Tracking the baryon number with heavy-ion collisions

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2023 Annual RHIC and AGS Users' Meeting

Supported in part by:
What carries baryon number, quark vs. baryon Junction?

Conventional picture

Baryon Junction [1, 2]

Net-Baryon at mid-rapidity

- Net-Baryon = $p - \bar{p}$.
- More baryons than antibaryons, even at midrapidity.
- Expected yield of $p - \bar{p}$ is low. Collision time is too short for a lot of valence quarks to be stopped.

Net-Baryon at mid-rapidity

• Changes with collision energy
  • Higher energy => Less interaction time.

• Normalized net-Baryon yield at mid-rapidity shows a clear exponential dependence on $\delta y$.
  • Exponential factor too small to be explained by the valence quark picture.

C. Shen and B. Schenke, PRC 105, 064905 (2022)
Baryon stopping from Junction

- Quarks carry most momentum and are contracted into thin “pancakes” at high energy.
  - Quarks have less time to interact due to contracted longitudinal length.

- Junction carries lower momentum and is less contracted.
  - Junction is made of low-x gluons.
  - More time to interact with other partons.
  - Enhanced baryon stopping at mid-rapidity.

Figure from D. Kharzeev, Physics Letters B 378, 238 (1996)

Baryon stopping from Junction

- Three methods to test the hypothesis:
  - Net-proton yield as a function of rapidity in hadronic Au+Au collisions.
  - Net-Baryon in photonuclear collisions.
Beam energy dependence using Au+Au results from BES-I data
Net-proton yield at mid-rapidity as a function of beam rapidity in hadronic Au+Au collisions

- Regge theory predicts \( \left. \frac{dN}{dy} \right|_{y=0} \propto e^{-ay_{\text{beam}}} \).
- Measured \( a \approx 0.65 \).
- Expected \( a \approx 2.5 \) from PYTHIA 6.4 e + p simulation [1, 2, 3].
- Slope does not depend on centrality.
  - Not caused by multiple scatterings.

**Au + Au BES-I data**
STAR, PRC 79, 034909 (2009) and STAR, PRC 96, 044904 (2017)

![Net-proton yield graph](chart.png)

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Net-Baryon vs. Net-Electric charge in Isobar collisions
Electric charge of quarks

Figure 5.3. Experimental measurements of the total cross section for the reaction $e^+e^- \rightarrow$ hadrons, from the data compilation of M. Swartz, Phys. Rev. D (to appear). Complete references to the various experiments are given there. The measurements are compared to theoretical predictions from Quantum Chromodynamics, as explained in the text. The solid line is the simple prediction (5.16).

$$\sigma(e^+e^- \rightarrow \text{hadrons}) \xrightarrow{E_{cm} \rightarrow \infty} 3 \cdot \left(\sum_i Q_i^2\right) R_i,$$

(5.16)

M. E. Peskin, D. V. Schroeder, An Introduction to Quantum Field Theory, Addison-Wesley Publishing Company, 1995
Net-Baryon (B) vs. Net-Charge (Q)

- Charged meson: Carry Q.
- Proton: Carry B and Q.
- Neutron: Carry B.
- Define $\Delta Q = Q(R_u + R_u) - Q(Z_r + Z_r)$

**Question:** $\Delta Q = \frac{B A Z}{A}$ (at $|y| < 0.5$).

- $B = (N_p - N_{\bar{p}}) + (N_n - N_{\bar{n}})$
- $Q = (N_{\pi}^+ + N_{K}^+ + N_p) - (N_{\pi}^- + N_{K}^- + N_{\bar{p}})$
If quarks carry the baryon number

- $B_{\text{init}} = 96 \times \text{Const.}$
- $\Delta Q_{\text{init}} = Q_{\text{init}} (R_u - Z_r) = 96 \times \text{Const} \times 4/96.$
- If baryon number and charge number are carried by quarks, $B/\Delta Q \times \Delta Z/A$ should be 1 throughout the collision evolution at mid-rapidity.

\[ B = (N_p - N_\bar{p}) + (N_n - N_\bar{n}) \]
\[ Q = (N_{\pi^+} + N_K^+ + N_p) - (N_{\pi^-} + N_K^- + N_\bar{p}) \]

- For $R_u$, $A = 96$, $Z = 44$
- For $Z_r$, $A = 96$, $Z = 40$

Tot. Baryon = $96 \times \text{Const}$
Tot. p = Tot. Baryon $\times Z/A$
If Baryon Junction carries the baryon number

- Baryon Junction only carries a fraction of valence quark’s momentum.
- Junction has enough time to interact -> More baryon stopping.
- Net-Baryon > Net-Charge.

\[ B = (N_p - N_{\bar{p}}) + (N_n - N_{\bar{n}}) \]
\[ Q = (N_{\pi^+} + N_{K^+} + N_p) - (N_{\pi^-} + N_{K^-} + N_{\bar{p}}) \]

Somewhere above 1

Ru or Zr
- For Ru, A = 96, Z = 44
- For Zr, A = 96, Z = 40

\[ \text{Tot. Baryon} = 96 \times \text{Const} \]
\[ \text{Tot. p} = \text{Tot. Baryon} \times \frac{Z}{A} \]
Net-Baryon number ($B$)

- $B = (N_p - N_{\bar{p}}) + (N_n - N_{\bar{n}})$.

