

Baryon and electric charge stoppings in nuclear collisions and the role of strangeness

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Abstract

It has been challenging to quantitatively understand the stopping of incoming nucleons in nuclear collisions, and recently it has been proposed that comparing the baryon stopping with electric charge stopping can help address the question. Here we focus on the $B/Q \times Z/A$ ratio, which can strongly depend on rapidity although its value is one for the full phase space. We find that this ratio is very sensitive to the difference between strange and anti-strange rapidity distributions (the $s - \bar{s}$ asymmetry), and slightly more anti-strange quarks at mid-rapidity would lead to a ratio well below one. This is the case for Zr+Zr and Ru+Ru isobar collisions at 200A GeV from a multi-phase transport (AMPT) model. Without the $s - \bar{s}$ asymmetry, the AMPT model would give a mid-rapidity $B/Q \times Z/A$ ratio at or above one. In addition, the AMPT model gives $B/\Delta Q \times \Delta Z/A < 1$ at mid-rapidity for isobar collisions at all centralities, which strongly contradicts the recent data from the STAR Collaboration. We further find that the $B/\Delta Q \times \Delta Z/A$ ratio is very sensitive to the net-light quark (u, d) stoppings, but it is less sensitive to the $s - \bar{s}$ asymmetry than the $B/Q \times Z/A$ ratio by a factor of 3.

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I. INTRODUCTION

In high energy heavy-ion collisions, nucleons from the incoming nuclei deposit their energy to form a hot and dense phase of matter called the quark-gluon plasma (QGP) [1]. As a result, how much the initial nucleons stop or lose energy is important as it determines the initial energy density and net-baryon density that will affect the equation of state and the evolution of the created matter. Although the net baryon number per event is a conserved quantity, how it is redistributed in the phase space including its rapidity distribution [1–3] is not well understood. In the traditional QCD picture or the standard model, each quark carries a baryon number of one-third while each antiquark carries negative one-third, while a baryon consists of three valence quarks that are the carriers of both the net-baryon number and net-electric charge. On the other hand, the baryon junction model has been proposed [4–6], where a baryon is composed of three quarks connected by a Y-shaped string junction. Naively, the baryon junction is expected to be more easily stopped since it does not need to carry a large fraction of the incoming nucleon’s momentum.

Recently the ratio $B/Q \times Z/A$ has been proposed [7] as an observable for studying the baryon stopping mechanism, where B and Q respectively represent the net-baryon and net-electric charge within a given acceptance (e.g., at mid-rapidity), and Z and A are respectively the atomic number and mass number of the incoming nucleus in symmetric A+A collisions. The naive expectation is $B/Q \times Z/A = 1$, because this is true for the full phase space due to the corresponding conservation laws. By comparing the experimental data with models that incorporate different stopping mechanisms, we expect to learn more about the physics responsible for baryon (and electric charge) stopping [8–10]. As the net-electric charge is very difficult to measure experimentally, the Zr+Zr and Ru+Ru isobar collisions at RHIC provide a good opportunity because of the large statistics and cancellation of certain systematic errors. The STAR Collaboration has measured the difference of the net-electric charge between Ru+Ru and Zr+Zr isobar collisions (ΔQ) as well as the ratio $B/\Delta Q \times \Delta Z/A$ [11, 12]. Again, the naive expectation is $B/\Delta Q \times \Delta Z/A = 1$ since this is true for the full phase space.

Our study here addresses the above ratios between the net-baryon stopping and net-electric charge stopping. We first examine these ratios at the parton level. We then present results from A Multi-Phase Transport (AMPT) Model [13, 14], including the ratios versus

rapidity and centrality at different evolution stages of the created matter. Recent studies from transport models such as UrQMD [8, 9, 15] and AMPT [8, 10, 13] have shown $B/Q \times Z/A < 1$ at mid-rapidity, meaning more charge stopping than baryon stopping. We shall show that the main cause of this is due to slightly more anti-strange than strange quarks at mid-rapidity. In addition, we investigate the $B/\Delta Q \times \Delta Z/A$ ratio and its sensitivity to the stopping of different quark flavors.

