Article ID: 1007-4627(2014) 03-0306-09

Spin Effects in Intermediate-energy Heavy-ion Collisions

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Abstract: In this paper, we report and extend our recent work where the nucleon spin-orbit interaction and its spin degree of freedom were introduced explicitly for the first time in the isospin-dependent Boltzmann-Uehling-Uhlenbeck transport model for heavy-ion reactions. Despite of the significant cancellation of the time-even and time-odd spin-related mean-field potentials from the spin-orbit interaction, an appreciable local spin polarization is observed in heavy-ion collisions at intermediate energies because of the dominating role of the time-odd terms. It is also found that the spin up-down differential transverse flow in heavy-ion collisions is a useful probe of the strength, density dependence, and isospin dependence of the in-medium spin-orbit interaction, and its magnitude is still considerable even at smaller systems.

Key words: IBUU transport model; spin-orbit interaction; heavy-ion collision

CLC number: O571.6; **Document code:** A **DOI:** 10.11804/NuclPhysRev.31.03.306

1 Introduction

Understanding the fundamental nuclear force is one of the main tasks of nuclear physics. Although in free space the low energy nucleon-nucleon (NN) interaction is well understood from studying NN scattering data[1], many interesting questions regarding the in-medium nuclear interaction remain unsolved due to the difficulties of dealing with many-body problems from the first principle. The nuclear spin-orbit interaction, which is one of the important components of the nuclear force, was first phenomenologically introduced in order to explain the magic number of nuclei sixty-five years ago[2−3]. However, until now properties of the in-medium spin-orbit interaction, especially its density and isospin dependence, are still quite uncertain, and they are related to many interesting questions in studying properties of drip-line nuclei[4], the astrophysical r-process[5], and the location of stability island for superheavy elements[6−7]. From the standard form of the Skyrme energy density functional, the spin-orbit interaction can be viewed as a density-independent one and favors the coupling between nucleons of the same isospin based on the Schrödinger equation, while the relativistic mean-field (RMF) model gives a density-dependent spin-orbit interaction with the same coupling strength between nucleons of the same or different isospins if we do non-relativistic expansion for the Dirac equation. The RMF model can somehow better explain the kink of the charge radii for lead isotopes than the Skyrme-Hartree-Fock model unless a weak isospin dependence of the spin-

Received date: 8 Sep. 2013; **Revised date:** 16 Oct. 2013

Foundation item: Hundred Talents Program of Chinese Academy of Sciences (Y290061011); US National Science Foundation (PHY-0757839, PHY-1068022); National Aeronautics and Space Administration issued through Science Mission Directorate(NNX11AC41G); CUSTIPEN (China-U.S. Theory Institute for Physics with Exotic Nuclei) Foundation from DOE(DE-FG02-13ER42025)

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orbit interaction is introduced to the latter[8−9]. To better understand the density dependence of the spin-orbit coupling, experiments to compare the shell structures of the so-called 'bubble nuclei' with normal nuclei are planned[10−11]. In addition, there are experiments indicating a decreasing strength of the spin-orbit coupling with the increasing isospin asymmetry in neutron-rich nuclei[12−13].

Despite the extensive studies of the spin-orbit interaction in nuclear structure, there are only a few studies discussing its effects in heavy-ion collisions. For instance, it has been found that introducing the spin-orbit interaction to the time-dependent Hartree-Fock (TDHF) model for low-energy heavy-ion reactions would affect the fusion threshold energy[14] and induce a local spin polarization[15−16], while the partonic spin-orbit interaction may result in the polarization of the quark-gluon plasma formed in non-central relativistic heavy-ion collisions[17]. However, to our best knowledge, so far there is no study on the effects of the spin-orbit interaction in intermediate-energy heavy-ion collisions. On the other hand, several facilities for measuring the spin polarization of projectile fragments through their γ or β decay in peripheral collisions have been developed at GSI and RIKEN for about twenty years[18−19]. The spin-flip probability can be obtained in pp and pA scatterings at AGS and RHIC energies by measuring the analyzing power[20]. We have recently incorporated the nucleon spin-orbit interaction and the nucleon spin degree of freedom into an isospin-dependent Boltzmann-Uehling-Uhlenbeck (IBUU) transport model[21]. Compared with studies on properties of finite nuclei, heavy-ion collisions allow us to adjust the density, the isospin asymmetry, and the energy of the system. It thus provides a useful tool for studying in detail properties of in-medium nuclear spin-orbit interaction.

