Testing the baryon-junction conjecture in photonuclear processes and isobar collisions at RHIC

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A puzzling feature of ultra-relativistic nucleus-nucleus collisions is the apparent substantial baryon excess in the midrapidity region. It was proposed that baryon number could be carried by a non-perturbative Y-shaped topology of gluon fields, called the baryon junction, rather than by the valence quarks. The stopping of baryon junctions is predicted to lead to a characteristic exponential distribution of net-baryon density with rapidity and could resolve the puzzle. In this context we point out that the rapidity density of net-baryons near midrapidity indeed follows an exponential distribution with a slope of $-0.61 \pm 0.03$ as a function of beam rapidity in the existing global data from A+A collisions at AGS, SPS and RHIC energies. To further test if quarks or gluon junction carry the baryon quantum number, we propose to study the absolute magnitude of the baryon vs. charge stopping in isobar collisions at RHIC. We also argue that semi-inclusive photon-induced processes ($\gamma + p/A$) at RHIC kinematics provide an ideal opportunity to search for the signatures of the baryon junction and to shed light onto the mechanisms of observed baryon excess in the midrapidity region in ultra-relativistic nucleus-nucleus collisions. Such measurements can be further validated in $e + p/A$ collisions at the EIC.

I. INTRODUCTION

A puzzling feature of ultra-relativistic nucleus-nucleus collisions is the observation of substantial baryon asymmetry in the central rapidity (mid-rapidity) region. Global data from the RHIC energy scan indicate that the mid-rapidity net-baryon density follows an exponential distribution with beam rapidity [1, 2]. Such a phenomenon is striking, as baryon number is strictly conserved, so net-baryon number cannot be created in the system and therefore must come from the colliding objects. In a conventional picture, the valence quarks carry baryon quantum number in both the target and projectile. At sufficiently high energies one expects these valence quarks to pass through each other and end up far from mid-rapidity in the fragmentation regions [3].

However, substantial baryon asymmetry is experimentally observed at mid-rapidity both at RHIC [1, 2] and at LHC energies ($\sqrt{s_{NN}} = 900$ GeV) [4, 5]. As shown in Fig. 1, global data from the Alternating Gradient Synchrotron (AGS) [6], the Super Proton Synchrotron (SPS) [7], and RHIC [1, 2, 8] indicate that for central heavy-ion collisions the mid-rapidity net-baryon density follows an exponential distribution with the variable $\delta y = Y_{\text{beam}} - Y_{\text{cm}}$, where $Y_{\text{beam}}$ is the beam rapidity and $Y_{\text{cm}}$ is the center-of-mass rapidity. This variable $\delta y$ can be referred to as the “rapidity loss” which for mid-rapidity protons produced in a collider experiment is equal to beam rapidity: $\delta y = Y_{\text{beam}}$ as $Y_{\text{cm}} = 0$. A single collision energy therefore gives rise to a single point on Fig. 1. The displayed uncertainties are those from the statistical and systematic uncertainties combined in quadrature. The dotted line is an exponential fit to the data, which yields $\frac{dN_{p^-}/dy}{N_{\text{part}}^2} = 1.1 \exp(-0.61 \delta y)$. A number of outstanding questions arise by looking at Fig. 1. What is the underlying process that led to non-zero net-protons at mid-rapidity? Why do we see an exponential damping of net-proton density as we move away from beam rapidity? What are the implications of the the damping factor of 0.61? As we discuss later, conventional models simulating heavy-ion collisions use model inputs implemented in $p + p$ collisions with “popcorn” (PYTHIA), diquarks (UrQMD) or multiple strings (HIJING) [9] which cannot explain these features of the data.

![Figure 1](image-url)

**FIG. 1.** Exponential dependence of midrapidity ($y \approx 0$) baryon density per participant pair in central heavy ion collisions with $Y_{\text{beam}}$ which is equal to the rapidity difference between beam and detector midrapidity ($\delta y$) [1, 2, 4, 8].

