

Uranium on uranium collisions at relativistic energies

Bao-An Li*

Department of Chemistry and Physics, Arkansas State University, P.O. Box 419, Jonesboro, Arkansas 72467-0419

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Deformation and orientation effects on compression, elliptic flow, and particle production in uranium on uranium collisions (UU) at relativistic energies are studied within the transport model ART. The density compression in tip-tip UU collisions is found to be about 30% higher and lasts approximately 50% longer than in body-body or spherical UU reactions. The body-body UU collisions have the unique feature that the nucleon elliptic flow is the highest in the most central collisions and remains a constant throughout the reaction. We point out that the tip-tip UU collisions are more probable to create the quark gluon plasma (QGP) at Alternating Gradient Synchrotron and Super Proton Synchrotron energies, while the body-body UU collisions are more useful for studying properties of the QGP at higher energies.

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To better understand the J/ψ suppression mechanism in ultrarelativistic heavy-ion collisions, uranium on uranium (UU) collisions has been proposed recently to extend beyond Pb+Pb collisions at the CERN Super Proton Synchrotron (SPS) [1–4]. Many other outstanding issues regarding the corrections to hard processes, the relation between elliptic flow and equation of state, as well as the study of the QCD tricritical point may also be resolved by studying deformation and orientation effects in UU collisions at relativistic energies [4,5]. One of the most critical factors to all of these issues is the maximum achievable energy density in UU collisions. Because of the 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 deformation of uranium nuclei lets one gain particle multiplicity and energy density by aligning the two nuclei with their long axes head-on (tip-tip). Based on a schematic mass scaling of the energy density in relativistic heavy-ion collisions [7], Braun-Munzinger found a factor of 1.8 gain in energy density in the tip-tip UU collisions compared to the central Au+Au reactions [6]. More recently, Shuryak reestimated this factor and found it is about 1.3 using particle production systematics and geometrical considerations of relativistic heavy-ion collisions [4,5]. Using a simple Monte-Carlo model, Shuryak has also demonstrated that the orientation and the impact parameter between the two colliding uranium nuclei can be determined simultaneously using the experimentally accessible criteria [4,5]. Given the exciting new physics opportunities with UU collisions and the obvious discrepancy in the estimated gain of energy density, more quantitative studies with more realistic models are necessary. In this Rapid Communication, we report results of such a study. Besides a critical examination of the achievable density compression, we also study the nucleon elliptic flow and particle production in UU collisions with different orientations.

Our study is based on the relativistic transport model ART for heavy ion collisions. We refer the reader to Ref. [8] for details of the model and its applications in studying various aspects of relativistic heavy-ion collisions at beam ener-

gies from 1 to 20 GeV/nucleon. Uranium is approximately an ellipsoid with a long and short semiaxis

$$R_l = R \cdot \left(1 + \frac{2}{3} \delta \right) \quad (1)$$

and

$$R_s = R \cdot \left(1 - \frac{1}{3} \delta \right), \quad (2)$$

where R is the equivalent spherical radius and δ is the deformation parameter. For ^{238}U , one has $\delta=0.27$ and thus a long/short axis ratio of about 1.3 [9].

We have performed a systematic study of UU collisions at beam energies from 1 to 20 GeV/nucleon. We found similar deformation/orientation effects in the whole energy range studied. Typical results at beam energies of 10 and 20 GeV/nucleon will be presented in the following. Among all possible orientations between two colliding uranium nuclei, the tip-tip (with long axes head-on) and body-body (with short axes head-on and long axes parallel) collisions are the most interesting ones [1,5,6]. Shown in Fig. 1 are the evolution of central baryon densities in the UU collisions at a beam energy of 20 GeV/nucleon and an impact parameter of 0 and 6 fm, respectively. In these calculations the cascade mode of the ART model is used. For comparison we have also included results for collisions between two gold or spherical uranium nuclei. Indeed, it is interesting to notice that the tip-tip UU collisions not only lead to higher compressions but also longer reaction times. The body-body UU collisions lead to density compressions comparable to those reached in the Au-Au and spherical UU collisions. More quantitatively, a 30% more compression is obtained in the tip-tip UU collisions at both impact parameters. The high density phase (i.e., with $\rho/\rho_0 \geq 5$) in the tip-tip collisions lasts about 3–5 fm/c longer than the body-body collisions. We have seen the same deformation and orientation effects in the total energy density which also include the newly produced particles. The higher compression and longer passage time render the tip-tip UU collisions the most probable candidates to form the quark gluon plasma (QGP) at beam energies that are not very high, such as those currently available at the BNL Alternating Gradient Synchrotron (AGS) and CERN SPS.