2 Spin-orbit interaction

We start from the following effective in-medium spin-orbit interaction[22]

$$V_{so} = iW_0(\boldsymbol{\sigma}_1+\boldsymbol{\sigma}_2)\cdot\boldsymbol{k}\times\delta(\boldsymbol{r}_1-\boldsymbol{r}_2)\boldsymbol{k}' , \quad (1)$$

where W_0 is the spin-orbit coupling constant, $\boldsymbol{\sigma}_{1(2)}$ is the Pauli matrix, $\boldsymbol{k}=(\boldsymbol{p}_1-\boldsymbol{p}_2)/2$ is the relative momentum operator acting on the right with $\boldsymbol{p}=-i\nabla$, and $\boldsymbol{k}'$ is the complex conjugate of $\boldsymbol{k}$. From the Hartree-Fock method and the variational principle, the single-particle Hamiltonian can be expressed as

$$h_{\mathrm{q}} = \frac{p^2}{2m}+U_{\mathrm{q}}+U_{\mathrm{q}}^{\mathrm{s}} , \quad (2)$$

where q is the isospin index, U_{q} is the momentum-independent bulk mean-field potential fitted by the empirical properties of nuclear matter, *i.e.*, the binding energy $E_0 = -16$ MeV, the incompressibility $K_0 = 230$ MeV, and the symmetry energy $E_{\mathrm{sym}} = 30$ MeV and its slope parameter $L = 60$ MeV at saturation density $\rho_0 = 0.16\ \mathrm{fm}^{-3}$ similar to the parameterization as in a modified Skyrme-like interaction[23], and $U_{\mathrm{q}}^{\mathrm{s}}$ is the spin-related mean-field potential including the time-even contribution $U_{\mathrm{q}}^{\mathrm{s-even}}$ and the time-odd contribution $U_{\mathrm{q}}^{\mathrm{s-odd}}$

$$\begin{aligned} U_{\mathrm{q}}^{\mathrm{s-even}} =& -\frac{W_0}{2}[\nabla\cdot(\boldsymbol{J}+\boldsymbol{J}_{\mathrm{q}})]+ \\ & \frac{W_0}{2}(\nabla\rho+\nabla\rho_{\mathrm{q}})\cdot(\boldsymbol{p}\times\boldsymbol{\sigma}) , \end{aligned} \quad (3)$$

$$\begin{aligned} U_{\mathrm{q}}^{\mathrm{s-odd}} =& -\frac{W_0}{2}\boldsymbol{p}\cdot[\nabla\times(\boldsymbol{s}+\boldsymbol{s}_{\mathrm{q}})]- \\ & \frac{W_0}{2}\boldsymbol{\sigma}\cdot[\nabla\times(\boldsymbol{j}+\boldsymbol{j}_{\mathrm{q}})] , \end{aligned} \quad (4)$$

where

$$\rho = \sum_i \phi_i^\star \phi_i , \quad (5)$$

$$\boldsymbol{s} = \sum_i \sum_{\sigma,\sigma'} \phi_i^\star \langle\sigma|\boldsymbol{\sigma}|\sigma'\rangle\phi_i , \quad (6)$$

$$\boldsymbol{j} = \frac{1}{2i}\sum_i(\phi_i^\star\nabla\phi_i-\phi_i\nabla\phi_i^\star) , \quad (7)$$

$$\boldsymbol{J} = \frac{1}{2i}\sum_i\sum_{\sigma,\sigma'}(\phi_i^\star\nabla\phi_i-\phi_i\nabla\phi_i^\star)\times\langle\sigma|\boldsymbol{\sigma}|\sigma'\rangle , \quad (8)$$

are respectively the number, spin, momentum, and spin-current densities, with ϕ_i being the wave function of the ith nucleon. The second term in Eq. (3) is usually called the spin-orbit potential. We note that the first (second) term in Eq. (4) suppresses the first (second) term in Eq. (3) so that the system satisfies the Galilean invariance, *i.e.*, there is no frame-dependent spurious spin polarization[15]. We will return to this later.

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Including the density and isospin dependence to the spin-orbit interaction, Eqs. (3) and (4) can be modified into a more general form as

$$U_{\mathrm{q}}^{\mathrm{s-even}} = -\frac{W_0^\star(\rho)}{2}[\nabla\cdot(a\boldsymbol{J}_{\mathrm{q}}+b\boldsymbol{J}_{\mathrm{q}'})]+ \frac{W_0^\star(\rho)}{2}(a\nabla\rho_{\mathrm{q}}+b\nabla\rho_{\mathrm{q}'})\cdot(\boldsymbol{p}\times\boldsymbol{\sigma}) \ , \tag{9}$$

$$U_{\mathrm{q}}^{\mathrm{s-odd}} = -\frac{W_0^\star(\rho)}{2}\boldsymbol{p}\cdot[\nabla\times(a\boldsymbol{s}_{\mathrm{q}}+b\boldsymbol{s}_{\mathrm{q}'})]- \frac{W_0^\star(\rho)}{2}\boldsymbol{\sigma}\cdot[\nabla\times(a\boldsymbol{j}_{\mathrm{q}}+b\boldsymbol{j}_{\mathrm{q}'})]. \quad (q\neq q') \tag{10}$$