- We don’t measure (anti-)neutron spectrum. Approximated by thermal model assumption.

- $B = (N_p - N_{\bar{p}}) + N_{\bar{p}} \sqrt{\frac{N_d}{N_{\bar{d}}}} - N_p \sqrt{\frac{N_{\bar{d}}}{N_d}}$.

Assumption

In the framework of statistical thermal models [58] the particle multiplicity from a source of volume $V$ and chemical freeze-out temperature $T$ is given by

$$N_i = \frac{g_i V}{\pi^2 m_i^2} T K_2(m_i/T) \exp(\mu_i/T),$$

(7)

where $g_i$, $m_i$, and $\mu_i$ are the degeneracy, particle mass, and chemical potential of particle species $i$, respectively. This formula is valid in the Boltzmann approximation, which is reasonable for all hadrons and light nuclei. The chemical potential can be expressed as $\mu_i = B_i \mu_B + S_i \mu_S + Q_i \mu_Q$, where $B_i$, $S_i$, and $Q_i$ are the baryon number, strangeness, and charge, respectively, of particle species $i$, and $\mu_B$, $\mu_S$, and $\mu_Q$ are the corresponding chemical potentials for these conserved quantum numbers.

Extracted from STAR Collaboration, PRC 99, 064905 (2019)
Net-Charge difference (Ru+Ru – Zr+Zr)

- Define $R_{2\pi} = \frac{(N^+_\pi/N^-_\pi)_{Ru}}{(N^+_\pi/N^-_\pi)_{Zr}}$
- Define $\Delta Q = [(N^+_\pi + N^+_K + N_p) - (N^-_\pi + N^-_K + N_\bar{p})]_{Ru} - [N^-_\pi + N^-_K + N_\bar{p}]_{Zr}$
- $R_{2\pi} = \frac{(N^+_\pi/N^-_\pi)_{Ru}}{(N^+_\pi/N^-_\pi)_{Zr}} \approx \frac{1+(N^+_\pi-N^-_\pi)/N_-\pi}{1+(N^+_\pi-N^-_\pi)/N^-_\pi} \approx 1 + \Delta R_{Ru} - \Delta R_{Zr}$
- Focus on pion terms,
  - $(N^+_\pi - N^-_\pi)_{Ru} - (N^+_\pi - N^-_\pi)_{Zr} = N_{\pi, Ru} \times \Delta R_{Ru} - N_{\pi, Zr} \times \Delta R_{Zr}$
  - $\approx N_{\pi} (\Delta R_{Ru} - \Delta R_{Zr}) = N_{\pi} \times (R_{2\pi} - 1)$
- Where $N_{\pi} = 0.5 \times (N^+_\pi + N^-_\pi)$.
- Therefore, $\Delta Q = N_{\pi}(R_{2\pi} - 1) + N_K(R_{2K} - 1) + N_p(R_{2p} - 1)$.
- Double ratio reduces systematics uncertainty.
Recap what are needed.

• For baryon stopping $B$,
  • $N_p, N_{\bar{p}}, N_d, N_{\bar{d}}$ for Ru+Ru and Zr+Zr.

• For charge stopping difference $\Delta Q$,
  • $N^+_\pi, N^+_K, N_p, N^-\pi, N^-K, N_{\bar{p}}$ for Ru+Ru and Zr+Zr.
  • $R2_\pi, R2_K, R2_p$. 
STAR detector

- **Time Projection Chamber (TPC)**
  - Measures charged particle momentum with track curvature under B-field.
  - Identifies particle with energy loss per unit length (dE/dx).

- **Time-Of-Flight (TOF)**
  - Extends momentum range for particle identification.
  - Pile-up rejection.

- **Zero Degree Calorimeter (ZDC)**
  - Detect forward neutrons for event selection.

