Stopping effects in U+U collisions with a beam energy of 520 MeV/nucleon

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A Relativistic Transport Model (ART1.0) is applied to simulate the stopping effects in tip-tip and body-body U+U collisions, at a beam kinetic energy of 520 MeV/nucleon. Our simulation results have demonstrated that both central collisions of the two extreme orientations can achieve full stopping, and also form a bulk of hot, dense nuclear matter with a sufficiently large volume and long duration, due to the largely deformed uranium nuclei. The nucleon sideward flow in the tip-tip collisions is nearly 3 times larger than that in body-body ones at normalized impact parameter b/b_{max} < 0.5, and that the body-body central collisions have a largest negative nucleon elliptic flow v_{2} = −12% in contrast to zero in tip-tip ones. Thus the extreme circumstance and the novel experimental observables in tip-tip and body-body collisions can provide a good condition and sensitive probe to study the nuclear EoS, respectively. The Cooling Storage Ring (CSR) External Target Facility (ETF) to be built at Lanzhou, China, delivering the uranium beam up to 520 MeV/nucleon is expected to make significant contribution to explore the nuclear equation of state (EoS).

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I. INTRODUCTION

In recent years, the ultra-relativistic high energy heavy ion collisions performed at SPS/CERN and RHIC/BNL (√s_{NN} ∼ 10 − 200 GeV) focus on high temperature and low baryon density region in nuclear matter phase diagram to search a new form of matter with partonic degree of freedom-the quark-gluon plasma (QGP) [2, 3, 4, 5]. However, no dramatic changes of experimental observables, such as jet-quenching, elliptic flow and strangeness enhancement, have been observed yet [6]. On the other hand, the heavy ion collisions performed at the BEVALAC/LBNL and SIS/GSI in last two decades were used to produce hot and compressed nuclear matter to learn more about the nuclear equation of state (EoS) [13, 14] at high baryon density and low temperature region of the phase diagram. Although we have made great efforts to study the nuclear EoS, theoretically and experimentally, a solid conclusion can hardly be made. Then, it is still worthwhile to systematically study on the collision dynamics as well as the EoS observables. Recently, for more understanding of the nuclear matter phase diagram and EoS at high net-baryon density region, it is proposed to collide uranium on uranium target at External Target Facility (ETF) of Cooling Storage Ring (CSR) at Lanzhou, China with a beam kinetic energy of 520 MeV/nucleon. [10].

Uranium is the largest deformed stable nucleus, and has approximately an ellipsoid shape with the long and short semi-axis given by R_l = R_0(1 + 2δ/3) and R_s = R_0(1 − δ/3), respectively, where R_0 = 7 fm is the effective spherical radius and δ = 0.27 is the deformation parameter. Consequently, one has R_l/R_s = 1.3. In our simulation, we consider two extreme orientations: the so-called tip-tip and body-body patterns with the long and short axes of two nuclei are aligned to the beam direction, respectively [12], see Fig. 1 for illustration. The two types of orientations can be identified in random orientations of U+U collisions by making proper cutoffs in experimental data, such as the particle multiplicities, elliptic flow and so on [10, 11]. With the two extreme collision orientations, some novel stopping effects which are believed responsible for some significant experimental observables, such as particle production, collective motion as well as attainable central densities, can be obtained. Due to the large deformation of the uranium nuclei [11, 12], it is expected that the tip-tip collisions can form a higher densities nuclear matter with longer duration than in body-body or the spherical nuclei collisions, which is considered to be a powerful tool to study

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the nuclear matter phase transition at high baryon density \[12\], and the body-body central collisions may reveal a largest out-of-plane elliptic flow (negative \(v_2\)) at high densities, which can be a sensitive probe to extract the early EoS of the hot, dense nuclear matter \[12\,\[17\]. The novel experimental observables can be effectively utilized to study the possible nuclear matter phase transition and the nuclear EoS \[12\,\[13\,\[14\,\[15\,\[16\,\[17\,\[18\,\[19\,\[20\]. For comparing with tip-tip and body-body collisions, a type of gedanken “sphere-sphere” collisions without deformations of uranium nuclei are also included in the simulation.

