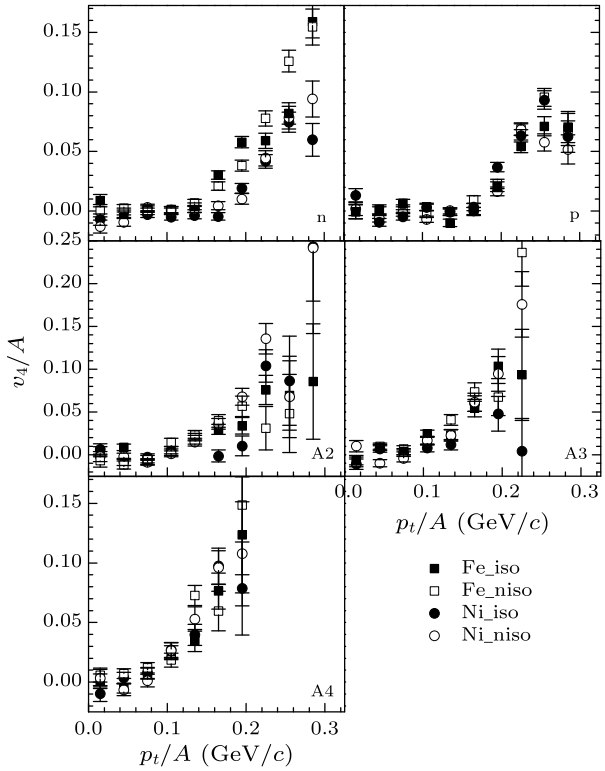

Fig. 5. The same as Fig. 2 but for v_4/A versus p_t/A.

So far, there have been rare studies on higher order flows experimentally and theoretically in this energy domain. Here we try to explore the behavior of v_3 and v_4. Figures 3 and 4 show the transverse momentum per nucleon dependence of the higher order flows of v_3 and v_4 per nucleon, respectively. The trend of v_3/A and v_4/A are similar to that of v_1/A and v_2/A, respectively, but they show a smaller magnitude of flows for a given particle in comparison with v_1/A and v_2/A, respectively. Nevertheless the magnitude of flows of v_3/A and v_4/A are not too small, hence the higher order flows should not be neglected in this energy region. The effects of symmetry potential and NN cross section on v_3/A and v_4/A are also approximately similar to their effects on v_1/A and v_2/A, i.e., symmetry potential and NN cross section make the flows smaller and seem to make a repulsion effect. However, compared with the v_1/A sensitivity to symmetry potential and the NN cross section, v_3/A and v_4/A are not so salient especially for heavier fragments.

In summary, we have investigated the behavior of anisotropic flows per nucleon as a function of transverse momentum per nucleon for light fragments at rapidity from 0 to 0.8 for the simulations of 55 MeV/nucleon ^{58}Fe+^{58}Fe and ^{58}Ni+^{58}Ni peripheral collisions by the IDQMD model with the potential parameters of the hard EOS w/o symmetry energy term, respectively. It is shown that the v_1/A and v_3/A of light fragments at a rapidity of 0–0.8 are negative and decrease monotonously with p_t/A, while v_2/A and v_4/A are positive and increase monotonously with p_t/A at low and middle p_t/A, respectively. The values of anisotropic flows per nucleon are compared for the two systems with or without the symmetry energy effect. It is found that anisotropic flows are smaller for the ^{58}Ni+^{58}Ni system and for flows simulated with symmetry potential. In other words, anisotropic flows per nucleon are sensitive to the isospin-dependent symmetry potential and NN cross section which mainly cause a repulsion effect in this energy region, simply not so salient for higher order anisotropic flows and heavier fragments.

References

[1] Ollitrault J 1992 *Phys. Rev.* D **46** 229
[2] Sorge H 1997 *Phys. Lett.* B **402** 251
Sorge H 1997 *Phys. Rev. Lett.* **78** 2309
Sorge H 1999 *Phys. Rev. Lett.* **82** 2048
[3] Danielewicz P et al 1998 *Phys. Rev. Lett.* **81** 2438
[4] Teaney D and Shuryak E V 1999 *Phys. Rev. Lett.* **83** 4951
[5] Kolb P F et al 2000 *Phys. Rev.* C **62** 054909
[6] Zheng Y M et al 1999 *Phys. Rev. Lett.* **83** 2534
[7] Perslam D and Gale C 2002 *Phys. Rev.* C **65** 064611
[8] Lukasik J et al 2004 *Phys. Lett.* B **608** 223
[9] Adams J et al (STAR Collaboration) 2004 *Phys. Rev. Lett.* **92** 052302
Adams J et al (STAR Collaboration) 2005 *Phys. Rev.* C **72** 014904
Adams J et al (STAR Collaboration) 2005 *Phys. Rev. Lett.* **95** 122301
[10] Chen J H, Ma Y G et al 2006 *Phys. Rev.* C **74** 064902
[11] Ma Y G 2006 *J. Phys.* G **32** S373
[12] Yan T Z, Ma Y G et al 2006 *Phys. Lett.* B **638** 50
[13] Yan T Z, Ma Y G et al 2007 *Chin. Phys. Lett.* **24** 3388
[14] Yan T Z, Ma Y G, Cai X Z et al 2007 *Chin. Phys.* **16** 1009
[15] Aichelin J 1991 *Phys. Rep.* **202** 233
[16] Ma Y G and Shen W Q 1995 *Phys. Rev.* C **51** 710
[17] Zhang F S, Chen L W, Zhao Y M et al 1999 *Phys. Rev.* C **60** 064604
[18] Liu J Y, Guo W J, Ren Z Z et al 2006 *Chin. Phys.* **15** 1738
[19] Wei Y B, Ma Y G, Shen W Q et al 2004 *J. Phys.* G **30** 2019
[20] Ma Y G, Wei Y B et al 2006 *Phys. Rev.* C **73** 014604
[21] Wen W X, Jin G M and Zhong J Q 1996 *High Enery Phys. Nucl. Phys.* **20** 148 (in Chinese)
[22] Wilson W K, Lacey R et al 1992 *Phys. Rev.* C **45** 738
[23] Sullivan J P and Péter J 1992 *Nucl. Phys.* A **540** 275
[24] Lacey R, Elmaani A et al 1993 *Phys. Rev. Lett.* **70** 1224
[25] He Z Y, Angelique J C et al 1996 *Nucl. Phys.* A **598** 248