In the above, $W_0^\star(\rho)$ can be replaced by $W_0(\rho/\rho_0)^\gamma$ where the γ factor can be adjusted to mimic the density dependence of the spin-orbit coupling. Parameters a and b are included to study the isospin dependence of the spin-orbit coupling while preserving the Galilean invariance. From a standard Skyrme functional form[24], the spin-orbit coupling is density-independent, *i.e.*, $\gamma=0$, and $a=2$ and $b=1$ are obtained as in Eqs. (3) and (4), while equal values for a and b, and a nonzero value for γ were predicted within a relativistic mean-field model[9]. Neglecting the density dependence of $W_0^\star$, the spin-orbit coupling constant W_0 is roughly between 80 MeV·fm^5 and 150 MeV·fm^5 from various studies[25–27], while the values of γ, a, and b are still quite uncertain. In the following calculation, we choose $W_0=150$ MeV·fm^5, $\gamma=0$, $a=2$, and $b=1$ unless stated.

3 Introducing spin to IBUU transport model

The IBUU transport model[28–29] has been very successful in studying intermediate-energy heavy-ion collisions, especially the isospin effects. However, in the previous studies, the spin effects are neglected as only spin-averaged quantities such as the equation of state of the produced nuclear matter are the objects under the main concern. To introduce spin effects into the IBUU model, each nucleon now has an additional degree of freedom, *i.e.*, a unit vector representing the expectation value of its spin $\boldsymbol{\sigma}$, through which the probability of its spin at arbitrary direction can be calculated from the projection on that direction. The spin, momentum, and spin-current densities can be calculated by using the test particle method[30–31] similar to the number density ρ, *i.e.*,

$$\rho(\boldsymbol{r}) = \frac{1}{N_{\mathrm{test}}}\sum_i \delta(\boldsymbol{r}-\boldsymbol{r}_i), \tag{11}$$

$$\boldsymbol{s}(\boldsymbol{r}) = \frac{1}{N_{\mathrm{test}}}\sum_i \boldsymbol{\sigma}_i\delta(\boldsymbol{r}-\boldsymbol{r}_i), \tag{12}$$

$$\boldsymbol{j}(\boldsymbol{r}) = \frac{1}{N_{\mathrm{test}}}\sum_i \boldsymbol{p}_i\delta(\boldsymbol{r}-\boldsymbol{r}_i), \tag{13}$$

$$\boldsymbol{J}(\boldsymbol{r}) = \frac{1}{N_{\mathrm{test}}}\sum_i (\boldsymbol{p}_i\times\boldsymbol{\sigma}_i)\delta(\boldsymbol{r}-\boldsymbol{r}_i). \tag{14}$$

In addition, the equations of motion in the presence of the spin-related mean-field potentials can now be written as

$$\frac{\mathrm{d}\boldsymbol{r}}{\mathrm{d}t} = \frac{\boldsymbol{p}}{m}+\frac{W_0^\star(\rho)}{2}\boldsymbol{\sigma}\times(a\nabla\rho_{\mathrm{q}}+b\nabla\rho_{\mathrm{q}'})- \frac{W_0^\star(\rho)}{2}\nabla\times(a\boldsymbol{s}_{\mathrm{q}}+b\boldsymbol{s}_{\mathrm{q}'}), \tag{15}$$

$$\frac{\mathrm{d}\boldsymbol{p}}{\mathrm{d}t} = -\nabla U_{\mathrm{q}}-\nabla U_{\mathrm{q}}^{\mathrm{s-even}}-\nabla U_{\mathrm{q}}^{\mathrm{s-odd}}, \tag{16}$$

$$\frac{\mathrm{d}\boldsymbol{\sigma}}{\mathrm{d}t} = W_0^\star(\rho)[(a\nabla\rho_{\mathrm{q}}+b\nabla\rho_{\mathrm{q}'})\times\boldsymbol{p}]\times\boldsymbol{\sigma}- W_0^\star(\rho)[\nabla\times(a\boldsymbol{j}_{\mathrm{q}}+b\boldsymbol{j}_{\mathrm{q}'})]\times\boldsymbol{\sigma}. \tag{17}$$