II. BARYON AND CHARGE STOPPINGS AT THE PARTON LEVEL

We now consider the parton phase of the dense matter under the traditional picture where the baryon and electric charge are carried by quarks and antiquarks. Let us use f_i as the short notation for the rapidity distribution dN/dy of quark flavor i after the collision of two relativistic heavy ions, we then have

$$\begin{aligned} f_B &\equiv \frac{dN_B}{dy} = (f_u - f_{\bar{u}} + f_d - f_{\bar{d}} + f_s - f_{\bar{s}})/3, \\ f_Q &\equiv \frac{dN_Q}{dy} = (2f_u - 2f_{\bar{u}} - f_d + f_{\bar{d}} - f_s + f_{\bar{s}})/3. \end{aligned} \quad (1)$$

For high energy symmetric A+A collisions at a given centrality, a fraction p of the nucleons in each incoming nucleus will be participant nucleons and converted into partons. Since we neglect the effect of neutron skin in this study, the same fraction of protons in each incoming nucleus will interact. For each quark flavor, we write its total number as $N_i = \int f_i dy$, and we have $N_s = N_{\bar{s}}$. When we integrate over the full phase space, we get

$$\begin{aligned} B &= 2pA = (N_u - N_{\bar{u}} + N_d - N_{\bar{d}})/3, \\ Q &= 2pZ = (2N_u - 2N_{\bar{u}} - N_d + N_{\bar{d}})/3, \\ \rightarrow B/Q \times Z/A &= 1. \end{aligned} \quad (2)$$

The last relation above may be called the naive expectation, since it is only valid in full phase space. At a given rapidity, $B/Q \times Z/A = f_B/f_Q \times Z/A$ depends on several variables in Eq.(6), because in general the quark rapidity distributions can all be different, e.g., $f_u \neq f_d$ and/or $f_s \neq f_{\bar{s}}$.

A useful limit is the isospin-symmetric case where $A = 2Z$ (like ^{40}Ca or ^{20}Ne), where we expect $f_u = f_d \equiv f_q$ and $f_{\bar{u}} = f_{\bar{d}} \equiv f_{\bar{q}}$, Eq.(6) then reduces to

$$B \equiv f_B = (2f_q - 2f_{\bar{q}} + f_s - f_{\bar{s}})/3, \quad Q \equiv f_Q = (f_q - f_{\bar{q}} - f_s + f_{\bar{s}})/3. \quad (3)$$

If $f_s = f_{\bar{s}}$ (i.e., strange and anti-strange quarks have the same rapidity distribution), we then have

$$B/Q \times Z/A = 1 \text{ at any } y, \quad (4)$$

regardless of the stoppings of net-light quarks (meaning u, d in this study). Equivalently, if we find $B/Q \times Z/A \neq 1$ at a certain rapidity for symmetric A+A collisions with $A = 2Z$, this breaking of the naive expectation is caused by the strange and anti-strange asymmetry according to Eq.(3), where strange quarks and anti-strange quarks must have different shapes in the rapidity distribution. We note that the neutron skin effect [16–19] will modify some of the above relations. Nevertheless, the above analysis clearly demonstrates the essential role that strange quarks play in the $B/Q \times Z/A$ ratio.

III. RESULTS FROM A MULTI-PHASE TRANSPORT MODEL

We now study the stopping of baryon and electric charges with the AMPT model [13], which allows us to study the stoppings at different stage of the dense matter’s evolution. The string melting AMPT model (AMPT-SM) consists of four main components: the initial conditions, partonic interactions, conversion from partonic to hadronic matter via quark coalescence, and hadronic interactions. Note that this version of the model includes the improvement that conserves the net electric charge of each event exactly [14]. It also includes a quark coalescence with the reversed coalescence order, where it searches for baryon or anti-baryon partners before searching for meson partners. This has been found to lead to better descriptions of baryons and anti-baryons similar to the new quark coalescence model [20], where the order is removed and a quark has the freedom to form either a meson or a baryon depending on the coalescence distance. Furthermore, the HIJING1 model [21] for the AMPT initial condition orders the A nucleons according to the z-coordinate values and assigns the first Z nucleons as protons. Since this artifact affects the initial electric charge stopping, we have removed the artifact in the AMPT model used for this study by breaking the artificial association of the z-coordinate with the nucleon charge. We then apply this AMPT model to isobar ($A = 96$) collisions at $\sqrt{s_{NN}} = 200$ GeV. Note that in this study we use the Woods-Saxon density distribution to sample nucleons in the isobar nuclei. Including the neutron skin [17] and deformations of the isobar nuclei [19], which is left for future work, could

lead to modifications of the electric charge stopping and consequently the baryon-to-charge ratios.