*Electronic address: Bali@navajo.astate.edu

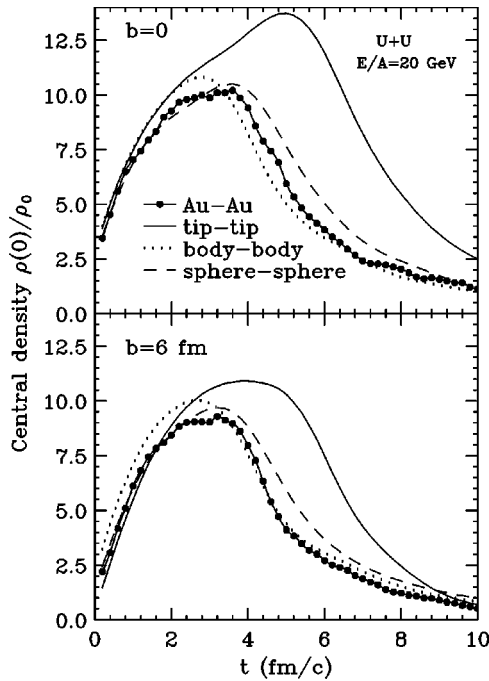


FIG. 1. The evolution of central baryon density in Au-Au (filled circles), tip-tip (solid line), body-body (dotted line), and sphere-sphere (dashed line) UU collisions at a beam energy of 20 GeV/nucleon and an impact parameter of 0 (upper panel) and 6 fm (lower panel), respectively.

At BNL Relativistic Heavy Ion Collider (RHIC) and CERN Large Hadron Collider (LHC) energies, the energy densities in colliding spherical heavy nuclei (e.g., Au and Pb) are already far above the predicted QCD phase transition density. A 30% increase in energy density due to deformation is probably not as critical as in fixed-target experiments at lower beam energies. A more important issue is how to detect signatures of the QGP and extract its properties. How the deformation of uranium nuclei may help to address this issue? To answer this question we have studied the nucleon elliptic flow in UU collisions with different orientations. Although our studies are only performed in the beam energy range of 1–20 GeV/nucleon, the deformation and orientation effects are found to be rather energy independent. Our results thus may have useful implications to heavy-ion collisions at even higher energies. The elliptic flow reflects the anisotropy in the particle transverse momentum (p_t) distribution at midrapidity, i.e.,

$$v_2 = \langle (p_x^2 - p_y^2) / p_t^2 \rangle, \quad (3)$$

where $p_x(p_y)$ is the transverse momentum in (perpendicular to) the reaction plane and the average is taken over all particles in all events [10–12]. The v_2 results from a competition between the “squeeze-out” perpendicular to the reaction plane and the “in-plane flow.” It has been shown recently in many studies that the elliptic flow is particularly sensitive to the equation of state of dense matter [13–21]. Thus, the analysis of v_2 is one of the most promising tools for detecting signatures of the QGP and extracting its properties [22–27].

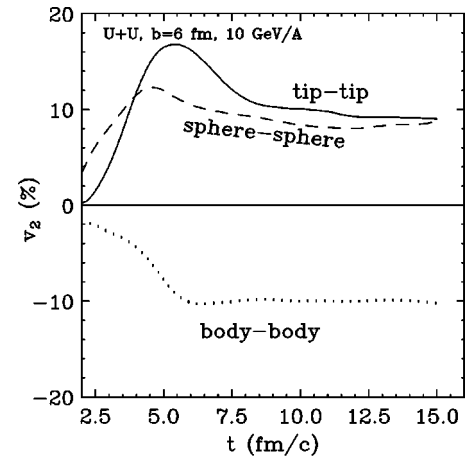


FIG. 2. The nucleon evolution of elliptic flow in the UU collisions at a beam energy of 10 GeV/nucleon and an impact parameter of 6 fm.

Shown in Fig. 2 are the evolution of the nucleon elliptic flow in UU collisions with different orientations at a beam energy of 10 GeV/nucleon and an impact parameter of 6 fm. We initialized the two uranium nuclei such that their long axes are in the reaction plane in both tip-tip and body-body collisions. It is seen that both the tip-tip and sphere-sphere collisions lead to a strong “in-plane flow” (positive v_2) while the body-body reactions result in a large “squeeze-out” (negative v_2). The tip-tip and sphere-sphere collisions cannot sustain the higher v_2 created around the maximum compression. This is due to the strong subsequent competition between the “in-plane flow” and “squeeze-out” of baryons. For the body-body collisions the “squeeze-out” phenomenon dominates throughout the whole reaction because of the strong shadowing of matter in the reaction plane. The v_2 in body-body UU collisions can therefore sustain its early value. The elliptic flow in body-body UU collisions is therefore a better probe of the high density phase. This point is seen more clearly in the impact parameter dependence of the elliptic flow as shown in Fig. 3. Unique to the body-body UU collisions, the strength of elliptic flow is the highest in the most central collisions where the shadowing effect in the reaction plane is the strongest. While in tip-tip and sphere-sphere UU collisions the elliptic flow vanishes in the most central collisions due to symmetry. Therefore, the “squeeze-out” of particles including newly created ones perpendicular to the reaction plane in very central body-body UU collisions can provide direct information about the dense matter formed in the reaction. This is clearly an advantage of using the body-body collisions over the tip-tip collisions. Of course, at collider energies it is more important to study the elliptical flow at midrapidity for newly produced particles, such as pions which are even more sensitive to the nuclear shadowing effects [28,29,16].