It is therefore important to discuss an alternative picture of the structure of a baryon and its corresponding mechanism for stopping that was originally introduced...
about two decades ago. Contrary to the standard assumptions, it was proposed [3] that in high-energy collisions the baryon number is traced by non-perturbative Y-shaped configurations of gluon fields, called the baryon junctions [10], rather than valence quarks. Such junctions are the only possible gauge-invariant structure of the baryon wave function, and have been widely studied in Lattice QCD [11, 12]. Baryon junctions are flux-tube configurations that contain an infinite number of gluons and typically carry a minuscule fraction of the colliding nucleons’ momentum compared to the valence quarks \(x_J \ll x_V\), where \(x_J\) and \(x_V\) are the fraction of momentum carried by the baryon junction and valence quarks, respectively. Unlike valence quarks, the junctions from a target hadron/nucleus have sufficient time to interact and be stopped by the soft parton field of the projectile in the mid-rapidity region, even in high energy collisions [3]. While the baryon junction is stopped at a particular rapidity \(y\), the valence quarks may be pulled away, producing a \(q\bar{q}\) pair in the process, which will populate the region between \(y\) and the fragmentation region characterized by beam rapidity \(Y_{\text{beam}}\). The produced baryons are expected to: 1) have low transverse momentum due to the soft partons involved in the process, 2) may have different quark content than the colliding baryons, since junctions are blind to quark flavor, and, 3) will be accompanied by many pions, therefore leading to high multiplicity events. However, the most important feature of the baryon-junction stopping process is the characteristic exponential damping of the cross section with the rapidity loss variable \((\sim \exp(-\alpha_J(y - Y_{\text{beam}}}))\) determined by the Regge intercepts of the baryon junction \((\alpha_J)\) (see Ref. [3]).

Such a fundamental conjecture about baryons has never been tested successfully in an experiment. First, let us consider the rapidity distribution of net-baryons in \(p + p\) or heavy-ion \(A + A\) collisions at a fixed energy. It is not straightforward to study the signatures of an exponentially falling cross section with rapidity as in hadronic and symmetric \(A + A\) collisions the stopping of both target \((\sim \exp(\alpha_J(y - Y_{\text{beam}})))\) and projectile \((\sim \exp(-\alpha_J(y + Y_{\text{beam}})))\) will contribute leading to a nearly symmetric distribution. Regardless, if one considers the production of net-baryons at mid-rapidity \((y=0)\), one expects to see an exponential drop with beam rapidity \(\exp(-\alpha_J Y_{\text{beam}})\). The damping factor was predicted to be \(\alpha_J \simeq 0.5\) in Ref [3] for double-baryon stopping and \(\alpha_J = 1/2 - (\alpha_P(0) - 1) = 0.42\) for single-baryon stopping using \(\alpha_P(0) = 1 = 0.08\) [13]. We argue that the trend of global net-proton density data from \(A + A\) collisions shown in Fig. [4] is consistent with this picture and that the extracted damping factor of \(0.61 \pm 0.03\) is qualitatively consistent with the value of \(0.42\) predicted by the Regge theory. The small difference could arise from several other effects related to multiple hadronic interactions in central \(A + A\) collisions. Later on we discuss that the implementation of hadronization based on the PYTHIA-6 model predicts a much stronger dependence of net-proton density, which is approximately \(\exp(-2.5(y - Y_{\text{beam}}))\) and is inconsistent with global \(A + A\) data. A recent modeling of heavy ion collisions indicates that indeed the inclusion of the aforementioned baryon junction is essential for describing mid-rapidity net-proton density at RHIC [14]. This gives us a necessary impetus to investigate this further and to perform a decisive test of the baryon junction conjecture in an experimental and data-driven way.

