Monte-Carlo Simulation and Study of Sideward Flow for $^{238}U\,^{238}U$ Collisions at CSR Energy Area*

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Abstract The ART(a Relativistic Transport) Model is applied for studying the UU collisions at a beam kinetic energy about 0.52GeV/nucleon. We discuss the time evolution and the centrality dependence for sideward flow of nucleons and pions at two extreme orientation UU collisions. It is found that the collective (side) flow is developed in the high density region and has a saturation in the expansion phase, so it is a sensitive probe for the reaction dynamics in the high density region. A distinct transition from pion flow to antiflow, which is relative to nucleons flow, occurs at the impact parameters of about 8fm and 2fm in tip-tip and body-body UU collisions, respectively. The pion flow is a result of the competition between the collective flow of baryon resonances and the shadowing of spectators through rescatterings and reabsorptions.

Key words mean field, deformation, transverse flow, shadowing

1 Introduction

The goal of high-energy heavy ion collision program is to identify and study the properties of new form of matter with partonic degrees of freedom[1, 2]. Naturally, the equation of state (EOS) parameters (i.e. density, pressure gradient and temperature) is the key question under study. In recent years the program has focused on high energy region, i.e. the low baryon-density region of the nuclear phase diagram[3]. Several experimental facts like jet-quenching and the Number-of-Constituent-Quark(NCQ) Scaling of elliptic flow[4] have demonstrated that hot and dense matter has been produced in those collisions at RHIC (the Relativistic Heavy Ion Collider)[5].

However, the fact that we have not observed any dramatic changes in these observations reminds us that perhaps we should perform an aim at high baryon density region to 'see' the effect of phase transition. The Heavy Ion Research Facility in Lanzhou (HIRFL)-Cooler Storage Ring (CSR) could make a significant contribution in the partonic matter search.

Prospects for new physics in uranium-on-uranium(UU) collision in CSR energy area due to deformation and orientation effects have aroused much interest from the heavy-ion community[6, 7]. Recently, Heinz and Kuhlman advocated the use of deformed uranium nuclei instead of gold nuclei at RHIC program[8]. Uranium is the most deformed stable nucleus. For ^{238}U, the ratio of the long-axis over short-axis is as large as 1.3[9]. Because of deformation, UU collisions at the same beam energy and impact parameter but different orientations are expected to form dense matter with different compressions and lifetimes. In particular, the large deformation of uranium nuclei makes it possible to increase the particle multiplicity, the reaction time, the central energy the and baryon density by aligning the long axes of the

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two uranium nuclei. This is a powerful tool for studying the physics of high-baryon density and medium effects.

We define the collisions with long axes of two uranium nucleus aligned (plumbed) with the beam as the tip-tip (body-body) configurations (as in Ref. [7]). Other collision orientations are between them as a result of uranium nuclei deformation. In ART[10], the target and projection are respectively fixed at $\frac{b}{2}$ and $-\frac{b}{2}$ of x-axes. The initial momentum of projection is along the positive direction of z-axes.

2 Results and discussions

Collective flow has been shown to be useful for extracting the interesting properties of superdense hadronic matter in high-energy nuclei-nuclei collisions. In particular, the transverse collective action, which does not exist but only has a longitudinal movement in the original collision, can help us understand some details about the reactive dynamics.

We use the effective centrality which is defined with $\tilde{b} = b/b_{\max}$ to replace the impact parameter b. Here $b_{\max}$ is the maximum for minimum bias events, corresponding to the tip-tip and body-body UU collisions are 13fm and 19fm respectively.

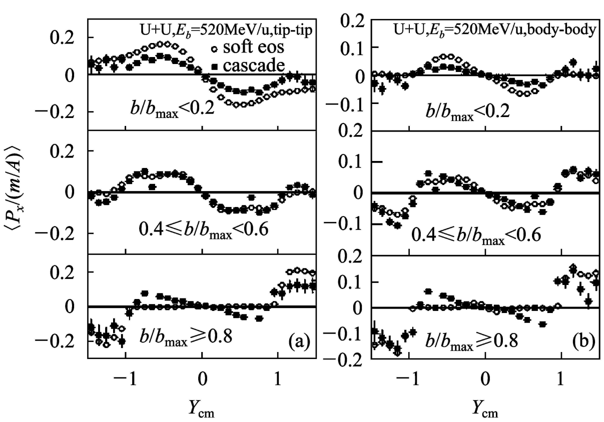

Fig. 1. Baryon average transverse velocity in the reaction plane as a function of rapidity for tip-tip (a) and body-body (b) UU collisions at $E_b = 0.52$GeV/u and at $\tilde{b} < 0.2$ (top window), $0.4 \leqslant \tilde{b} < 0.6$ (middle window) and $\tilde{b} \geqslant 0.8$ (bottom window), respectively.