A. Baryon and charge stoppings for isobar systems

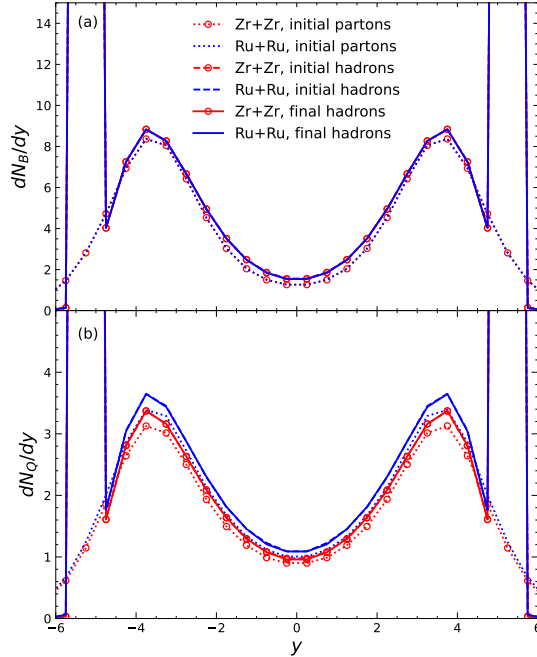


FIG. 1: The rapidity distributions of (a) the net-baryon number and (b) the net-electric charge in minimum bias isobar collisions at $\sqrt{s_{NN}} = 200A$ GeV from the AMPT-SM model from initial partons (dotted), initial hadrons (dashed) and final state hadrons (solid).

Figure 1 shows the rapidity distributions of the net-baryon number in panel (a) and the net-electric charge in panel (b) from the AMPT-SM model for minimum bias Zr+Zr and Ru+Ru isobar collisions at 200A GeV. Solid curves are the results for final state hadrons (i.e., after the hadron cascade and resonance decays), while dashed curves represent the results of initial hadrons (without the hadron cascade but with resonance decays). We see that the hadron cascade has little effect on these distributions. The results at the parton level right after string melting but before the parton cascade, as calculated via Eq.(6), are also shown as dotted curves; they are quite similar to the final hadron distributions (except

for the beam rapidity regions). In addition, we see the expected features that the two isobar systems have essentially the same net-baryon distributions but different net-electric charge distributions.

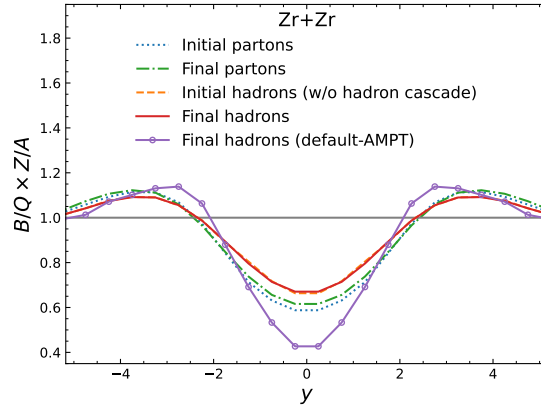


FIG. 2: The $B/Q \times Z/A$ ratio from the AMPT-SM model as a function of rapidity at different stages of the evolution of minimum bias Zr+Zr collisions; the ratio from the default AMPT model (curve with circles) is also shown.

We show in Fig. 2 the $B/Q \times Z/A$ ratio versus rapidity at four different stages of the time evolution of minimum bias Zr+Zr collisions at 200A GeV from the AMPT-SM model. We see that the rapidity distributions have a similar shape and are all well below unity at mid-rapidity. The parton cascade has a small effect on the $B/Q \times Z/A$ rapidity distribution, while the hadron cascade almost has no effect. The result from the default version of the AMPT model [13] is also well below unity at mid-rapidity, although it has a weaker parton cascade phase but a stronger hadron cascade phase and uses the Lund fragmentation for hadronization instead of quark coalescence.

B. The role of strangeness on the $B/Q \times Z/A$ ratio

To further understand why the naive expectation is badly broken, we plot in Fig. 3 the rapidity distributions of initial quarks in Zr+Zr collisions and the hypothetical Cd+Cd isobar collisions (at $A = 96$), where initial quarks refer to the quarks and antiquarks produced by the string melting mechanism [13] before the parton cascade. Note that the isobar Cd+Cd collisions are hypothetical since there is no known ^{96}Cd isotope; we simulate their collisions to

