Dependence of net-hyperon production at mid-rapidity on beam energy and its implication on baryon number carrier

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Abstract. The conventional picture of baryon number is that each valence quark inside a baryon carries 1/3 unit of baryon number. However, an alternative picture exists where the center of a Y-shaped topology of gluon fields, called the baryon junction, carries 1 unit of baryon number. Previous analysis suggests that the nature of the baryon number carrier is sensitive to net-proton yields at mid-rapidity in heavy-ion collisions, and experimental measurements potentially challenge the conventional picture. In this study, we analyzed published data from the BES-I program at RHIC, which performed Au+Au collisions at center-of-mass energies ranging from 7.7 to 200 GeV. We investigated the rapidity dependence of net-hyperon yields after correcting for strangeness production suppression, and found that the net-hyperon yields at mid-rapidity follow an exponential dependence on the beam rapidity. This behavior is consistent with Regge model predictions. Moreover, the exponential slopes for net-Λ, net-Ξ, and net-Ω are consistent with each other, suggesting that the baryon transport is flavor blind. Conventional models like `PYTHIA`, which use valence quarks as the baryon number carrier, have difficulty reproducing this transport behavior.

1 Introduction

The baryon number (B) is a conserved quantity in quantum chromodynamics (QCD). While mesons, like pions and kaons, carry zero baryon number ($B = 0$), baryons such as protons and neutrons carry one unit ($B = 1$). The conventional quark model assigns 1/3 unit of the baryon number to each quark. However, an alternative theory proposes that the entire unit of the baryon number is carried by the baryon junction, a non-perturbative Y-shaped topology of gluons connected to all three valence quarks. Neither scenario has been verified experimentally. Recent proposals have outlined experimental approaches to distinguish these scenarios in high-energy hadronic and photon-induced collisions [1].

Here, we report the dependence of net-hyperon yields, after correcting for the strange quark production suppression, on δy by compiling published data on hyperon production at mid-rapidity in heavy-ion collisions. Here, $\delta y = y_{beam} - y_{CM}$, where y_{beam} is the beam rapidity and $y_{CM} \sim 0$ denotes the rapidity where the net-hyperon yields are measured. Such a dependence is quantified by fitting the net-hyperon yields with $f(\delta y) \sim e^{-\alpha_B \delta y}$. Since baryon junction is flavor blind [1], one would expect the transport behavior of hyperons to resemble that of inclusive baryons. Specifically, we will inspect if the fitted α_B for net-Λ, net-Ξ and net-Ω are consistent with each other and with that of net-p at various centralities. Furthermore, predictions of α_B for net-hyperons from various versions and tunes of the `PYTHIA` event generator will be compared to our results.

2 Beam energy dependence of net-hyperon yields

Using published data from RHIC BES-I program, we compute net-Λ, net-Ξ and net-Ω yields, $(dN/dy)_{\Lambda-\bar{\Lambda}}/\langle N_{\text{part}}\rangle$, $(dN/dy)_{\Xi-\bar{\Xi}}/\langle N_{\text{part}}\rangle$, and $(dN/dy)_{\Omega-\bar{\Omega}}/\langle N_{\text{part}}\rangle$, within the rapidity range of $|y| < 0.5$ in Au+Au collisions at center-of-mass energies ($\sqrt{s_{\text{NN}}}$) of 7.7, 11.5, 19.6, 27, 39, 62.4 and 200 GeV [2–5]. Here $\langle N_{\text{part}}\rangle$ is the average number of participating nucleons in a given centrality class of Au+Au collisions.

Since strange quarks must be pair-produced, we need to account for the effects associated with the strange quark production to isolate the effect of baryon transport. We gauge the difficulty of strange quark production using the $K^-(s\bar{u})/\pi^-(d\bar{u})$ yield ratio in Au+Au collisions. The correction for the strangeness production suppression is performed by dividing the net-hyperon yields by $(K^-/\pi^-)^n$, where n is the number of valence strange quarks in the hyperon. Figure 1 shows that net-hyperon yields follow exponential dependence on δy as the Regge theory predicted. The fitted α_B values are shown in Fig. 2a, and they agree with each other within 2σ for all hyperons and net-protons. There is a mild centrality dependence for peripheral collisions, but it disappears if we use K^-/π^- from 0-10% centrality for all centralities instead as Fig. 2b shows. It indicates that this centrality dependence is a result of changes in K^-/π^- ratio in peripheral collisions, rather than a change in baryon transport mechanism.