It is also of considerable interest to study deformation and orientation effects on particle production. Shown in Fig. 4 are the multiplicities of pions and positive kaons as a function of impact parameter. The maximum impact parameter for the tip-tip and body-body UU collisions are $2R_s$ and $2R_l$, respectively. As one expects, the central (with $b \leq 5$

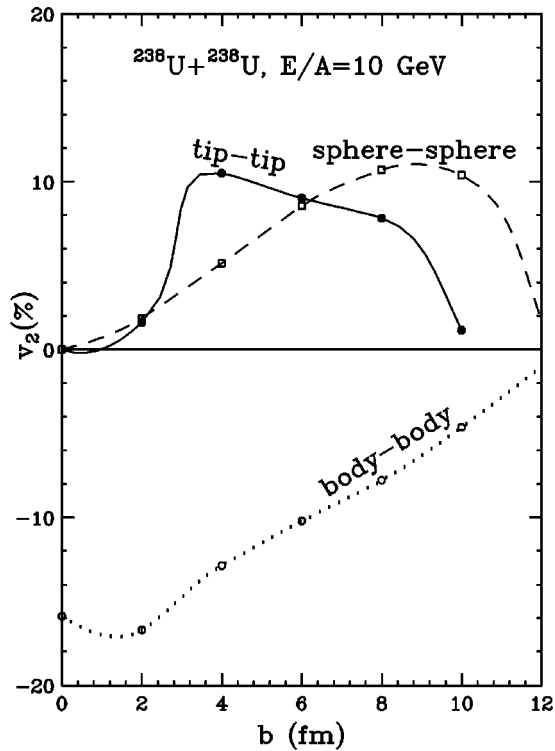


FIG. 3. The impact parameter dependence of nucleon elliptic flow in the tip-tip (solid line), body-body (dotted line), and sphere-sphere (dashed line) UU collisions at a beam energy of 10 GeV/nucleon.

fm) tip-tip UU collisions produce more particles due to the higher compression and the longer passage time of the reaction. At larger impact parameters, the smaller overlap volume in the tip-tip collisions leads to less particle production than the body-body and sphere-sphere reactions. Also as one expects from the reaction geometry, the multiplicities in the body-body collisions approach those in the sphere-sphere collisions as the impact parameter reaches zero. In the most central collisions, the tip-tip UU collisions produce about 15% (40%) more pions (positive kaons) than the body-body and sphere-sphere UU collisions. These deformation and orientation effects on particle production are consistent with those on density compression shown in Fig. 1. Compared to pions, kaons are more sensitive to the density compression since most of them are produced from second chance particle (resonance)-particle (resonance) scatterings at the energies studied here [30].

In summary, using the ART model we have studied the deformation and orientation effects on the compression, elliptic flow, and particle production in uranium on uranium (UU) collisions at relativistic energies. The compression in the tip-tip UU collisions is about 30% higher and lasts ap-

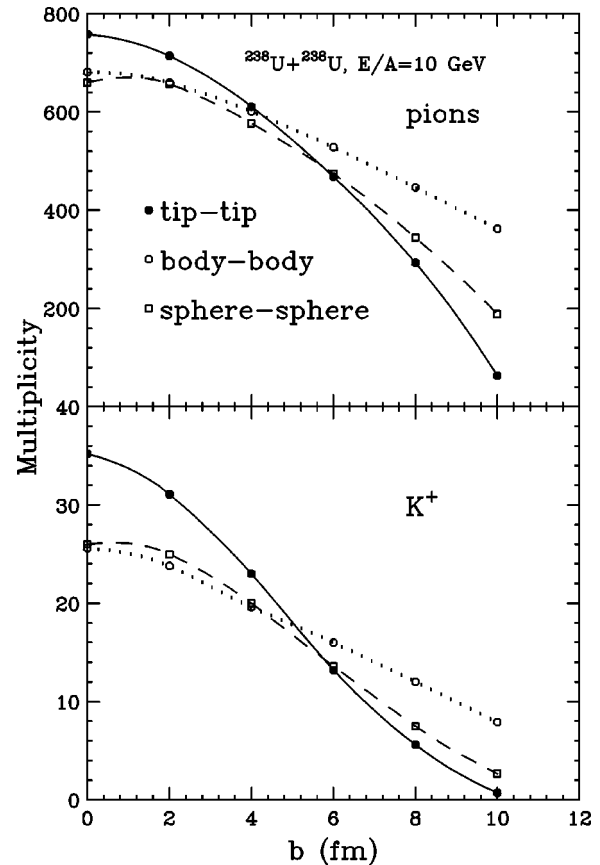


FIG. 4. The impact parameter dependence of pion (upper panel) and positive kaon (lower panel) production in the tip-tip (solid line), body-body (dotted line), and sphere-sphere (dashed line) UU collisions at a beam energy of 10 GeV/nucleon.

proximately 50% longer than in the body-body or spherical UU collisions. Moreover, we found that the nucleon elliptic flow in the body-body UU collisions have some unique features. We have pointed out that the tip-tip UU collisions are more probable to create the QGP at the BNL AGS and CERN SPS energies. While at BNL RHIC and CERN LHC energies, the ‘‘squeeze-out’’ of particles in the central body-body collisions is more useful for studying properties of the QGP.

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