The ART1.0 model \[21\,\[22\] derived from Boltzmann-Uehling-Uhlenbeck (BUU) model \[23\] has a better treatment of mean field and Pauli-Blocking effects \[23\] than cascade models \[24\]. The fragments production mechanism and partonic degree of freedom are not present in the ART1.0 model. A soft EoS with compressibility coefficient \(K = 200\,\text{MeV}\) is used throughout the simulation and the beam kinetic energy of uranium nuclei is set to 520 MeV/nucleon if not specifically indicated. In the next section, we discuss about the stopping power ratio and selection of impact parameter \(b\). In Sec. 3, the evolution of baryon and energy densities as well as thermalization of central collision systems are studied. In Sec. 4, some experimental observables, such as nucleon sideward flow and elliptic flow are also investigated. We summarize our results in Sec. 5.

II. STOPPING POWER OF TIP-TIP AND BODY-BODY COLLISIONS

Large stopping power can lead to remarkable pressure gradient in the compressed dense matter. It is generally also considered to be responsible for transverse collective motion \[22\], the maximum attainable baryon and energy densities as well as thermalization of collision systems. Thus, the study of the stopping power in U+U collisions may provide important information for understanding the nuclear EoS and collision dynamics.

A. Selection of impact parameter

The nuclear stopping power and geometric effects in U+U collisions rely strongly on the impact parameter \(b\). Considering the conceptual design of the CSR-ETF detector \[10\], two methods are invoked here to estimate the impact parameter. The first one is the multiplicity of forward neutrons with polar angle \(\theta < 20^\circ\) in the lab frame which can be covered by a forward neutron wall. The other method is to make use of the parameter \(E_{\text{rat}}\) \[26\], which is the ratio of the total transverse kinetic energy to the total longitudinal one. The particles are also required to be within \(\theta < 20^\circ\) in the lab frame, while the two qualities are calculated within the center of mass system (c.m.s.).

\[
E_{\text{rat}} = \frac{\sum_i E_{t_i}}{\sum_i E_{z_i}}
\]

The normalized impact parameter \(b/b_{\text{max}}\) is used to represent centralities of tip-tip and body-body collisions and the \(b_{\text{max}}\) of the two cases are quite different from each other. As shown in Fig. 2 with either method, obvious linear dependence of the normalized impact parameter are demonstrated in both tip-tip and body-body near central collisions. Then, the two methods can be combined to determine the impact parameter to identify the most central collision events in both tip-tip and body-body collisions.

B. Stopping power ratio definition and evolution

It is difficult to obtain a universally accepted estimate of the nuclear stopping power in heavy ion collisions due to a proliferation of definitions of the concept \[27\]. The stopping power ratio \(R\) \[28\] is employed to measure the degree of stopping and defined as:

\[
R = \frac{2}{\pi} \sum_j |P_{t_j}|/\sum_j |P_{z_j}|
\]

, the total nucleon transverse momentum \(|P_{t_j}|\) divided by the total absolute value of nucleon longitudinal momentum \(|P_{z_j}|\) in the c.m.s.. The ratio is wildly used to describe the degree of thermalization and nuclear stopping by low and intermediate energies heavy ion collisions. It’s a multi-particle observable on an event-by-event basis, which for an isotropic distribution is unity.

Fig. 3 shows the time and normalized impact parameter dependence of the stopping ratio \(R\) for three conditions: tip-tip, body-body and sphere-sphere collisions.
FIG. 3: (Color online) (a) The time evolution of the stopping ratio $R$ in tip-tip, body-body and sphere-sphere central collisions, and (b) the stopping ratio $R$ as a function of $b/b_{\text{max}}$ in minimum biased collisions.

When the ratio $R$ reaches the value of 1, full stopping of the collision system is considered to be achieved, and the momenta is also isotropy, which are not sufficient but necessary for thermal equilibrium of collision systems [28]. For $R > 1$, it can be explained by preponderance of momentum flow perpendicular to the beam direction [29]. It is shown that all of the three conditions can achieve full stopping when the stopping ratio $R=1$, the corresponding time for body-body and tip-tip central collisions are about 15 fm/c and 25 fm/c, respectively. Larger stopping ratio and faster evolution to full stopping are observed for body-body central collisions than tip-tip and sphere-sphere ones at the early stage, which may indicate a more violent colliding process for body-body central collisions due to the sizable initial transverse overlap region. Although the stopping ratio of tip-tip central collisions is lowest than the other two cases at the early time, it raises sharply later and even exceeding one. So, it means that longer reaction and passage time can be obtained in tip-tip central collisions than body-body and sphere-sphere ones, which may indicate the nucleons in tip-tip collisions can undergo more binary collisions to reach higher transverse momentum.

In Fig. 3(b), the $R$ of the three conditions are gradually decrease with the increase of the normalized impact parameter. When $b/b_{\text{max}} < 0.5$, the ratio is always larger for tip-tip collisions than the other two cases, while for $b/b_{\text{max}} > 0.5$ all of the three conditions almost have the same stopping power ratio.