Let's consider a nucleus moving freely with a fixed momentum $\boldsymbol{p}$ per nucleon. If we neglect the Fermi motion of nucleons, we have $\nabla\times\boldsymbol{j}\sim\nabla\times(\boldsymbol{p}\rho)=\nabla\rho\times\boldsymbol{p}$ and $\nabla\cdot\boldsymbol{J}\sim\nabla\cdot(\boldsymbol{p}\times\boldsymbol{s})=-\boldsymbol{p}\cdot(\nabla\times\boldsymbol{s})$. Thus, the time-odd terms (Eq. (10)) exactly cancel the time-even terms (Eq. (9)) and there is no spurious spin excitation as mentioned before. During heavy-ion collisions, where z is the beam axis and the distance between the centers of the two colliding nuclei in the x direction is the impact parameter b, things can be different. Since initially the spins of nucleons are randomly distributed, the second terms in Eqs. (9) and (10) are most important for inducing local spin polarization. As the density gradient $\nabla\rho$ is mainly along the x axis during the collision process in non-central collisions, the spin $\boldsymbol{\sigma}$ of a nucleon favors the direction of $\boldsymbol{p}\times\nabla\rho$, *i.e.*, the y direction perpendicular to the reaction plane (x–o–z), to lower the energy as can be seen from the second term in Eq. (9). On the other hand, the second term in Eq. (10) makes the nucleon spin $\boldsymbol{\sigma}$ parallel to $\nabla\times\boldsymbol{j}$, which is roughly in the opposite direction of $\boldsymbol{p}\times\nabla\rho$. We note that the momentum of each nucleon is different during the collision process, and the argument of exact cancellation is no

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longer valid. The result of the competition between the time-even terms and the time-odd terms determines the final direction of the nucleon spin. We will refer in the following a nucleon with its spin in the $+y$ ($-y$) direction as a spin-up (spin-down) nucleon.

So far we have been dealing with the mean-field potential part of the transport model, while the scattering process should also be treated with care. It was found that the spin of a nucleon may flip after NN scatterings[32] from spin-related NN interactions. Although it was shown that the spin-flip probability is appreciable and dependent on the energy and momentum transfer[33], it is still not well determined due to the lack of the knowledge of in-medium spin-related NN interactions. In the present work, we randomize the spins of the two nucleons after each NN scattering unless stated. In addition, the phase space can be further divided after including the spin degree of freedom, and a spin-dependent Pauli blocking is introduced so that the final states of the two nucleons after scatterings are not allowed to have the same spin and isospin.

4 Results and discussions

Before we do full spin calculation, we test what will happen if we only include the time-even spin-related mean-field potentials (Eq. (9)), as this is similar to the case of the so-called 'spin hall effect' in the electron transport calculation[34]. Initially we put the two nuclei far away from each other and the spins of nucleons are randomly distributed. When the two nuclei touch each other, a strong spurious spin polarization has already been developed in the moving process, as shown in Fig. 1, with the participant nucleons mostly spin-down ones and the spectator nucleons mostly spin-up ones. During the collision process, the spin polarization of the participant nucleons gradually vanishes due to the NN scatterings and spin mixing effects. After the collision, big fragments from the spectator matter are mostly spin-up ones.

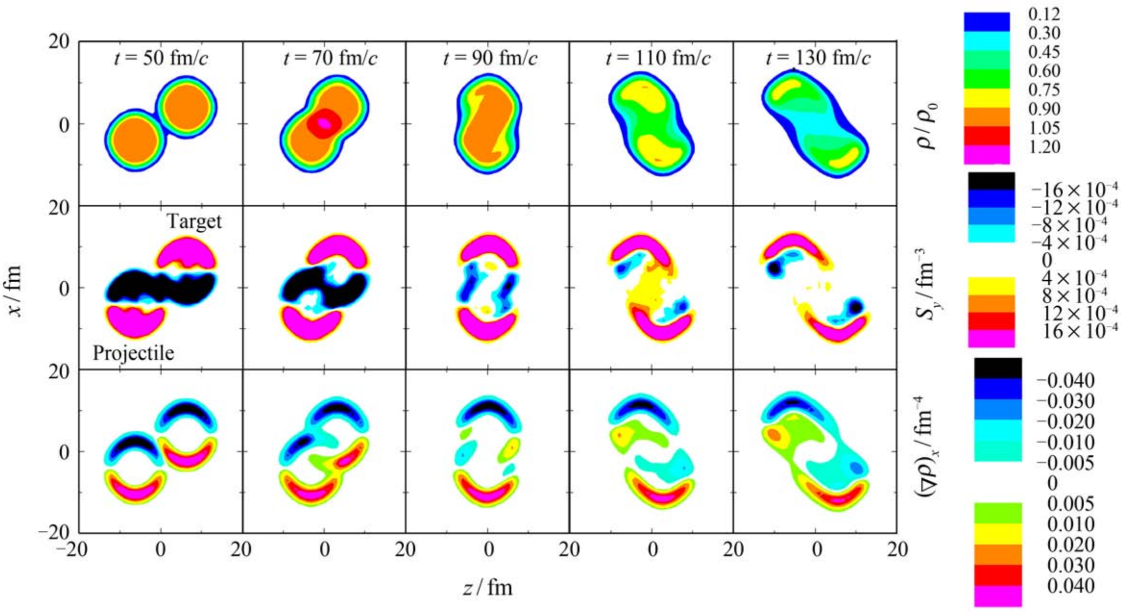

Fig.1 (color online) Contours of the reduced number density (first row), the y component of the spin density (second row), and the x component of the density gradient (third row) in the reaction plane at different time steps in Au+Au collisions at a beam energy of 50 MeV/u with impact parameter $b = 8$ fm. Only time-even terms are included. A similar plot can be found in Ref. [1].