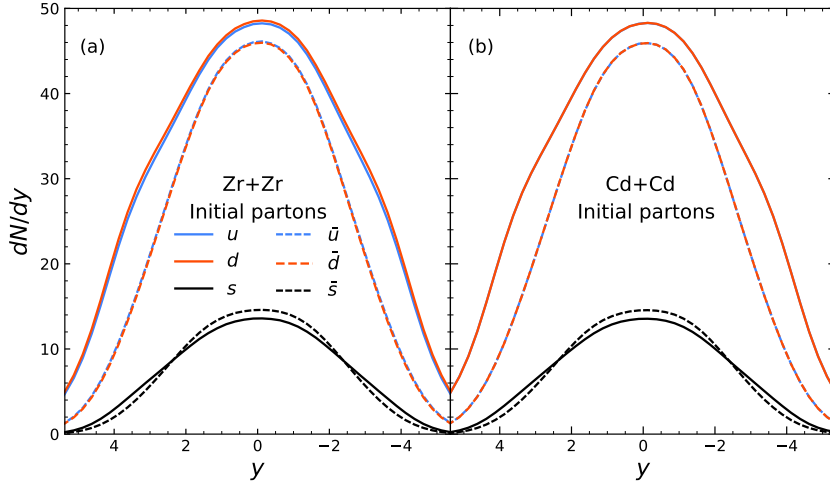


FIG. 3: Rapidity distributions of initial quarks from the AMPT-SM model for minimum bias (a) Zr+Zr and (b) Cd+Cd isobar collisions at 200A GeV.

demonstrate the roles of strangeness and isospin since the ^{96}Cd nucleus is isospin-symmetric. We see in Fig. 3 a small but obvious difference between strange and anti-strange quark rapidity distributions, which is similar for the two collision systems. Around mid-rapidity ($|y| \lesssim 2$) there are more anti-strange than strange quarks while the opposite happens at large rapidities. Around mid-rapidity, this asymmetry leads to a negative contribution to the net-baryon number but a positive contribution to the net electric charge as shown in Eq.(6); thus this $s - \bar{s}$ asymmetry suppresses the $B/Q \times Z/A$ ratio. For the isospin-symmetric ^{96}Cd system, we see in Fig. 3(b) that u and d quarks have the same rapidity distribution and so do $\bar{u}$ and $\bar{d}$ quarks. Therefore, the difference in the s and $\bar{s}$ distributions, i.e., $f_s \neq f_{\bar{s}}$, is the only reason for $B/Q \times Z/A \neq 1$ for Cd+Cd collisions according to Eqs. (3)-(4).

To demonstrate how a seemingly small $s - \bar{s}$ asymmetry can give a large deviation of $B/Q \times Z/A$ from unity, let us rewrite the quark level Eq.(6) as

$$B = (f_{net-u} + f_{net-d} + f_{net-s})/3, \quad Q = (2f_{net-u} - f_{net-d} - f_{net-s})/3, \quad (5)$$

where $f_{net-u} \equiv f_u - f_{\bar{u}}$ reflects the net- u quark stopping. For collisions of most nuclei where $Z \sim A/2$, we then get

$$B/Q \times Z/A \simeq \frac{Z}{A} \left(\frac{f_{net-u} + f_{net-d}}{2f_{net-u} - f_{net-d}} \right) \left(1 + \frac{3f_{net-s}}{2f_{net-q}} \right) \quad (6)$$

$$\text{with } f_{net-q} \equiv (f_{net-u} + f_{net-d})/2 \quad (7)$$

at the first order of f_{net-s}/f_{net-q} . In particular, for the isospin symmetric $^{96}\text{Cd}+^{96}\text{Cd}$ isobar collisions, we have $f_{net-u} = f_{net-d}$ and thus get

$$B/Q \times Z/A \simeq 1 + \frac{3}{2} \frac{f_{net-s}}{f_{net-q}}. \quad (8)$$

Although the $s - \bar{s}$ asymmetry (i.e., f_{net-s}/f_s) is quite small ($\lesssim 10\%$) as shown in Fig. 3, f_{net-s}/f_{net-q} is much higher than that, and it causes a big deviation of the mid-rapidity $B/Q \times Z/A$ from unity.