Putting all the numbers together one expects the cross section of single baryon stopping to follow a similar exponential dependence of rapidity in \(p + p\) collisions [3]. Clearly, this exponential dependence with damping factors predicted by Regge theory is a verifiable signature of the stopping of baryon junctions. We argue that photon induced interactions on hadrons and nuclei provide a unique opportunity in this context. First, the photon is the simplest object which may fluctuate into a single dipole to interact, to first order, with only a gluon, a quark, or a baryon junction. Secondly, due to the absence of baryons in one of the colliding objects the characteristic exponential shape may be visible in \(\gamma + p\) and \(\gamma + A\) interactions – something that can be tested in ultra peripheral collisions (UPCs) at RHIC and at the EIC. Indeed, if the baryons are carried by the gluon junctions and not by valence quarks, there would be a measurably smaller amount of charge stopping than baryon stopping. We propose to measure this effect using the RHIC isobar collisions which changed the colliding nucleus charge from Ruthenium (Ru) with \((Z = 44)\) to Zirconium (Zr) with \((Z = 40)\) without changing the number of baryons \((A = 96)\) [15]. The key feature of the isobar collisions is that the detector acceptance and efficiency all cancel out between these two colliding systems and therefore allow us to detect very small differences in the charge stopping by changing the charge of the initial nuclei [10].

II. INCLUSIVE PHOTON-INDUCED PROCESSES AT RHIC

Fig. 2(left) shows the diagram of inclusive deep inelastic scattering (DIS, \(\gamma^* + p/A \rightarrow X\)) at HERA and at the future EIC in \(e + p/A\) collisions. Processes with virtuality of the exchanged photons \(Q^2 > 1\) (GeV/c)^2 are referred to as DIS, but the majority of \(e + p/A\) collisions have \(Q^2\) much less than 1 (GeV/c)^2 and are instead referred to as photoproduction processes [20]. Such photoproduction processes in \(\gamma^* + Au\) can also be studied in UPCs at RHIC and LHC. Figure 2(right) shows the typical kinematics for UPCs at RHIC. For the STAR experiment, UPC datasets with photonuclear processes are available for \(Au + Au\) collisions at center of mass energy per nucleon \(\sqrt{s_{NN}} = 54\) and 200 GeV and for \(d + Au\) collisions at \(\sqrt{s} = 200\) GeV. In UPCs the gold ions are the source of quasi-real photons. The size \((R_A \sim 1.2 A^{1/3})\) and charge \((Z = 79)\) of gold ions (mass number \(A = 197\)) and the Lorentz boost \(\gamma_L = 27 - 100\) at RHIC determines
the energy of the quasi-real photons $E_\gamma = \gamma_L(hc/R_A) = 0.8 - 2.8$ GeV. The virtuality and transverse momentum are $Q^2 \simeq E_\gamma/\gamma_L \simeq (hc/R_A)^2 = 0.0008 \text{ GeV}^2$. The typical range of the center of mass energy of the photnucleon system is $W_{\gamma N} = \sqrt{4E_\gamma E_A} \approx 9 - 34$ GeV for $\sqrt{s_{NN}} = 2E_A = 54 - 200$ GeV. These numbers are close to what are quoted in Ref [21]. However, it is not straightforward to estimate the range of the momentum fraction of the partons on which the photon scatters (Bjorken-x) in these interactions as they are process dependent. Due to limited control, the distribution of various kinematic parameters, particularly $x, W_{\gamma N}$, in UPCs can only be estimated using Monte-Carlo models or more sophisticated data-driven methods [22].