III. BARYON, ENERGY DENSITY AND THERMAL EQUILIBRIUM

Considering the discrepancy of stopping power between tip-tip and body-body collisions, it is interesting to study further about the baryon and energy densities evolution in both cases. As the full stopping and deformation effects in U+U collisions, it is believed higher local baryon and energy densities system with long duration can be created, which is considered to be a significant condition to study the nuclear EoS at high baryonic density region.

A. The evolution of baryon and energy densities

The evolution of baryon and energy densities in the central zone of tip-tip and body-body as well as Au+Au central collisions are illustrated in Fig. 4.

In Fig. 4, it is observed the maximum attainable baryon and energy densities for both tip-tip and body-body central collisions are about $3.2 \rho_0$ and 0.8 GeV/fm$^3$, respectively, while the Au+Au one are about $2.6 \rho_0$ and 0.6 GeV/fm$^3$. Both the baryon and energy densities in U+U collisions are higher than the Au+Au one. Once a baryon density threshold of $\rho > 2.5 \rho_0$ is required, the corresponding duration in tip-tip central collisions $\sim 20$ fm/c (from $\sim 8$ fm/c to $\sim 28$ fm/c) is longer than $\sim 10$ fm/c (from $\sim 8$ fm/c to $\sim 18$ fm/c) of body-body one, which is as predicted. But the peak densities have no significant discrepancy between the two cases unlike those at the energy region of the Alternating Gradient Synchrotron (AGS) [12], which may be attribute to the full stopping at the CSR energy.

B. Thermalization of the U+U collision systems

As mentioned before, the stopping ratio $R = 1$ is a necessary but not sufficient condition for thermal equilibrium of the collision system. In order to approach a thermal equilibrium, a long duration of reaction is needed for nucleons to undergo sufficient binary collisions. As
shown in Fig. 3(a), obvious long duration has been obtained in both tip-tip and body-body central collisions. It is therefore possible thermal equilibrium at the time of freeze-out can be achieved.

The Fig. 3(a) is the evolution of the volume with the high baryon density ($\rho > 2.5 \rho_0$) for tip-tip, body-body and Au+Au central collisions, respectively. Both tip-tip and body-body central collisions have larger volumes than Au+Au one at the same beam kinetic energy 520 MeV/nucleon. Although the maximum volume attainable for body-body central collisions ($\sim 220 \text{fm}^3$) is about two times larger than tip-tip one ($\sim 120 \text{fm}^3$), the peak volume of tip-tip central collisions lasts a much longer time of $\sim 10 \text{fm/c}$ (from $\sim 15 \text{fm/c}$ to $\sim 25 \text{fm/c}$) and much more stable than body-body one. To estimate the temperature at the freeze-out time, the scaled mean kinetic energy of all hadrons in a sphere of radius $2\text{fm}$ around the system mass center is calculated as $\frac{2}{3} < E_k >$, which is utilized to reflect the thermalization temperature $T$ of the collision system approximately. As illustrated in Fig. 3(b), both tip-tip and body-body central collisions show a flat region about 75 MeV and the corresponding time range are about 10 fm/c to 28 fm/c and 10 fm/c to 18 fm/c, respectively. Considering the time range of the flat region in Fig. 3(b) associating with the corresponding range in Fig. 3(a) and also looking back to Fig. 3, we obtain a large volume of hot, dense nuclear matter in both tip-tip and body-body central collisions. Consequently, the extreme circumstance of sufficiently high temperature and density for a significant large volume and long duration $12, 22$ has been formed in tip-tip and body-body central collisions, which can provide a good opportunity to study the nuclear EoS as well as particles in medium properties, especially for tip-tip case.

The time of freeze out should be cautiously determined for estimating the thermalization temperature of collision system. In Fig. 4 the multiplicity evolution of free pion which are not bounded in baryon resonances and pion still bounded inside the excited baryon resonances ($\Delta, N^*$) (unborn pion) are displayed. At the Lanzhou CSR energy region (520 MeV/nucleon), the production and destruction of the $\Delta$ resonances are mainly through $NN \rightarrow N\Delta$ and $\Delta \rightarrow N\pi$ reactions in which the $\Delta$ decay rate is always higher than that of the formation of this resonance and the production of pion is predominated by the decay of the $\Delta$ resonances $\Delta \rightarrow N\pi$. The total multiplicity of pion, $\Delta$ and $N^*$ approaches a saturated level after a period of evolution, indicating the freeze-out time about $t=28 \text{fm/c}$ and $t=18 \text{fm/c}$ for tip-tip and body-body central collisions, respectively. The larger maximum attainable total multiplicity of pion, $\Delta$ and $N^*$ and freeze out earlier indicates a existent of faster evolution and more violently reaction process for the body-body central collisions than tip-tip case consisting with the discussing before.

