Novel Rapidity Dependence of Directed Flow in High-Energy Heavy-Ion Collisions

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For high-energy nucleus-nucleus collisions, we show that a combination of space-momentum correlations characteristic of radial expansion, together with the correlation between the position of a nucleon in the nucleus and its stopping, results in a very specific rapidity dependence of directed flow: a reversal of sign in the midrapidity region. We support our argument by RQMD model calculations for Au + Au collisions at $\sqrt{s} = 200A$ GeV.

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The study of anisotropic flow in high-energy nuclear collisions has attracted increasing attention from both experimentalists and theorists [1–4]. The rich physics of directed and elliptical flows [5–13] is due to their sensitivity to the system evolution at early time. Anisotropic flow in general is also sensitive to the equation of state [1,10] which governs the evolution of the system created in the nuclear collision.

The collective expansion of the system created during a heavy-ion collision implies space-momentum correlation in particle distributions at freeze-out. Simplified, this means that particles created on the left side of the system move in the left direction and particles created on the right side move in the right direction (on average). We will show that the rapidity dependence of directed flow of nucleons and pions can address this space-momentum correlation experimentally.

A sketch of a medium central symmetric heavy-ion collision is shown in Fig. 1, from before the collision [(a) and (b)] to the resulting distributions of $\langle x \rangle$ and $\langle p_x \rangle$ shown in (d). In Fig. 1(a) the projectile and target are shown before the collision in coordinate space. In Fig. 1(b) the overlap region is magnified and the "spectators" are not shown. It shows in a schematic way the number of nucleons and their position in the x-z plane (where $\hat{\mathbf{x}}$ is the impact parameter direction). Projectile nucleons (light color) at negative x suffer more rapidity loss than those at positive x, ending up closer to midrapidity. Assuming a positive space-momentum correlation [as indicated in Fig. 1(c)], these nucleons have negative $\langle p_x \rangle$, while those at positive x have positive $\langle p_x \rangle$. This results in a wiggle structure in the rapidity dependencies of $\langle x \rangle$ and $\langle p_x \rangle$ which is shown schematically in Fig. 1(d).

The shape of the wiggle, both the magnitude of $\langle p_x \rangle$ and the rapidity range, depends on the strength of the space-momentum correlation, the initial beam-target rapidity gap, and the amount of stopping. Therefore, the dependence of the wiggle on the collision centrality, system size, and center-of-mass energy may reveal important information on the relation between radial flow and baryon stopping. In addition, it has been shown that the magnitude of $\langle p_x \rangle$ depends on the nuclear matter equation of state [14].

The above picture changes for collisions at lower energies, where there is no clear rapidity separation between projectile and target nucleons at freeze-out, because nucleons cross over midrapidity. Moreover, when the time for the nuclei to pass each other becomes long relative to the characteristic time scale for particle production, the interactions between particles and spectators (so-called shadowing) become important. This has been pointed out by many people, most recently in [8,15,16]. This is consistent with the results of heavy-ion collisions, in the $2-158A$ GeV energy range, where the experimental observed slope around midrapidity in directed flow shows a trend from a positive value at $2A$ GeV [3] to almost zero at $158A$ GeV [4].

Note that the change of sign of directed flow at midrapidity has been discussed for Ca + Ca collisions at $350A$ MeV [17] and for Au + Au collisions at $11A$ GeV [11,12,18]. However, the physical origins on which

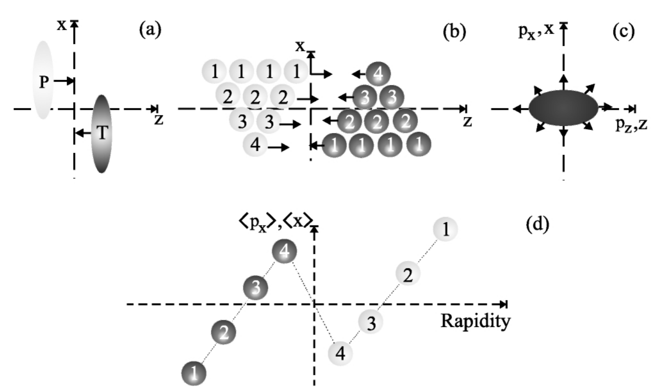

FIG. 1. A schematic sketch of a medium central symmetric heavy-ion collision in progressing time (a),(c) and the rapidity distribution of $\langle p_x \rangle$ and $\langle x \rangle$ in (d). In (b) the overlap region is magnified and the spectators are not shown. In these figures, x is the coordinate along the impact parameter direction and z is the coordinate along the projectile direction (for a more detailed description see text).