In the majority of cases the quasi-real photon fluctuates into a $q\bar{q}$ system (shown by the particles coming from the photon ($\gamma$) in Fig. 2) that scatters with the partons in the target nucleus, this is referred to as a resolved process [29]. If the baryon-junction picture is valid the following can happen: The $q\bar{q}$ system can interact with the incoming baryon ($J$) inside an incoming baryon (proton or neutron, shown by a red dot in Fig 2) of the target ion. Such an interaction may slow down or excite the junction at midrapidity. This junction will eventually acquire new quarks from the vacuum and become a baryon of different flavor (shown by a blue dot in Fig. 2) as junctions are flavor blind. This process will lead to production of additional mesons. Note that there will be enough time available for both the $q\bar{q}$ system and the junction to interact with each other since both of them carry a much smaller fraction of longitudinal momentum compared to the valence quarks. As a result the original valence quarks of the incoming baryon will fragment as mesons filling up the gap between the target and midrapidity. The details of the interaction between the $q\bar{q}$ system and the junction (depicted as a blob in Fig. 2) will determine the cross-section of this process. However, it is expected that since the projectile ($\gamma$) is baryon-free, the stopping of baryon in $\gamma + A$ processes will lead to a clear asymmetric dependence of net-baryon production with $y - Y_{beam}$ that can be tested in experiment. In hadronic collisions, Regge theory predicts a symmetric dependence of net-baryon to be $\exp(\alpha_f(y - Y_{beam})) + \exp(-\alpha_f(y + Y_{beam}))$ with $\alpha_f \approx 0.5$. In the most simplistic picture one expect to see an asymmetric dependence of $\exp(\alpha_f(y - Y_{beam}))$ in $\gamma + A$ processes, where $\alpha_f$ can be measured and directly compared to predictions from Regge theory. Therefore, the lower the target energy is, the more measurable net-baryon yield is expected to be at mid-rapidity.

Although we have limited control over the kinematics as compared to $e + p/Au$ DIS or photoproduction, UPCs provide the best shot for studying inclusive quasi-real photon-induced processes ($\gamma + A \rightarrow X$) off nuclei before the EIC era. Although UPCs have been studied for a long time, measurements of multi-particle production by triggering on high activity inclusive photonuclear processes have only started recently. Such an effort requires a high statistics data sample as well as large acceptance detec-
The search for collectivity in photonuclear processes has been already initiated at the Large Hadron Collider by the ATLAS and CMS collaboration [23 [24]. However, an experimental test of baryon conjecture remains untested due to limitations of particle identification capabilities. Due to higher collision energies, the target beam rapidity is large for experiments at the LHC. This leads to a smaller measurable baryon asymmetry at the central rapidity and constitutes a major challenge for these measurements. Therefore, the RHIC UPC program provides a unique opportunity in this context.

III. TRIGGERING INCLUSIVE PHOTON-INDUCED EVENTS

Monte-Carlo simulations using PYTHIA6 \((e+p)\), BeAGLE \((e+Au)\), and UrQMD \((Au+Au)\) event generators indicate that the main challenge identifying inclusive \(\gamma + p/Au\) interactions, which remains largely unexplored at RHIC (see Ref. [25]). Fig. 3 shows the pseudorapidity \((\eta)\) distribution of identified particles with transverse momentum \(p_T > 0.2\) GeV/c in inclusive \(e+p/Au\) DIS \((\gamma^*+Au, \gamma^* \rightarrow p)\) processes simulated using the EIC Monte Carlo BeAGLE [18 [19] with electron and ion beam energy of 10 and 27 GeV, respectively. The same is also repeated for inclusive \(e+p\) DIS using a PYTHIA 6.4 simulation resulting in very similar trends in the distributions. In these simulations, the virtuality of the exchanged photon is restricted to be \(Q^2 < 0.01\) GeV/c\(^2\) and photon energy is restricted to be \(E_\gamma < 2\) GeV to mimic \(\gamma+Au\) interactions in \(Au+Au\) UPCs at \(\sqrt{s_{NN}} = 54\) and 200 GeV. In the year 2017, when such a \(Au+Au\) \(\sqrt{s_{NN}} = 54\) GeV dataset was being accumulated, STAR mid-rapidity tracking was limited by the acceptance of the Time Projection Chamber (TPC) \(-1.0 < \eta < 1.0\) and the forward rapidity capability was limited to Beam-Beam Counters (BBCs) with an acceptance of \(3.8 < |\eta| < 5.1\), both of which measure charged hadrons. Fig. 3 shows the case in which the photon emitting ion was going in the negative rapidity or east going direction. As shown in Fig. 3 (left) a large amount of activity is seen in the west side BBC due to fragmentation protons while a gap is seen in the east side BBC. The pseudorapidity distribution of charged tracks that are mostly pions in the TPC is strongly asymmetric – this is something that can be measured and compared to model predictions. Most importantly the west side Zero Degree Calorimeter (ZDC) will see a few neutrons from the fragmenting ion while the east side ZDC will only see one or two neutrons due to Coulomb excitations that is not incorporated in these simulations. In terms of triggering the \(\gamma+Au\) interactions the most stringent selection criterion is that the ZDC east (ZDCE) detector should be restricted to have a single neutron hit (1n), while the ZDC west (ZDCW) is required to have more than one neutron (Xn) to trigger on \(\gamma+Au\) candidates with east-going photons, and vice versa. This additional requirement of single neutron hit (1n) instead of requiring zero neutrons (0n) in the photon-going direction can help us to reduce backgrounds from fixed target events and beam-gas events which also produce pseudorapidity asymmetry and can mimic \(\gamma+Au\) interactions. With
such a cut applied, additional asymmetric cuts on the BBCs help to improve the purity of our \(+\)Au interactions. The two timing detectors (VPDs) that measure the vertex positions in the collision direction can also be used to improve purity of the \(+\)Au candidates \cite{25}.