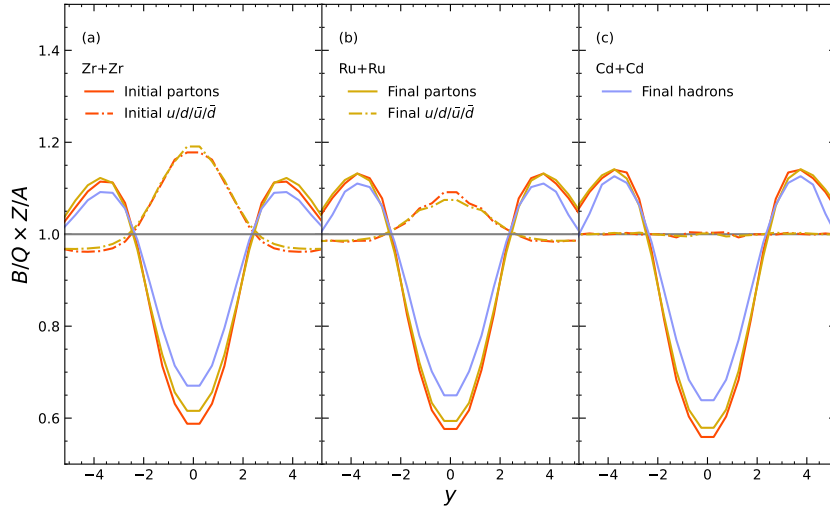


FIG. 4: The $B/Q \times Z/A$ ratio as a function of rapidity for minimum bias collisions of three isobar systems at 200A GeV from the AMPT-SM model, including results for initial partons and final partons with and without the inclusion of strange quarks as well as final state hadrons.

Figure 4 shows the $B/Q \times Z/A$ ratio as a function of rapidity for three isobar systems from the AMPT-SM model, where the results for initial partons (before the parton cascade), final partons (after the parton cascade), and final state hadrons are shown. When we only include light ($u, d, \bar{u}, \bar{d}$) quarks, we have $B/Q \times Z/A = 1.0$ at any rapidity for Cd+Cd collisions, consistent with Eq.(4); however, the $B/Q \times Z/A$ ratio changes drastically and becomes well below unity around mid-rapidity when we also include (anti)strange quarks. From Cd+Cd to Ru+Ru to Zr+Zr collisions, the isospin asymmetry of the incoming nuclei is increasing bigger, and consequently the $B/Q \times Z/A$ ratio for initial light quarks increasingly deviates from unity. The ratios for all three collision systems are very close to each other, either

for initial partons, final partons, or final hadrons, as long as strange particles are included; therefore, the $s - \bar{s}$ asymmetry in rapidity is the primary reason for $B/Q \times Z/A < 1$ at mid-rapidity in the AMPT-SM model.

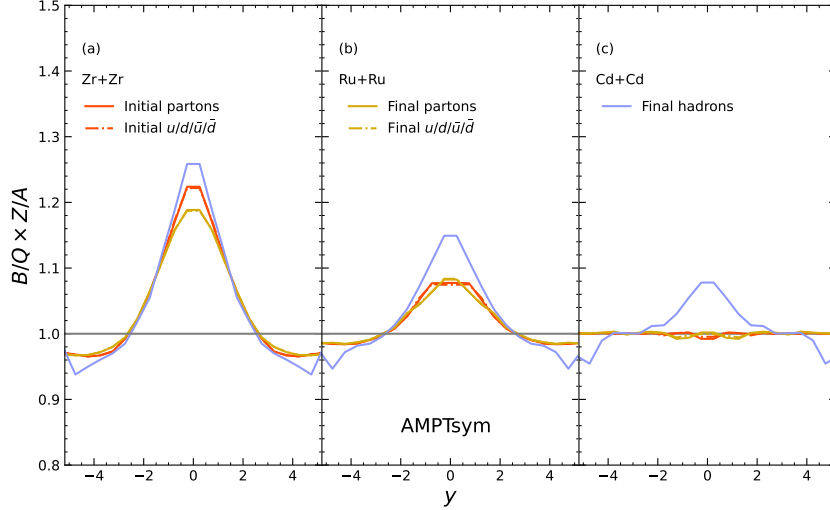


FIG. 5: Same as Fig. 4 but from a modified AMPT-SM model where the distributions of initial strange and anti-strange quarks are symmetrized to be the same.

Since the incoming nucleons carry net u and d quarks, it is natural for light quarks (u, d) to have a different shape of rapidity distribution from light antiquarks, as shown in Fig. 3. However, it is unclear why and how the rapidity distributions of s and $\bar{s}$ quarks are different from each other; naively one may expect their distributions to be the same since s and $\bar{s}$ are pair produced. To explore the effect of this uncertainty, we now test a modified version of the AMPT-SM model (denoted as AMPTsym), where we symmetrize the initial momentum as well as space-time distributions of s and $\bar{s}$ quarks before the parton cascade. Results from this model for the $B/Q \times Z/A$ ratios as functions of rapidity are shown in Fig. 5 for the three isobar systems. For Cd+Cd collisions in panel (c), the initial parton $B/Q \times Z/A = 1.0$ not only for light quarks but also after including the (anti)strange quarks as expected. A big difference from the normal AMPT-SM results is that the AMPTsym model produces $B/Q \times Z/A > 1$ for final hadrons at mid-rapidity for all three systems. In addition, we see that the parton cascade has little effect so that $B/Q \times Z/A \simeq 1.0$ for final partons in Cd+Cd collisions. On the other hand, hadronization (quark coalescence here) has some effect on the

$B/Q \times Z/A$ ratio, e.g., it changes the ratio away from unity for Cd+Cd collisions as shown in Fig. 5(c).