The corresponding temperature about 75 MeV at freeze-out time can be extracted from the Fig. 3(b), for both tip-tip and body-body central collisions. To further confirm this estimation, both the energy spectrum of the nucleon and negative-charged pion are studied within the polar angle range of $90^\circ \pm 10^\circ$ in the c.m.s.. The thermodynamic model $31$ predicts that the energy spectra will be represented by a temperature $T$ which characterizes a Maxwell-Boltzmann gas

$$\frac{d^2\sigma}{P E d\Omega} = \text{const} \times e^{-E_{\text{kin}}/T}$$

where $P$ and $E$ are the particle momentum and total energy in the c.m.s.. Both the energy spectra and the Boltzmann fit results are shown in Fig. 7. The inverse slope (e.g. temperature $T$) of the nucleons in tip-tip and body-body central collisions are about 73 MeV and 70
May be explained by considering an equilibrated different lower temperature than that of nucleon which out time. The spectra of negative-charged pion show a temperature extracted from the Fig. 5(b) at the freeze-out time. The nucleon fit temperature for tip-tip and body-body are about 73 MeV and 70 MeV, respectively and that of pion are about 56 MeV and 52 MeV, respectively. The nucleon fit temperature for tip-tip and body-body central collisions. However, it’s also possible that the collision system is still in a nonequilibrium transport process on its path towards kinetic equilibration [30].

In conclusion, thermalization (or near thermalization) of the collision system corresponding a freeze-out temperature about 75 MeV is likely to be achieved in both tip-tip and body-body central collisions. However, it’s also possible that the collision system is still in a nonequilibrium transport process on its path towards kinetic equilibration [30].

IV. THE COLLECTIVE FLOW OF U+U COLLISIONS

Stopping of nuclei in heavy ion collision can lead to pressure gradient along different directions, resulting in collective motion as spectators bounce-off [34] and participants squeeze-out effects [35]. Since last two decades, at Bevalac/LBNL and SIS/GSI energies the so-called "collective flow" analysis has been established [15, 34, 35, 36, 37] to study the collective motion of the products in heavy ion collisions. The collective flow resulting from bounce-off and squeeze-out effects, which can be explained well by the hydrodynamics model [24, 38], and also be in good agreement with the experimental data has been observed [39, 40]. Because of the large deformation of the uranium nuclei, a novel collective motion is expected [12], to be used to extract the medium properties and nuclear matter EoS information [15, 16, 17, 18, 19, 20].

To perform flow analysis, it is necessary to construct a imaginary reaction plane defined by direction of the beam (z) and the impact parameter vector b [13, 45, 46]. In our simulation, the x-z plane is just defined as the reaction plane with the beam direction along z positive direction and the impact parameter vector b along x positive direction. In last two decades, there are mainly two methods to study the collective flow at the low and intermediate energies. One is the sphericity method [28, 34, 41, 42] which yields the flow angle relative to the beam axis of the major axis of the best-fit kinetic energy ellipsoid, and the other is to employ the mean transverse momentum per nucleon projected into the reaction plane, $< p_x/A >$, as a function of c.m.s. normalized rapidity is illustrated for tip-tip and body-body collisions. With normalized impact parameter cutoff $(a)b/b_{max} <= 0.5$ $(b)b/b_{max} > 0.5$.

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$$\frac{dN}{d\phi} \sim 1 + \sum_n 2v_n \cos(n\phi)$$

(4)

Fig. 8 shows nucleon sideward flow, $< p_x/A >$, for both tip-tip and body-body minimum biased collisions.
FIG. 9: (a)The nucleon flow parameter $F$ and (b)the c.m.s. mid-rapidity ($-0.5 < y^0 < 0.5$), nucleon elliptic flow $v_2$ of three collision conditions as a function of normalized impact parameter $b/b_{max}$ with soft EoS.