From the equations of motion, the spin-dependent potentials not only affect the spin direction of a nucleon but also change its momentum in a spin-dependent way. The nucleon transverse flow, *i.e.*, the average transverse momentum $< p_x(y_{\rm r}) >$ in the reaction plane versus rapidity $y_{\rm r}$, is an important

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quantity for studying nucleon interactions in heavy-ion collisions[31, 35−36]. Since the mean-field potentials for spin-up nucleons and spin-down nucleons are now different, their transverse flows will be different as well, as shown in the left panel of Fig. 2. It is seen that the transverse flow of spin-up nucleons is slightly larger than that of spin-down ones, especially at large rapidities. This can be understood by looking at the evolution of the density gradient as shown in the third row of Fig. 1. By examining the time evolution, we found that the effects of the spin-orbit interaction on the transverse flow during the first 40 fm/c of the collision are mostly washed out due to violent interactions. The spin-dependent transverse flow is mainly determined by the dynamics afterwards. As the projectile (target) is still moving in the $+z$ $(-z)$ direction, the participant nucleons from the projectile (target) with negative (positive) $(\nabla\rho)_x$ give a more repulsive/attractive spin-orbit potential $[\nabla\rho\cdot(\boldsymbol{p}\times\boldsymbol{\sigma})>/<0]$ for spin-up/down nucleons. This leads to a larger transverse flow for spin-up nucleons than spin-down ones.

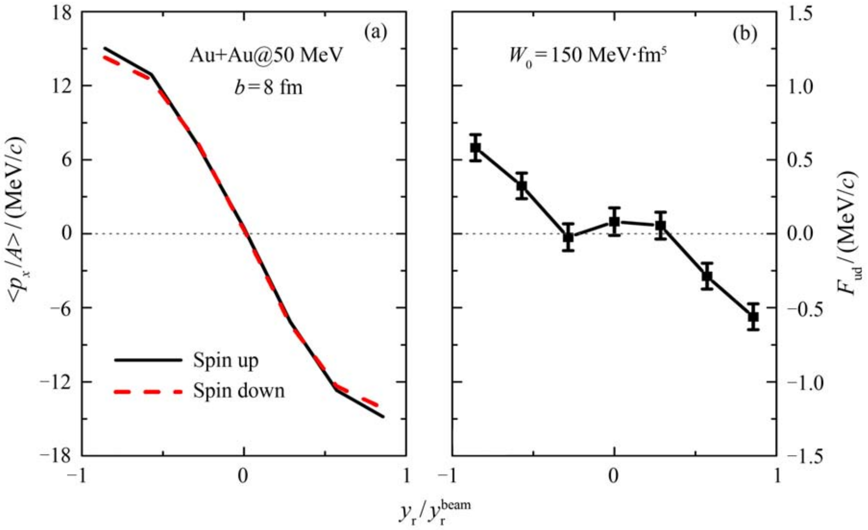

Fig. 2 (color online) Transverse flows of spin-up nucleons and spin-down nucleons (a) as well as spin up-down differential transverse flow (b) in the same reaction as in Fig. 1 with only time-even terms. A similar plot can be found in Ref. [1].

Similar to the neutron-proton differential transverse flow[37], we can define the spin up-down differential transverse flow

$$F_{\mathrm{ud}}(y_{\mathrm{r}})=\frac{1}{N(y_{\mathrm{r}})}\sum_{i=1}^{N(y_{\mathrm{r}})}\sigma_i(p_x)_i, \tag{18}$$

where $N(y_{\mathrm{r}})$ is the number of nucleons with rapidity y_{r}, and σ_i is $1(-1)$ for spin-up (spin-down) nucleons. The spin up-down differential transverse flow maximizes the effects of the opposite spin-related potentials for spin-up and spin-down nucleons while canceling out largely spin-independent contributions, as shown in the right panel of Fig. 2.

After including both the time-even terms and time-odd terms, the time evolution of the densities are shown in Fig. 3. It is seen that the number density evolution is almost the same, as the strength of the spin-related potentials is much smaller than that of the bulk potentials. Interestingly, although we use the same initial condition, there is almost no spin polarization before the two colliding nuclei touch each other. During the collision process, however, the spin polarization is gradually developed, with the participant nucleons mostly spin-up ones while the spectator nucleons mostly spin-down ones. Comparing the local spin polarization to that with only the time-even terms as shown in Fig. 1, we found that the time-odd terms are stronger than the time-even terms and dominate the results, *i.e.*, the contribution from the y component of the curl of the momentum density $(\nabla\times\boldsymbol{j})_y$ is important. It is seen that with full spin calculations, the direction of the local