Here we use the standard flow analysis in transport models as in Ref. [11]. Fig. 1 shows that the baryon average transverse velocity in the reaction plane as a function of rapidity for the tip-tip and body-body UU collisions at $E_b = 0.52$GeV/u and at $\tilde{b} < 0.2$, $0.4 \leqslant \tilde{b} < 0.6$ and $\tilde{b} \geqslant 0.8$, respectively. It is seen that the collective flow is the strongest in about midcentral collisions and significant differences exit between calculations with and without the mean field for both the tip-tip and body-body UU collisions at all three centralities.

Sideward flow is an odd function of the center-of-mass rapidity in symmetric nuclei-nuclei collisions. Therefore it is almost linear near the mid-rapidity. Furthermore, a saturation is observed near the projectional and target rapidities, resulting in a typical S shape[12]. Due to this peculiar dependence, and to acceptance considerations, the flow parameter is defined as

$$F = \left(\frac{\mathrm{d}p_x}{\mathrm{d}y}\right)\Big|_{y_{\mathrm{cm}}=0} . \tag{1}$$

Here, y_{cm} is the rapidity in the center-of-mass frame of reference. Fig. 2 shows the flow parameter as a function of time for tip-tip and body-body UU collisions at $E_{\mathrm{beam}} = 0.52$GeV/u and at the impact parameters of 2fm and 6fm respectively.

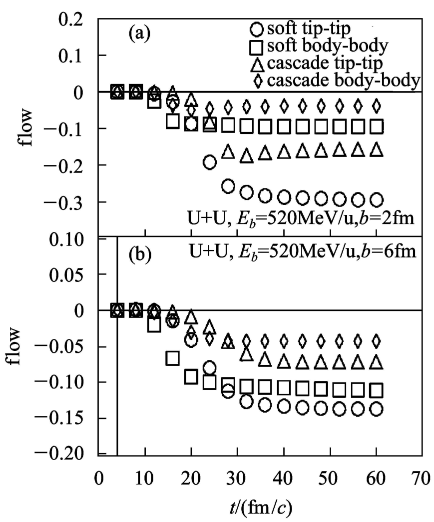

Fig. 2. Time evolution of the flow parameter in the tip-tip and body-body UU collisions at $E_b = 0.52$GeV/u and at the impact parameters of 2fm (a) and 6fm (b), respectively.

Flow has a saturation at the expansion phase (i.e. $t > 30$fm/c). Significant differences exist between calculations with and without the mean field for the tip-tip and body-body collisions. In particular, the flow parameter is about a factor of 2 larger in the case with the mean field because there are more substantial reciprocities in the case with the mean field than in the cascade case. In addition, the flow parameter is about 3 times in the tip-tip than the body-body UU collisions at $b=2$fm, but the ratio is decreased obviously at $b=6$fm. The flow parameter in the final stage is indistinctive nearly for the body-body UU collisions at $b=2$fm and $b=6$fm.

It can be seen from Fig. 1 that the strength of the so-called “bounce-off” effect at target or projectile rapidities is also much stronger in calculations with the mean field. To measure the strength of the “bounce-off” effect, we define the average total in-plane transverse momentum as

$$\langle p_x\rangle=\int_{-2}^{2}|\mathrm{d}p_x/\mathrm{d}y|\mathrm{d}y\ . \tag{2}$$

Here, the integral almost includes the full rapidity space. To see how the collective flow is a sensitive probe of the reaction dynamics for high density matter, we show in Fig. 3 the evolutions of the central baryon density and the total in-plane transverse momentum in the tip-tip and body-body UU collisions at $E_b=0.52$GeV/u and at $b=2$fm.