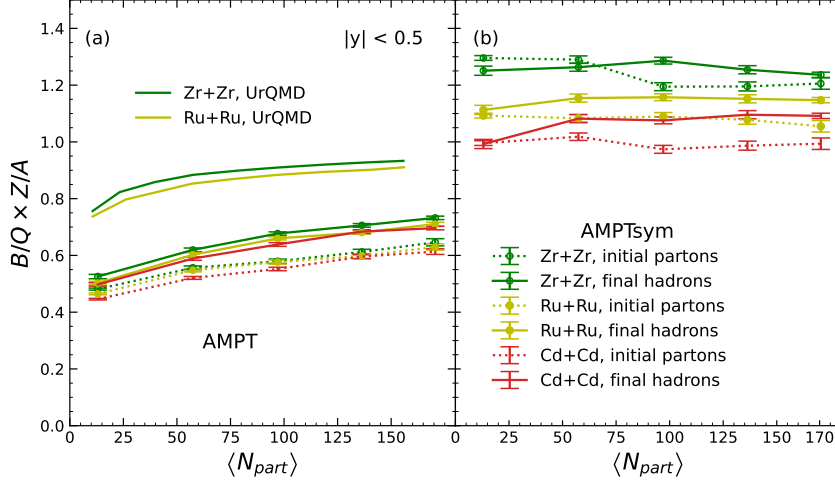


FIG. 6: The $B/Q \times Z/A$ ratio as a function of $\langle N_{\text{part}} \rangle$ for isobar collisions from (a) the normal AMPT-SM model and (b) the modified AMPT-SM model with symmetrized distributions for initial strange and anti-strange quarks. Results for initial partons and final hadrons from the AMPT models are shown, and results from the UrQMD model are also shown for comparison.

Figure 6 shows the $B/Q \times Z/A$ ratio at mid-rapidity as a function of the average number of participant nucleons in isobar collisions from the AMPT-SM models, where results for initial partons and final state hadrons are both shown. We see in panel (a) that the ratios from the normal AMPT-SM model all gradually increase with $\langle N_{\text{part}} \rangle$ but all stay below unity. Results from the UrQMD model [8] also show these features, although they are closer to unity. We find that about half of the $B/Q \times Z/A$ increase with $\langle N_{\text{part}} \rangle$ comes from overall $s - \bar{s}$ asymmetry as shown in Fig. 3, and the other half of the increase with $\langle N_{\text{part}} \rangle$ is due to the modest decrease of the $s - \bar{s}$ asymmetry with centrality (where $f_{\bar{s}}/f_s - 1$ decreases from $\sim 9\%$ in peripheral collisions to $\sim 7\%$ in central collisions). When we remove the initial $s - \bar{s}$ asymmetry in the rapidity distribution, the $B/Q \times Z/A$ ratios at mid-rapidity in panel (b) are mostly above one, where the ratios for initial partons in Cd+Cd collisions are consistent with one as expected from Eq.(4). Therefore, the $s - \bar{s}$ asymmetry in the initial rapidity distribution greatly affects the $B/Q \times Z/A$ ratio in nuclear collisions.

In addition, the $B/Q \times Z/A$ ratio at mid-rapidity depends on the isospin asymmetry

of the incoming nuclei, being the highest for Zr+Zr collisions and the lowest for Cd+Cd collisions (at the same $\langle N_{\text{part}} \rangle$). This is the case in Fig. 6 for both initial partons and final hadrons and for both AMPT-SM models (with or without the initial $s - \bar{s}$ asymmetry). This ordering also exists for Zr+Zr and Ru+Ru collisions from the UrQMD model [8]. Since the net-baryon distributions are essentially the same for the isobar collisions, this ordering results from the net-charge difference. For example, we find that the net-electric charge from light quarks ($u, d, \bar{u}, \bar{d}$) in Ru+Ru collisions at mid-rapidity is about 20% higher than that from Zr+Zr collisions, rather than the 10% we would naively expect from ΔZ .