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spin polarization is consistent with the results from TDHF calculations[15−16]. As time goes on, the spin polarization becomes weaker, and the big fragments from the spectator matter at the end of the collisions are spin-down ones. The time-odd terms not only change the spin polarization direction, but affect the spin depen dence of the transverse flow as well. As can be seen from the third row of Fig. 3, $(\nabla\times\boldsymbol{j})_y$ is positive for the participant matter from both the target and the projectile. Thus, the corresponding term of the time-odd spin-dependent potential in Eq. (10) is attractive for spin-up nucleons and repulsive for spin-down ones. This is contradictory to the case with only the time-even terms. As can be seen from the left panel of Fig. 4, the time-odd terms again dominate the results and lead to a larger transverse

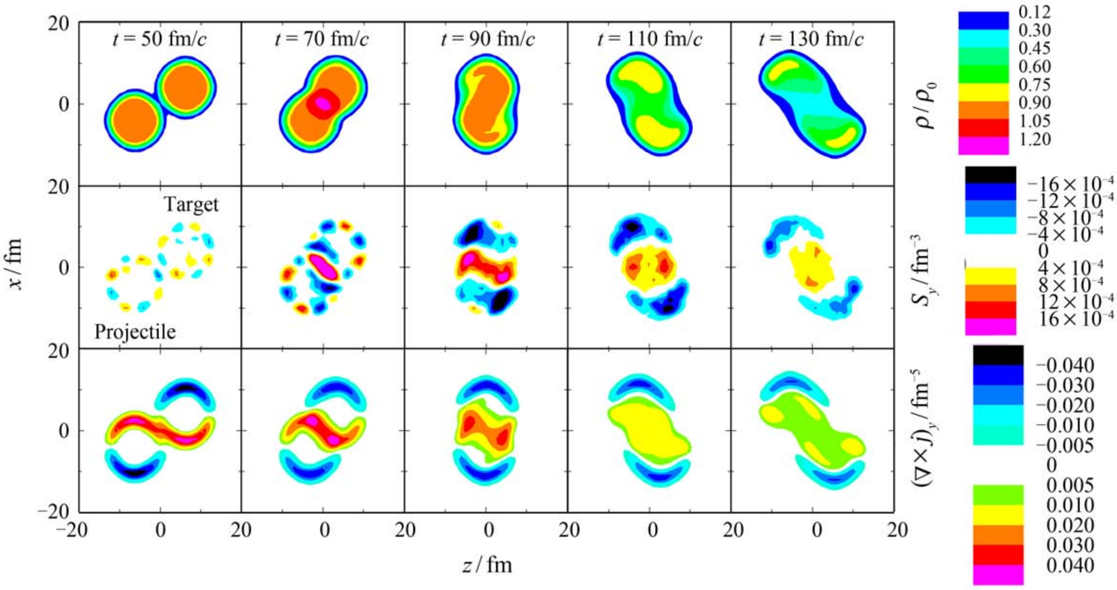

Fig. 3　(color online) Contours of the reduced number density (first row), the y component of the spin density (second row), and the y component of the curl of the momentum density (third row) in the reaction plane at different time steps in the same reaction as in Fig. 1. Both time-even terms and time-odd terms are included. A similar plot can be found in Ref. [1].

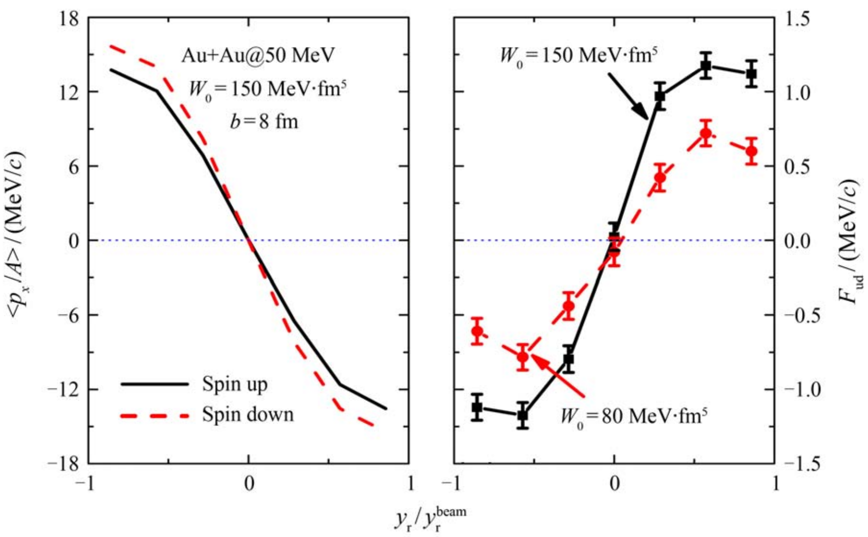

Fig. 4　(color online) Transverse flows of spin-up nucleons and spin-down nucleons (a) as well as spin up-down differential transverse flow with different values of spin-orbit coupling constant (b) in the same reaction as in Fig. 3 with both time-even terms and time-odd terms. A similar plot can be found in Ref. [1].