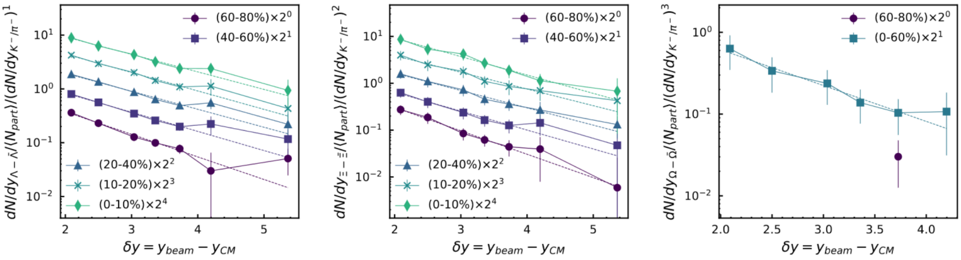
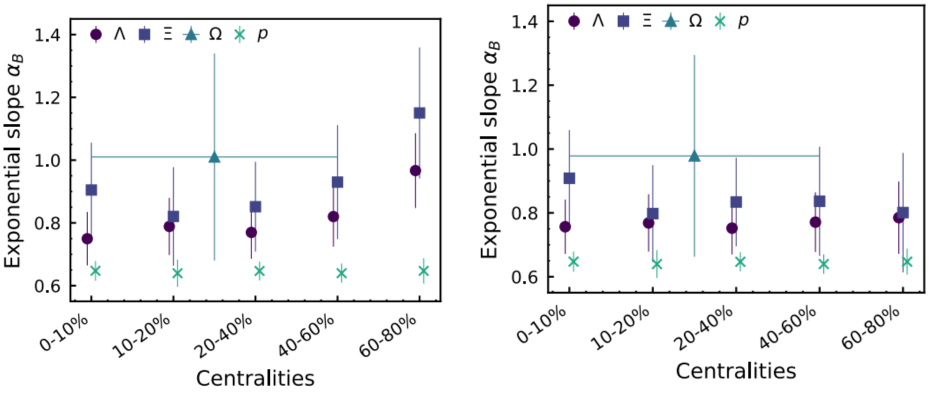


Figure 1: Net-Λ (left), net-Ξ (central) and net-Ω (right) yields within $|y| < 0.5$ as a function of δy in Au+Au collisions. These yields are scaled by $(K^-/\pi^-)^n$ in Au+Au collisions, where n is the number of valence strange quarks in the hyperon.

The independence of α_B on centrality shows that α_B is not affected by superfluous processes such as multiple scattering and reflects the inherent properties of baryon stopping mechanism, and therefore Au+Au results should be comparable to results from systems of other sizes. When other published data for Pb+Pb collisions at CERN SPS [6, 7] and by ALICE [8, 9], for 200 GeV Cu+Cu collisions by STAR [3], and for 200 GeV and 900 GeV p+p collisions by STAR [10] and ALICE [11] are included in the fit for central collisions, α_B values remain unchanged with combined fits show $\alpha_B(\Lambda) = 0.72 \pm 0.06$, $\alpha_B(\Xi) = 0.93 \pm 0.12$ and $\alpha_B(\Xi) = 1.02 \pm 0.32$. Values for Au+Au only fit can be found in Table 1.

3 Comparison between data and `PYTHIA`

Here, we compare slope parameters in p+p collisions predicted by the `PYTHIA` event generator, which employs valence quarks as the baryon number carriers, to those in Au+Au



(a) K^-/π^- varies with centralities.

(b) Always use K^-/π^- at 0-10% centrality.

Figure 2: Comparison of slope parameters for net-Λ, net-Ξ, net-Ω and net-p as a function of centrality from Au+Au collisions at $\sqrt{s_{\rm NN}}$ = 7.7 - 200 GeV. (a) used K^-/π^- at varying centralities, while (b) only used K^-/π^- at 0-10% for net-hyperon of different centralities.

Table 1: α_B values from measurements and `PYTHIA`.

	Data (0-60%)	Ver. 6.4	Ver. 6.4 (P0)	Ver. 6.4 (P12)	Ver. 8.3	Ver. 8.3 CR
Λ	0.72 ± 0.07	2.58 ± 0.03	1.15 ± 0.01	0.81 ± 0.01	1.18 ± 0.01	0.88 ± 0.01
Ξ	0.85 ± 0.13	N.A.	0.73 ± 0.05	0.52 ± 0.05	0.62 ± 0.08	0.55 ± 0.06
Ω	0.98 ± 0.32	N.A.	0.25 ± 0.10	0.04 ± 0.15	N.A.	N.A.
p	0.65 ± 0.07	0.74 ± 0.05	0.72 ± 0.02	0.35 ± 0.01	0.98 ± 0.02	0.69 ± 0.02

collisions. The fitted α_B values from `PYTHIA` are compared to measurements in Table 1. Values for some configurations of `PYTHIA` are marked as "N.A.", corresponding to cases where the `PYTHIA` distribution was not fitted due to presence of negative net-hyperon yield at any beam energy.

Not only does `PYTHIA` fail to reproduce the measured α_B, it also shows strong variations across hyperon species. `PYTHIA` 8.3 CR, which includes a partial implementation of the baryon junction picture, performs better than its non-CR counterpart as its predicted α_B values are closer to the measured values for both net-proton and net-Λ. This underscores the potential of implementing the baryon junction mechanism. However, it still fails to reproduce the slope parameter for net-Ξ and net-Ω, and does not eliminate the flavor dependence, as α_B values change significantly between net-Λ, and net-Ξ. This calls for a genuine inclusion of the baryon junction mechanism in event generators for a more rigorous test.

4 Summary

We investigated the validity of the baryon junction picture by analyzing net-hyperon yields in Au+Au collisions from RHIC BES-I program. After accounting for the difficulty associated with the strange quark production by dividing net-hyperon yield with $(K^-/\pi^-)^n$, net-hyperon yields at mid-rapidity ($|y| < 0.5$) exhibit the expected exponential dependence on beam rapidity. The extracted exponential slopes (α_B) for net-Λ, net-Ξ, and net-Ω are consistent with each other within uncertainty, which suggests a common transport mechanism for different hyperons and supports a flavor-blind baryon junction scenario. Predictions from different versions and tunes of `PYTHIA` event generator, which assigns baryon number to valence quarks in the incoming protons, are unable to replicate the transport behaviors for all the baryons examined.

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