C. The $B/\Delta Q \times \Delta Z/A$ ratio for isobar systems

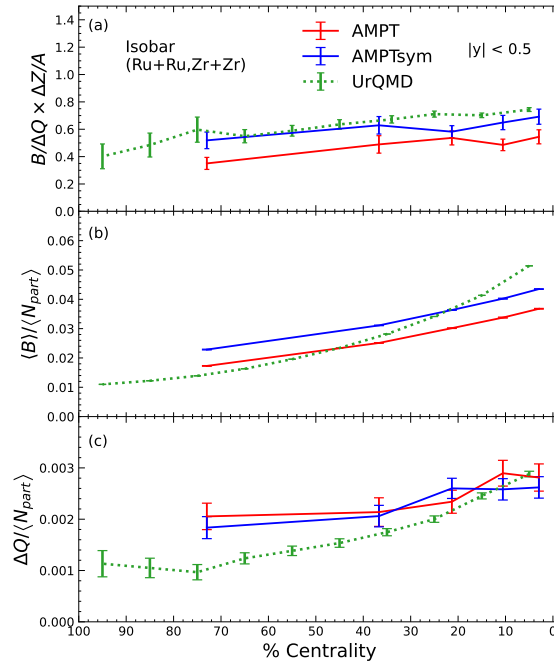


FIG. 7: (a) The $B/\Delta Q \times \Delta Z/A$ ratio, (b) the average net-baryon number, and (c) the difference of net electric charge for Ru+Ru and Zr+Zr collisions at mid-rapidity (scaled by $\langle N_{\text{part}} \rangle$) from the normal and $s - \bar{s}$ symmetrized AMPT-SM models versus centrality; UrQMD results [22] are also shown for comparison.

We now examine the difference between Ru+Ru and Zr+Zr isobar collisions in Fig. 7(a) by

plotting the $B/\Delta Q \times \Delta Z/A$ ratio of final hadrons at mid-rapidity as a function of centrality. We see that the ratios from both the normal AMPT-SM model and the AMPTsym model are well below unity at mid-rapidity, where the ratios from the AMPTsym model are higher and close to those from the UrQMD model. On the other hand, a recent study by the STAR Collaboration [12] showed that the $B/\Delta Q \times \Delta Z/A$ data for isobar collisions are much higher (mostly by a factor of 2 or more) than all the model results shown in Fig. 7(a) for all centralities. Therefore, the puzzle about the baryon versus charge stoppings in Ru+Ru and Zr+Zr isobar collisions still exists, regardless of the uncertainty about the initial $s - \bar{s}$ asymmetry.

We also show the average net-baryon number in Fig. 7(b) and the net-electric charge difference ($\Delta Q \equiv Q_{\text{Ru+Ru}} - Q_{\text{Zr+Zr}}$) in Fig. 7(c) at mid-rapidity for isobar collisions as functions of centrality, with both being scaled by $\langle N_{\text{part}} \rangle$. We see that the AMPT results are different from the UrQMD results while they overlap at certain centralities. The $\langle B \rangle / \langle N_{\text{part}} \rangle$ data values from the STAR Collaboration [12] are significantly higher than the model results in peripheral collisions while they are close to the values from the AMPTsym and UrQMD models for central collisions. On the other hand, the STAR $\Delta Q / \langle N_{\text{part}} \rangle$ data are close to the model results in peripheral collisions but are much lower (by about a factor of 2) than the model results for central collisions. As a result, the $B/\Delta Q \times \Delta Z/A$ STAR data at mid-rapidity are much higher than all the model results shown in Fig. 7(a) at all centralities. Note that the UrQMD results shown in Fig. 7 use the UrQMD $\langle N_{\text{part}} \rangle$ values [22] and are thus not the same as the UrQMD curves shown in the recent STAR study [12].

When the isobar collision system changes from Zr+Zr to Ru+Ru, we can write the changes of the net-baryon number and the net-electric charge at a given rapidity as

$$\Delta B = (\Delta f_{\text{net}-u} + \Delta f_{\text{net}-d} + \Delta f_{\text{net}-s})/3, \quad \Delta Q = (2\Delta f_{\text{net}-u} - \Delta f_{\text{net}-d} - \Delta f_{\text{net}-s})/3, \quad (9)$$

where $\Delta f_{\text{net}-u} = \Delta f_u - \Delta f_{\bar{u}}$. As shown in Fig. 8, we find from the normal AMPT-SM model that $\Delta f_{\text{net}-s} \simeq 0$ between Ru+Ru and Zr+Zr collisions (and also between Cd+Cd and Ru+Ru collisions). Given the observation $\Delta B \simeq 0$ among the three isobar systems, we then have $\Delta f_{\text{net}-u} \simeq -\Delta f_{\text{net}-d}$ and $\Delta Q \simeq \Delta f_{\text{net}-u}$, both of which are confirmed by Fig. 8. This is why the normal AMPT model and the AMPTsym model give about the same $\Delta Q / \langle N_{\text{part}} \rangle$ results in Fig. 7(c). At the parton level, we then get

$$B/\Delta Q \times \Delta Z/A \simeq \frac{\Delta Z}{A} \frac{B}{\Delta f_{\text{net}-u}} \simeq \frac{\Delta Z}{A} \left(\frac{2f_{\text{net}-q}}{\Delta f_{\text{net}-u}} \right) \left(1 + \frac{f_{\text{net}-s}}{2f_{\text{net}-q}} \right). \quad (10)$$