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flow for nucleons than spin-up ones. With both the time-even and the time-odd terms, the spin up-down differential transverse flow changes sign as shown in the right panel of Fig. 4. Also displayed is the result from a lower limit value of the spin-orbit coupling constant $W_0 = 80$ MeV·fm^5. The spin up-down differential flow is seen to be a sensitive probe of the spin-orbit coupling strength W_0. Although the spin is randomized after each NN scattering and part of the information of the spin-orbit interaction is lost in our transport model calculation, a 47% increase in W_0 still leads to an approximately 40% higher up-down differential flow far beyond the statistical errors.

The spin up-down differential transverse flow defined above may also be used to study the density and isospin dependence of the spin-orbit interaction. It is shown in Panel (a) of Fig. 5 that increasing the γ factor in Eqs. (9) and (10) generally reduces the spin up-down differential flow once the strength of the spin-orbit coupling at the saturation density is fixed. To test the application of our model on studying the isospin dependence of the spin-orbit interaction, we choose two extreme cases of pure like-nucleon coupling and pure unlike-nucleon coupling, corresponding to ($a = 3$, $b = 0$) and ($a = 0$, $b = 3$) in Eqs. (9) and (10), respectively. As the system considered is globally neutron-rich and $\nabla\rho_{\rm n}$ and $\nabla\times\boldsymbol{j}_{\rm n}$ are generally larger than $\nabla\rho_{\rm p}$ and $\nabla\times\boldsymbol{j}_{\rm p}$, respectively, the pure like (unlike)-nucleon coupling leads to an appreciably larger (smaller) spin up-down differential flow for neutrons than for protons. Moreover, the unlike-nucleon coupling generally reduces slightly the overall strength of the spin-related potentials and thus the spin up-down differential flow. Furthermore, we have studied the effects of the possible spin flip in NN scatterings on the spin up-down differential flow by setting spins of nucleons randomized, flipped, and unchanged after each NN scattering. As expected, the spin up-down differential flow becomes weaker with increasing spin-flip probability. However, it is very encouraging to see that the spin up-down differential flow is still considerable even if a 100% spin-flip probability is assumed, further proving the validity of using it as a probe of the spin-orbit coupling.

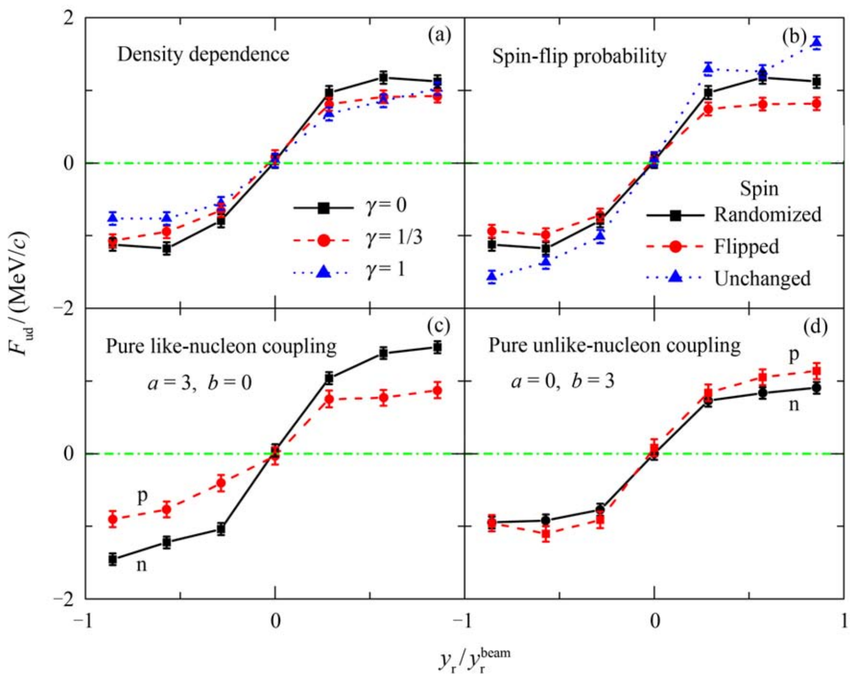

Fig. 5 (color online) Spin up-down differential transverse flows from different spin-orbit interactions, *i.e.*, different density dependences (a), different spin-flip probabilities after NN scatterings (b), pure like-nucleon coupling (c), and pure unlike-nucleon coupling (d) in the same reaction as in Fig. 3 with both time-even terms and time-odd terms. A similar plot can be found in Ref. [1].