IV. TEST OF BARYON JUNCTION HYPOTHESIS WITH \(+ p/Au\) INTERACTIONS

We have demonstrated that it is possible to identify \(+\)A collisions at RHIC. Indeed, the STAR Collaboration has presented preliminary results of such process \cite{26}. Aforementioned, the first indication of a successful selection of \(+\)Au processes will be an asymmetric pseudorapidity distribution \(dN/d\eta\) of inclusive charged hadrons at mid-rapidity. This is shown in Fig. \[\text{left}\] from simulations of inclusive \(e+p, e+Au\) collisions mimicking UPC kinematics using PYTHIA 6.4 and BeAGLE event generators, respectively. Both the simulations predict similar distributions of \(dN/d\eta\) when normalized at \(\eta = 0\). On the same plot the predictions from UrQMD model for min-bias \(Au+Au\) collisions at \(\sqrt{s_{NN}} = 54\) GeV is also shown for which a cut of \(1Xn\) was applied. In this case a toy Monte Carlo was used to simulate the response of the ZDC detectors with inputs from STAR data on correlations between TPC and ZDC \cite{25}. Even after using cuts of ZDCs similar to what will be used for selection of \(+\)Au candidates by STAR one finds a very symmetric distribution of \(dN/d\eta\) for \(Au+Au\) events which is in high contrast to the PYTHIA and BeAGLE predictions. We also find that these events in UrQMD models that pass the \(1Xn\) criteria of ZDC are mostly ultra-central \(Au+Au\) events and can be eliminated by a cut of the total number of tracks in TPC. This limits the contamination of \(Au+Au\) events in \(+\)Au-rich event selection.

Given an enriched sample of \(+\)Au processes are collected in experiment, it is important to discuss the expectations of net-baryon distributions in such processes. For this we will consider net-protons as a proxy for net-baryons and use a PYTHIA 6.4 simulation that does not include baryon junctions. In \(+\)Au processes, since the photon fluctuates into a dipole of quark and antiquark, it would interact with one quark or a gluon junction creating mesons or baryons at mid-rapidity at the first-order perturbative limit. In this picture one would expect very little baryon stopping relative to the \(Au+Au\) collisions in the absence of a baryon-junction mechanism as shown in the PYTHIA simulation in Fig. \[\text{right}\]. In this figure the distributions of net particles (net-pion, net-kaon and net-protons) are plotted with \(y - Y_{beam}\) for \(+ p\) collisions. Here the photon-going direction is chosen to be along the negative rapidity direction. A much steeper distribution is observed for net-protons as compared to net-pion and net-kaon distributions. To guide the eye, two solid lines are drawn to demonstrate that PYTHIA 6.4 predicts a rapidity dependence of net-proton which is close to exp(2(\(y - Y_{beam}\))) as compared to exp(0.5(\(y - Y_{beam}\))) that is predicted for the stopping of baryon junctions.