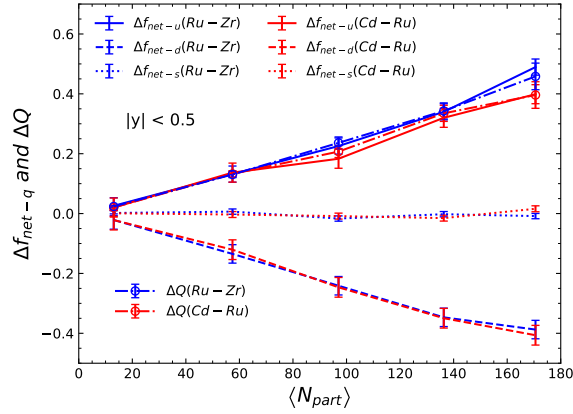


FIG. 8: The differences of the net-quark number of different flavors and the net-electric charge at mid-rapidity from the AMPT-SM model as functions of $\langle N_{part} \rangle$ between Ru+Ru and Zr+Zr isobar collisions and between Cd+Cd and Ru+Ru isobar collisions.

Since ΔQ essentially does not depend on the (anti)strange distributions, the isobar $B/\Delta Q \times \Delta Z/A$ ratio is very sensitive to the net-light quark (u, d) stoppings and their change between the two isobar systems, but it is less sensitive to (anti)strange distributions and the $s - \bar{s}$ asymmetry. This is very different from the $B/Q \times Z/A$ ratio, which is very sensitive to the $s - \bar{s}$ asymmetry. Comparing the above Eq.(10) with Eq.(6), we find that the $B/Q \times Z/A$ ratio is more sensitive to the $s - \bar{s}$ asymmetry by a factor of 3 than the $B/\Delta Q \times \Delta Z/A$ ratio.

IV. CONCLUSION

The stopping of baryons in nuclear collisions has not been well understood, and it is closely related to the question of whether a quark or a gluon junction carries the baryon number. It is also possible that (anti)quarks carry the baryon number in general, while a gluon junction that joins three quarks together topologically carries the baryon number of a color-singlet baryon in the confined phase and thus affects the baryon number transport in nuclear collisions. Recently it has been proposed that comparing the net-baryon with the net-electric charge in nuclear collisions can help address the question, e.g., with the $B/Q \times Z/A$ ratio at mid-rapidity. Here we study the baryon and charge stoppings in nuclear collisions, where it is known that the $B/Q \times Z/A$ ratio can strongly depend on the rapidity,

although its value is one for the full phase space. We find that the $B/Q \times Z/A$ ratio depends crucially on the difference between strange and anti-strange quark rapidity distributions (the $s - \bar{s}$ asymmetry), and having several percent more anti-strange than strange quarks at mid-rapidity would lead to a ratio well below one for Zr+Zr and Ru+Ru isobar collisions. This is why the string melting version of the AMPT model gives $B/Q \times Z/A < 1$ at mid-rapidity. On the other hand, if the initial strange and anti-strange quarks have the same rapidity distribution, the $B/Q \times Z/A$ ratio at mid-rapidity becomes one or higher for isobar collisions. For collisions of isospin symmetric nuclei such as ^{40}Ca , the $B/Q \times Z/A$ ratio would deviate from unity only because of this $s - \bar{s}$ asymmetry, when the neutron skin effect is neglected.

In addition, we find that the $B/\Delta Q \times \Delta Z/A$ ratio depends crucially on the net-light quark (u, d) stoppings and their change between the two isobar systems, but it is less sensitive to the $s - \bar{s}$ asymmetry than the $B/Q \times Z/A$ ratio by a factor of 3. For isobar collisions, the AMPT model gives $B/\Delta Q \times \Delta Z/A < 1$, regardless of whether the $s - \bar{s}$ asymmetry is removed. Since a recent STAR Collaboration study shows $B/\Delta Q \times \Delta Z/A$ data much higher than the values from the AMPT model and the UrQMD model, there is an interesting puzzle about baryon versus electric charge stoppings. Experimental data on the net-baryon and net-electric charge from different hadron species including strange and non-strange hadrons would provide more information to constrain the unmeasured $B/Q \times Z/A$ ratio and advance our understanding of baryon and charge stoppings.

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