as a function of normalized rapidity, $y^0 = Y_{cm}/y_{cm}$, in which $Y_{cm}$ represents the particle rapidity in c.m.s. and $y_{cm}$ is the rapidity of the system mass center. To extract the nuclear EoS information and also demonstrate the discrepancies of the nucleon sideward flow in tip-tip and body-body collisions, the cascade events [49], which neglect the mean field and pauli blocking effects are employed here to compare with the soft EoS case. In Fig. 9(a),(b), with a soft EoS, it is noted that either tip-tip or body-body collisions show a spectator bounce-off effect revealing an obvious "S" shape [17, 19] at the mid-rapidity region of $-0.5 < y^0 < 0.5$, while the cascade one appear a almost vanishing nucleon sideward flow. It can be understand by the nucleon sideward flow is related to the mean field, which is mainly responsible for the pressure gradient of the stopping nuclei, while the mean field has a strong dependence of the nuclear EoS. Therefore, the nucleon sideward flow is thought to be a good indirect probe to extract the nuclear EoS information, especially tip-tip case for its largely remarkable sideward flow. A cutoff on normalized impact parameter is also applied to explore the impact parameter dependence of nucleon sideward flow. As shown in Fig. 9(b), when $b/b_{max} > 0.5$ the curves of soft EoS and cascade are almost superposed with each other, while for $b/b_{max} < 0.5$ large discrepancy is observed. The situation is quite similar to Fig. 3(b), almost the same stopping power for $b/b_{max} > 0.5$ and large discrepancy for $b/b_{max} < 0.5$ in tip-tip and body-body minimum biased collisions, which means there exists a correlation between nuclear stopping power and sideward flow [33].

The normalized impact parameter dependence of the collective flow of nucleon is further studied, by analyzing the "flow parameter" $F$ [19] and also elliptic flow $v_2$ for both tip-tip and body-body as well as Au+Au minimum biased collisions. The flow parameter $F$ is a customarily used quality to describe the nucleon sideward flow quantitatively defined as

$$ F = \frac{d < p_x/A >}{dy^0} \bigg|_{y^0=0} $$

the slope of the mean transverse momentum per nucleon projected into the reaction plane at $y^0 = 0$.

In Fig. 9(a), with $b/b_{max} > 0.5$, the nucleon flow parameter $F$ of tip-tip and body-body collisions are with similar value. This similarity, along with the almost same stopping ratio $R$ in Fig. 3(b), indicates a existence of similar pressure gradient effects on nucleon sideward flow in the two collision orientations. While for $b/b_{max} < 0.5$, the flow parameter $F$ of tip-tip collisions is nearly 3 times larger than that of body-body case. Even the sideward flow of Au+Au collisions is larger than the body-body one. It is further confirmed the tip-tip nucleon sideward flow is a more sensitive probe to extract the information of nuclear EoS than that of body-body one. The prominence high of the nucleon sideward flow in tip-tip collisions may be resulted from the stronger pressure gradient between the participants and spectators in the reaction plane than body-body one, due to the largely deformed nuclei.

The normalized impact parameter dependent of nucleon elliptic flow $v_2$ at the mid-rapidity region ($-0.5 < y^0 < 0.5$) is displayed in Fig. 9(b). A significant negative elliptic flow $v_2$ at this energy region is consistent with the excitation function of the elliptic flow studied before [50]. An largest negative $v_2$ about $-12\%$ in body-body central collisions is observed which reflects the large geometric and squeeze-out effects in the collisions. While for tip-tip and Au+Au ones the maximum negative $v_2$ are obtained at mid-centrality. Since both high baryon, energy densities and large elliptic flow effects, which reflects an early EoS of the hot dense compression nuclear matter [17], are available in body-body central collisions. Thus the body-body nucleon elliptic flow can also be taken as a sensitive probe of nuclear EoS. The novel behaviors of nucleon collective flow in tip-tip and body-body collisions are mainly attributed to the large deformation of the uranium nuclei.

V. SUMMARY

In summary, the CSR-ETF at Lanzhou provide a good opportunity to systematically study the nuclear EoS at the high net-baryon density region of nuclear matter phase diagram. Due to the novel stopping effects in largely deformed U+U collisions, the simulation based on ART1.0 demonstrates that full stopping can be achieved and also a bulk of hot, high densities nuclear matter with large volume and long duration have been formed in both tip-tip and body-body collisions. Large nucleon sideward flow in tip-tip collisions and the significant negative nucleon elliptic flow in body-body central collisions can provide a sensitive probe to extract nuclear EoS information.
Thus the extreme circumstance and the novel collective flow in both tip-tip and body-body collisions can provide a good condition and sensitive probe to study the nuclear EoS, respectively. More experimental observables of U+U collision dynamics should be further studied, due to the geometric effects.

VI. ACKNOWLEDGEMENT

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