The experimental measurements of baryon stopping by selecting \(+\)Au processes at RHIC is a work in progress.
Recently, the STAR Collaboration [26] presented the preliminary results on $\bar{p}/p$ ratio in $\gamma+Au$ relative to peripheral $Au+Au$ collisions at small transverse momentum at the Quark Matter 2022 conference. It indicates more baryon stopping in $\gamma+Au$ collisions. Further studies are ongoing in this direction. It is possible that the $\gamma+Au$ event selection of asymmetric multiplicity in the forward rapidities enhances the photon interactions with the baryon junctions in the nucleus [23]. Studying the dependence of the baryon rapidity shift as a function of rapidity relative to the ion beam rapidity and, if possible, at different beam energies would uniquely identify the stopping mechanism, and therefore providing insights into the carrier of the baryon number.

V. TEST OF BARYON JUNCTION HYPOTHESIS WITH ISOBAR COLLISIONS

The valence quarks carry electric charge, the question is whether at the same time they also carry the baryon quantum number. In the following discussions we refer electric charge as “charge” for simplicity. One of the most straightforward investigations of whether valence quarks carry baryon number is to study the correlations of charge and baryon stopping in $A+A$ collisions. Recent measurements of the Breit-Wheeler process in $A+A$ collisions. Recent measurements of the Breit-Wheeler process in $A+A$ collisions at RHIC [27] ($\gamma + \gamma \rightarrow e^+e^-$) and the LHC [28] ($\gamma + \gamma \rightarrow \mu^+\mu^-$) show that the experimental measurements, even in violent $A+A$ collisions, match well with the QED calculations [29]. Such QED calculations are performed with the assumption that projectile and target nuclear charge distributions maintain their trajectory and velocity throughout the course of the collisions. This seems to point to the possibility of a small charge stopping at the initial stage. It is actually challenging to perform an experimental measurement of charge stopping. It was proposed in the 1990s to use the forward bremsstrahlung to measure the charge stopping at the initial impact [30]. And while this was a creative idea, it is a very difficult proposal for experiments without a successful follow-up. For a recent proposal in this direction we refer the readers to Ref [31]. Another possibility is to directly measure the charge excess from the final-stage hadrons at the midrapidity. However, particle detectors usually have finite acceptance and tracking efficiency in momentum space and extrapolations of those particles to low momentum are different depending on the mass and collective effects expected to be present in heavy ion collisions. In addition, different interaction cross sections between positive and negative hadrons of interest with detector material complicates net-charge yield measurements. The situation is made worse due to the isospin balance in the final state. For example, in $p+p$ collisions, one would expect that $\pi^-/\pi^+ < 1$ and $\bar{p}/p < 1$ simply due to net positive charge of colliding protons. However, in $A+A$ collisions [1], one would expect $\pi^-/\pi^+ > 1$ and $\bar{p}/p < 1$ due to the detailed balance of isospin from neutron excess and most of the stable colliding nuclei going through processes such as $n + X \leftrightarrow p + \pi^- + X$. The charge excesses in pions and baryons have opposite sign in $A+A$ collisions and they would cancel to the first order. All of these complications have prevented previous experiments from obtaining a precise measurement of absolute charge stopping at midrapidity.

In 2018, RHIC performed a set of isobar collisions of $^{96}$Ru+$^{48}$Ru and $^{96}$Zr+$^{40}$Zr [13]. The data set collected by the STAR collaboration is of high statistics (2 Billion events/species) and quality. The isobar run was conducted in such a way that several aforementioned systematic uncertainties will be cancelled in the ratio of observables between the two isobar species. We propose that this can be used to study if valence quarks (reflected in the charge) and baryons are shifted to midrapidity from the beam rapidity (or stopped) in the same way. If the total charge and baryon number are shifted differently from beam rapidity to midrapidity, it would indicate that baryon number is not correlated with the valence quarks and may likely be carried by the baryon junction [16]. Measurements of net baryons at midrapidity can be performed using net protons as we discussed earlier. However, the absolute measurement of net charge is highly nontrivial. The net charge can be measured as $Q = (N_{\pi^+} + N_{K^+} + N_p) - (N_{\pi^-} + N_{K^-} + N_p)$. We propose a method to precisely measure the charge stopping using double ratios at midrapidity in isobar collisions. For example, the double ratio of pions can be defined as