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these predictions are based are different from what we discuss in this Letter. In 350A MeV Ca + Ca collisions the wiggle originates from a combination of repulsive nucleon-nucleon collisions and an attractive mean field. The repulsive nucleon-nucleon collisions dominate at the midrapidity region and lead to a positive slope for $\langle p_x \rangle$ versus rapidity. The attractive mean field dominates at beam and target rapidities and leads to a negative slope. In 11A GeV Au + Au collisions the wiggle is caused by the longitudinal hydrodynamic expansion of a tilted source [11]. It has been noticed that in hydro calculations the wiggle only appeared if a quark gluon plasma (QGP) equation of state is used. The QGP equation of state is a prerequisite to reach the stopping needed to create this tilted source. The predicted wiggle in this Letter does not assume a QGP equation of state. The other main difference is that in our prediction we specifically assume incomplete stopping.

The arguments used in this Letter which lead to a change of sign of directed flow at midrapidity are valid on general grounds. However, to test the picture quantitatively we study Au + Au collisions at $\sqrt{s} = 200A$ GeV in an impact parameter range $b = 5-10$ fm, using the relativistic quantum molecular dynamics (RQMD V2.4) model in cascade mode [19].

To characterize directed flow, we use the first Fourier coefficient v_1 [4,20] of the particle azimuthal distribution. At a given rapidity and transverse momentum the coefficient is determined by $v_1 = \langle \cos\phi \rangle$, where ϕ is the azimuthal angle of a particle relative to the reaction plane angle ($\hat{\mathbf{x}}$ direction in Fig. 1). Similarly, a Fourier coefficient can be determined in coordinate space, $s_1 = \langle \cos\phi_s \rangle$ [16], where ϕ_s is the azimuthal angle of a particle, determined from the freeze-out coordinates x and y, relative to the reaction plane angle. Figure 2 shows the RQMD calculations of v_1 and s_1 for nucleons and pions in Au + Au collisions at RHIC energy. Indeed, the shape at midrapidity for nucleons is consistent with the picture described above: both v_1 and s_1 show a negative slope at midrapidity. For larger rapidities the s_1 values leave the ordinate scale.

Pions are produced particles and their space-rapidity correlation is different from that of nucleons shown in Fig. 1(d). Because of the asymmetry in the numbers of colliding target and projectile nucleons, the pions produced at positive x shift toward positive rapidity. The pions produced at negative x shift toward negative rapidity. This results in a positive space-rapidity correlation without a wiggle [see Fig. 2(b) (open circles)]. Because of the space-momentum correlation, the momentum distribution tends to follow the space distribution. This leads to the positive slope of v_1 at midrapidity for the pions [see Fig. 2(b) (filled circles)]. However, shadowing by nucleons is also important in the formation of pion directed flow. The contribution is relatively small in the midrapidity region, where in high-energy nucleus-nucleus collisions the

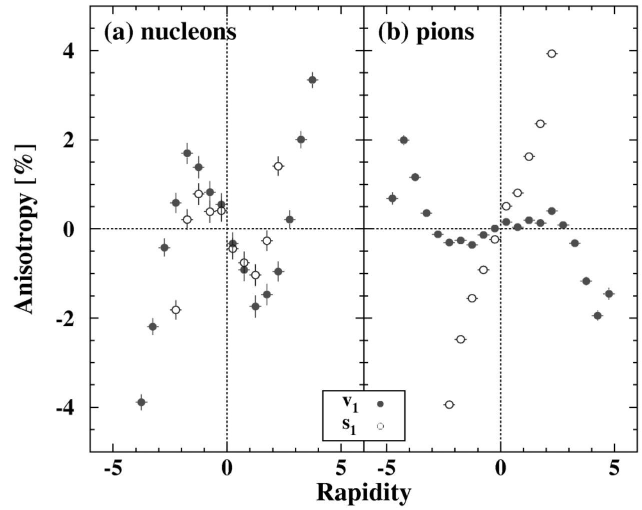

FIG. 2. RQMD calculations of v_1 (filled circles) and s_1 (open circles) for (a) nucleons and (b) pions.

nucleon-to-pion ratio is small. At beam-target rapidity the shadowing becomes dominant, this explains why s_1 has the opposite sign from v_1 for pions close to beam-target rapidity.

In this Letter we have shown that the combination of space-momentum correlations characteristic of radial expansion, together with the correlation between the position of a nucleon in the nucleus and its stopping, results in a wiggle in the rapidity dependence of directed flow in high-energy nucleus-nucleus collisions. Moreover, the amount of stopping and the space-momentum correlation depend on the equation of state, and this affects the strength of the wiggle around midrapidity [14]. Finally, because the wiggle appears at midrapidity, it is accessible by the current SPS experiment NA49 and the near future RHIC experiments. The study of its dependence on collision centrality, system size, and the center-of-mass energy may reveal important information on the relation between collective radial flow and baryon stopping.

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