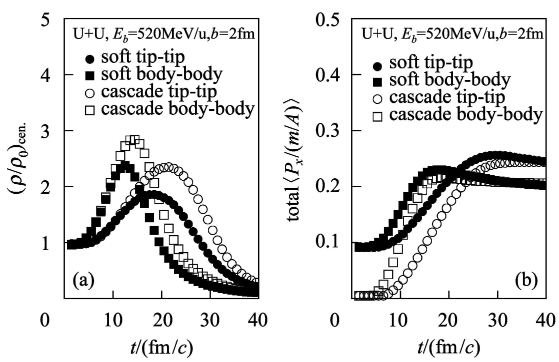

Fig. 3. The evolution of the central baryon density (a) and the total in-plane transverse momentum (b) in the tip-tip and body-body UU collisions at $E_b=0.52$GeV/u and at an impact parameter of 2fm.

It is clearly seen that the flow is mainly generated in high density region and almost does not change in the expansion phase. In the early stage the total in-plane transverse momentum is large in the case with the mean field as a result of the fermi energy. The final flow parameters in the tip-tip collisions is larger than in the body-body at the same impact parameters from different (with and without the mean field) models. This difference is mainly due to more participants of tip-tip than body-body UU collision at both impact parameters. The total in-plane transverse momentum decreases slightly before reaching its final value as a result of the reflection of hot baryons from the cold spectator nucleons.

Shown in Fig. 4 are the average transverse momentums of nucleons and pions as a function of the center-of-mass rapidity in different centralities for the tip-tip and body-body UU collisions, respectively. One can clearly see that the average transverse momentum of pions is much smaller than that of nucleons both in the tip-tip and the body-body UU collisions. However detailed study reveals that the flow direction of nucleons is nearly unchanged but the magnitude of nucleons flow decreases from the center collisions to the peripheral collisions and that pions have a weak flow in the central collisions (with the effective centrality $\tilde{b}<0.2$) and antiflow in the peripheral collisions (with the effective centrality $\tilde{b}>0.8$) with respect to the flow direction of nucleons.

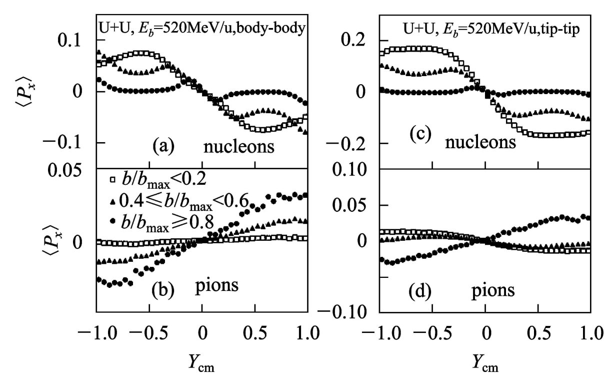

Fig. 4. The average transverse momentums of nucleons (top window) and pions (bottom window) as a function of the center-of-mass rapidity in different centralities for the tip-tip (right window) and body-body (left window) UU collisions at $E_b=0.52$GeV/u and at $\tilde{b}<0.2$, $0.4\leqslant\tilde{b}<0.6$ and $\tilde{b}\geqslant0.8$, respectively.

It is interesting to mention that the transition from pion flow (antiflow) to antiflow (flow) which occurs at an impact parameter of 3fm in Au+Au collisions has been predicted at BEVALAC and/or SIS/GSI energies[13], and confirmed by experiments. It is due to the fact that the direction of pion flow (of the sign of average transverse momenta) is a result of the competition between the collective flow of baryon resonances and the shadowing of spectators through rescatterings and reabsorptions. In the ART model pions are produced either directly from the particle-particle collisions or from the decay of resonances. In the central collisions pions are produced throughout the whole reaction volume, and there is thus little shadowing effect. If the colliding particle pairs or baryon resonances which produce pions have a large flow velocity, then the produced pions would also have a certain flow velocity in the same direction as the nucleons as a result of momentum conservation. However, because of the production kinematics, the pions flow is much reduced. On the other hand, in the peripheral collisions the shadowing effect from the spectators dominates and therefore results in the apparent antiflow of pions in the opposite direction of nucleons flow.