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We have further studied the system-size dependence of both the total transverse flow and the spin up-down differential transverse flow, and they are illustrated in Fig. 6 for ^{197}Au+^{197}Au and ^{124}Sn+^{124}Sn collisions at the beam energy of 50 MeV/u. We use a smaller impact parameter for ^{124}Sn+^{124}Sn collisions so that the two colliding systems can be compared at the same centrality. It is found that due to the higher density reached in ^{197}Au+^{197}Au collisions, the interaction is more repulsive and total transverse flow is larger for ^{197}Au+^{197}Au collisions than for ^{124}Sn+^{124}Sn collisions, as shown in Panel (a). On the other hand, because the effect from the spin-orbit interaction is mostly related to the density gradient, which is similar as can be seen from the density profiles, the spin up-down differential transverse flow is only slightly smaller in ^{124}Sn+^{124}Sn collisions, as displayed in Panel (b). This shows that the spin up-down differential transverse flow is a robust probe of the in-medium spin-orbit interaction, as its magnitude is still considerable even in smaller systems.

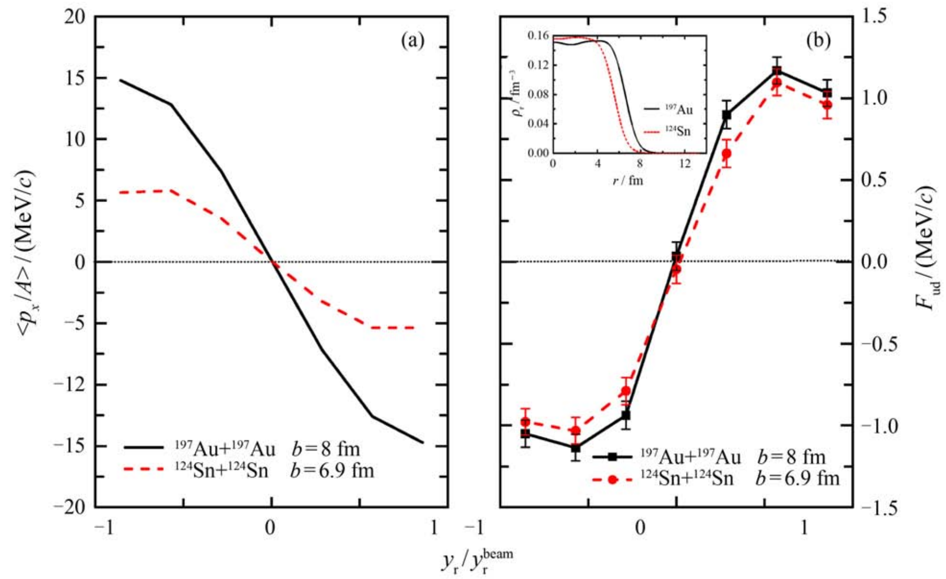

Fig.6 (color online) Total Transverse flow (a) and spin up-down differential transverse flow (b) for ^{197}Au+^{197}Au and ^{124}Sn+^{124}Sn collisions at the beam energy of 50 MeV/u. The density profiles for ^{197}Au and ^{124}Sn are shown in the inset.

5 Summary

We have recently started investigating spin effects in intermediate-energy heavy-ion collision by incorporating the spin-orbit interaction and the spin degree of freedom in the IBUU transport model. It is found that the time-odd contributions from the spin-orbit interaction is important as they help preserve the Galilean invariance and overwhelm the effects from the time-even contributions. The local spin polarization is observed during the collision process, and the spin up-down differential transverse flow is found useful for probing the strength, density dependence, and isospin dependence of the spin-orbit coupling despite the uncertainties of the spin-flip probability after NN scatterings. Besides for Au+Au collisions, the magnitude of the spin up-down differential transverse flow is still considerable in Sn+Sn collisions at the same centrality, indicating that it is a robust probe of the in-medium spin-orbit interaction even at smaller systems.

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中能重离子碰撞中的自旋效应

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摘要： 详细介绍并深化了在IBUU输运模型中引入核子的自旋轨道相互作用及其自旋自由度来研究重离子反应的工作。虽然自旋相关的平均场势中时间反演对称项与时间反演不对称项的贡献相反，但依然观察到体系存在局域自旋极化。发现最终的结果由时间反演不对称项决定，可以利用重离子碰撞中自旋向上核子与自旋向下核子的横向差分流来研究介质中自旋轨道相互作用的性质，包括其强度、密度依赖性和同位旋依赖性，而且即使在小体系下该差分流依然不失为自旋轨道相互作用的良好探针。

关键词： IBUU输运模型；自旋轨道相互作用；重离子碰撞

收稿日期： 2013-09-08； **修改日期：** 2013-10-16

基金项目： 中国科学院百人计划项目(Y290061011)；美国自然科学基金(PHY-0757839和PHY-1068022)，美国科学任务理事会资助的国家航空与空间管理基金(NNX11AC41G)；美国能源部资助的中美合作奇异核物理科研基金(DE-FG02-13ER42025)

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