$$R_{2\pi} = \frac{(N_{\pi^+}^{Ru}/N_{\pi^+}^{Zr})/(N_{\pi^-}^{Ru}/N_{\pi^-}^{Zr})}{(N_{\pi^+}^{Ru}/N_{\pi^+}^{Zr})/(N_{\pi^-}^{Ru}/N_{\pi^-}^{Zr})} \simeq 1 + \left(\frac{N_{\pi^+}^{Ru}/N_{\pi^+}^{Zr}}{N_{\pi^+}^{Zr}/N_{\pi^+}^{Zr}}\right)$$

(1)

expanding to first and second terms around $N_{\pi^+}/N_{\pi^-} - 1$ in each collision system. Similarly, for kaons and protons one can measure the corresponding double ratios $R_{2K}$ and $R_{2p}$. Therefore, the charge difference at midrapidity between the two isobar collision systems is:

$$\Delta Q = N_\pi [(R_{2\pi} - 1) + \frac{N_K}{N_\pi}(R_{2K} - 1) + \frac{N_p}{N_\pi}(R_{2p} - 1)] \equiv \frac{N_K}{N_\pi} R_{2K} + \frac{N_p}{N_\pi} R_{2p} \Delta Q_{\pi}$$

(2)

Here, the expansion approximation is again up to second term of $(N_{\pi^+}/N_{\pi^-} - 1)$ assuming $\Delta Q \ll Q \ll N_{\pi}$, and the notations $N_{\pi}$ refers to the average yield of $\pi^+$ and $\pi^-$ yields: $N_{\pi} = (N_{\pi^+} + N_{\pi^-})/2$. The same is true for kaons and protons: $N_K = (N_{K^+} + N_{K^-})/2$ and $N_p = (N_p + N_{\bar{p}})/2$. The preliminary data presented by the STAR Collaboration at the Quark Matter 2022 conference [22] indicate all the double ratios are at around $1 \times 10^{-3}$ with very small statistical and systematical uncertainties for all centralities. This confirms the validity of our approximation of $\Delta Q/N_{\pi} \simeq 10^{-3} \ll Q/N_{\pi} \simeq 10^{-2} \ll 1$. Since from RHIC A+A data [1] it is known that $N_K/N_{\pi} \simeq 0.1$ and $N_p/N_{\pi} \simeq 0.1$, we find $\Delta Q \simeq N_{\pi} \times 1.2 \times 10^{-3}$. This charge difference at midrapidity is expected to arise due to the charge difference in the atomic numbers between the isobars $\Delta Z = 44 - 40 = 4$ for $^{96}$Ru+$^{48}$Ru and $^{96}$Zr+$^{40}$Zr.
At the most fundamental level $\Delta Q$ will be related to the difference in the valence quark stopping between the two isobars. If the valence quarks also carry the baryon quantum number, $\Delta Q$ will be strongly correlated to the baryon stopping.

How does $\Delta Q$ compare to the expected charge difference if all the baryon stopping also shifts the valence quarks? The baryon stopping in 20-50% isobar collisions should be similar to 50-60% $Au+Au$ collisions and is the same for $Ru+Ru$ and $Zr+Zr$ due to the same mass number ($A=96$). From Table VIII of Ref. [1], we obtain $(N_p - N_p)/N_x = 0.02 \pm 0.002$. The baryon-to-pion ratio is $B/N_x = A_f \times (N_p - N_p)/N_x$ where $A_f$ is isospin factor with an imbalance between final-state neutrons and protons $[\text{1}]^{33}$ and estimated to be 2.2. Therefore, $B/N_x = 0.044$. If this baryon stopping is completely due to valence quark stopping, we would expect the charge stopping to be $\Delta Q' = \Delta Z/A \times B = N_x \times 4/96 \times 0.044 \simeq N_x \times 2 \times 10^{-3} \simeq 2 \times \Delta Q$. This indicates that the baryon stopping is about a factor of 2 larger than the charge stopping. However, it is important to reduce all the uncertainties and study potential small effects from nuclear structures $[31]$ to make a discovery. The precise charge stopping measurement is a crucial experimental advance uniquely enabled by the isobar collisions.