In CSR energy area, it is predicted that there will be a transition at a less impact parameter for the same nuclei-nuclei collisions than in SIS/GSI as a result of lower energy and stronger nuclear stopping. It is demonstrated that the transition from pion flow to antiflow occurs at the impact parameters of 2fm and 8fm in the body-body and tip-tip UU collisions, respectively. Because of the deformation which reduces the bounce-off strength in the body-body UU collisions, the sideward flow of pions and nucleons is smaller than in the tip-tip collisions at the same impact parameter. As a result the transition for flow about impact parameter is unconspicuous in the body-body collisions, or even absent. The larger shadowing effect becomes important for the smaller pions transverse momentum and a transition impact parameter is due to the fact that the spectators fly away with very smaller longitudinal momentum in these reactions and thus have more effects on pions from the participant region as compared with the heavy ion collisions at SIS/GSI energies.

For more clearly demonstrating the above explanation, Fig. 5 shows the center-of-mass rapidity dependence of the average transverse momentum in the reaction plane from free pions and bound pions from the decay of baryon resonances which are still present at 100fm/c in different centralities.

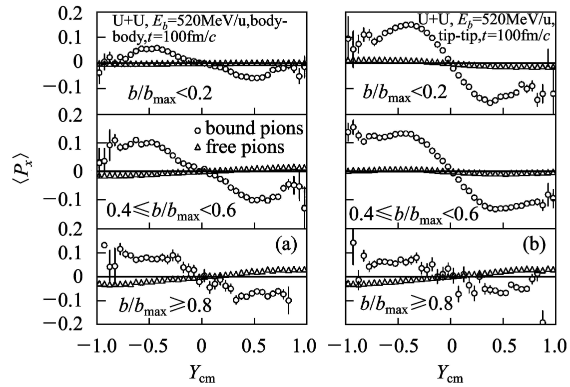

Fig. 5. The average transverse momentums of bound and free pions in the reaction plane as a function of the center-of-mass rapidity for the tip-tip and body-body UU collisions at $E_b = 0.52$GeV/u and at $\tilde{b} < 0.2$, $0.4 \leqslant \tilde{b} < 0.6$ and $\tilde{b} \geqslant 0.8$, respectively.

From Fig. 5, it is seen that the bound pions have a typical S-shaped transverse momentum distribution similar to those for nucleons in both the central and peripheral collisions. The flow behavior of bound pions is due to the colletive flow of baryon resonances from which they are produced. However, free pions which are produced earlier either directly from the particle-particle collisions or from the decays of resonances have generally gone through several annihilation-production cycles which can destroy their collectivity, and more importantly they also have more chances to be rescattered by the spectators. In the central collisions free pions show less collectivity than bound pions, but they still have flow in the same direction as nuclons. However, in the peripheral collisions free pions show a distinct antiflow behavior due to the shadowing of spectators. The final pion transverse momentum distribution in the reaction plane reflects the complicated reaction dynamics of pion production, reabsorption and rescattering.

3 Summary

We employ the ART (a Relativistic Transport) Model for simulating and studying the UU collisions at $E_b = 0.52$GeV/u. Based on the standard flow analysis, the time evolution and the centrality dependence for sideward flow of nucleons and pions at two extreme orientation UU collisions are studied. It indicats that the collective flow is developed in the high density region and has a saturation in the expansion phase. A distinct transition from pion flow to antiflow, which is relative to nucleons flow, occurs at the impact parameters of about 8fm and 2fm in the tip-tip and body-body UU collisions, respectively. The pion flow is a result of the competition between the collective flow of baryon resonances and the shadowing of spectators through rescatterings and reabsorptions. The study of pion (anti) flow may reveal interesting information about the in-medium cross sections of elementary processes involving pions and baryon resonances.

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CSR能区UU碰撞侧向流蒙特卡罗模拟与研究*

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摘要 应用ART模型研究了E_b=520MeV/u的UU碰撞. 探讨了在两种极端方位UU碰撞下, 核子和π在反应平面内的横向流的时间演化以及对碰撞中心度的依赖关系. 研究表明, 流在高密区域发展并且在膨胀相稳定, 因而它是高密区域反应动力学的一个敏感探针. 对头头和体体UU碰撞, 末态π相对于核子的横向流分别在大约$b=9$fm和$b=2$fm处存在明显的正向到负向的改变. π的这种行为是重子共振态和旁观者的遮蔽效应(再散射和再吸收)共同作用的结果.

关键词 平均场 形变 横向流 遮蔽

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