VI. OPPORTUNITIES WITH FUTURE RHIC RUN AND EIC

Recently collected data and remaining years of RHIC runs along with the extended pseudorapidity reach offered by the recent upgrade of the STAR detector will provide unique opportunities for future measurements. The forward and the mid-rapidity upgrade program of STAR that includes: 1) the inner Time Projection Chamber (iTPC, $-1.5 < \eta < 1.5$), 2) highly granular forward Event-Plane Detectors (EPD, $2.1 < |\eta| < 5.1$) and, 3) newly installed forward tracking and calorimetry system (FTS & FCS, $2.5 < \eta < 4$). With the combination of these three sub-systems the asymmetric pseudorapidity distributions of charged hadrons in $\gamma+Au$ interactions can be captured over six units of pseudorapidity. This will improve the trigger purity and will provide a wider range of rapidity for net-baryon measurements.

The $\gamma + p$ candidates will be triggered by detecting one neutron (1n) in the deuteron going direction and simultaneously requiring no restrictions on neutron (Xn) in the gold going direction in $d+Au$ collisions for which an online trigger was installed during the 2021 year of data taking. Similar cuts can also be applied to select $\gamma+Au$ interactions in $Au+Au$ UPCs at $\sqrt{s_{NN}} = 200$ GeV for datasets from the years 2019 and 2023-25. During the collection from the year 2019, wide acceptance EPDs were already installed that help improve the trigger purity by requiring asymmetric hits in the east and west sub-systems. For the anticipated 2023 and 2025 runs, the forward tracking and calorimeter systems will be fully operational $[35]$. An anticipated $p+Au$ run of RHIC in the year 2024 will provide an opportunity to collect a high statistics sample of $\gamma + p$ processes.

Measurements of photonuclear collisions at the LHC have reduced background from hadronic peripheral collisions by requiring what they call “pseudorapidity sum-gaps”. These are cuts that select for events where the particles produced on the photon-going side are more spread out in space than the particles produced on the ion-going side. This is done by ordering the measured tracks and clusters for a given event in $\eta$ and summing the difference in $\eta$ for adjacent particles, $\Delta \eta$. Such a criterion increase the purity of the $\gamma + A$ sample by requiring the sum-gap on the photon-going side, $\Sigma, \Delta \eta$, to be large $[22, 36]$. Guidance from model calculations are used to obtain the optimum value of $\Sigma, \Delta \eta$ cut. A similar approach can be adopted using the extended pseudorapidity capabilities of the STAR detector for $Au+Au$ run in the year 2023-25.

In our study, we use event generators in $e+A$ and $e+p$ collisions to study the photonuclear process. It is clear that such semi-inclusive processes could be cleanly identified and analyzed in the future EIC since there is no background nucleus-nucleus collisions. In addition, the dependence of the stopping with photon virtuality $\gamma^* + A \rightarrow X + p$ can be performed in the future EIC. However, it does require that the detectors that can cleanly identify protons and antiprotons at low momentum. Our proposal will also complement measurements of backward photoproduction of mesons at the EIC in exclusive processes such as $\gamma^* + p \rightarrow \omega + p$ at far-forward rapidity $[37, 39]$. For a detailed discussion on the connection of such processes with baryon stopping we refer the readers to Ref $[40]$.

VII. SUMMARY

Baryon number is one of the most strictly conserved physics quantities in the Universe. We presented three possible observables which may shed light into what carries this quantum number: is it quarks or a gluonic topological junction? All evidence points to the possibility of a gluon junction playing a significant role in the baryon stopping experimentally observed in rapidity distributions in central $A+A$, isobar and $\gamma+A$ collisions. Future data analyses and experiments with the proposed observables would provide conclusive answers to this fundamental question.

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