- **Beam-Beam counter (BBC)**
Spectra from Isobar

STAR Preliminary, $|y| < 0.5$,
Ru + Ru $\sqrt{s_{NN}} = 200$ GeV

\[ d^2N/(2\pi p_T dp_T) \text{[(GeV/c)^{-2}]} \]

Transverse Momentum $p_T$ (GeV/c)

No feed-down correction

$\pi^+$

$\pi^-$

$p$

$\bar{p}$

$K^+$

$K^-$

$\text{Blast-wave}$

$0 - 10 \% x^2$

$10 - 20 \% x^2$

$40 - 60 \% x^2$

$60 - 80 \% x^2$

STAR Preliminary, $|y| < 0.5$,
Zr + Zr $\sqrt{s_{NN}} = 200$ GeV

No feed-down correction

$\pi^+$

$\pi^-$

$p$

$\bar{p}$

$K^+$

$K^-$

$\text{Blast-wave}$

$0 - 10 \% x^2$

$10 - 20 \% x^2$

$40 - 60 \% x^2$

$60 - 80 \% x^2$
Double ratio R2s

π⁺/π⁻

K⁺/K⁻

STAR Preliminary
Isobar $\sqrt{s_{NN}}=200$ GeV
$-0.5 < y < 0.5$
statistical uncertainty only

$p/p$

Y. Li, QM22
Net-Charge and Net-Baryon compared to UrQMD separately

- UrQMD accurately reproduces baryon stopping at mid-rapidity in central collisions but not $\Delta Q$, probably because UrQMD has been tuned to net-proton measurements.
- Accurate measurement of charge stopping can be used for model tuning.
Experimental result on Net-Charge and Net-Baryon

- $B/\Delta Q \times \Delta Z/A > 1$.
- Model calculations (Herwig $p + p$ (B/Q*Z/A, $Z=A=1$) [1] and UrQMD [2]) cannot describe our data.
- Decrease with decreasing $\langle N_{\text{part}} \rangle$.
  - Similar trend seen in Trento model [3].
  - Trento model accounts for initial conditions only.
  - Consistent with change in neutron skin thickness differences.

[3]: H. Xu et al, PRC 105, L011901 (2022)
Net-Baryon in photonuclear collisions
Net-Baryon in photonuclear collisions

- Inclusive particle production in photonuclear collisions.
  - Large flux of quasi-real photons produced by ultra-relativistic large-Z nuclei.
  - Similar to eA collisions except that the photon has almost zero virtuality.
  - Probes the nucleus at low-\( x \).
Net-Baryon in photonuclear collisions

If Junction hypothesis is true:
• Quasi-real $\gamma \rightarrow q\bar{q}$.
• Interact with a Junction in target Au nucleus.
• Enhanced creation of mid-rapidity baryons.
  • Junction interaction time > quark interaction time.
  • More baryons are stopped in Junction picture.
• Regge theory: $dN/dy \propto e^{-\alpha_B(y-y_{beam})}$ in the direction of the target.
  • $\alpha_B$ is related to Regge intercept of Junctions (J. D. Brandenburg, N. Lewis, P. Tribedy, Z. Xu, arXiv:2205.05685 (2022)).
Selecting photonuclear events in Au + Au collisions at $\sqrt{s_{NN}} = 54.4$ GeV

- Asymmetric collision: target can only be traveling in one direction.
- Select events with,
  - Single neutron (1n) on ZDC east (ZDCE).
  - No activity in BBC east.
  - Multiple neutron (Xn) on ZDC west (ZDCW).
  - Activity in BBC west.
  - $|V_z^{(VPD)} - V_z^{(TPC)}| > 10$ cm.
  - vice versa (east $\leftrightarrow$ west).

Rapidity asymmetry in $\gamma A$-rich events


STAR Preliminary Au+Au 54.4 GeV

Chun Yuen Tsang, 2023 Annual RHIC and AGS Users' Meeting 2023
Net-proton yield as a proxy for Net-Baryon

• Net-proton yield is described by $\exp(-(1.06 \pm 0.05)y)$.

• PYTHIA-6, which has valence quarks as baryon number carrier, predicts a dependence of $\exp(-2.43y)$[1, 2, 3].

Net-proton exponential slope ($\alpha_B$)

- $\alpha_B \sim 0.6$ for Au+Au [1, 2].
- $\alpha_B \sim 1$ for $\gamma + \text{Au}$.  
- Predicted values from HERWIG and PYTHIA (both versions) disagree with data. 
  - PYTHIA 8 includes a Junction-like mechanism in final-state hadronization [3]. 
- Slopes for Junction-Junction (J+J) and Junction-Pomeron (J+P) predictions are more compatible with data [4].

Conclusion

• Exponential slope of mid-rapidity net-proton yield in hadronic Au+Au from BES-I < theoretical predictions.

• Observed significant net-proton yield $\gamma + \text{Au}$ collisions, whose slope against rapidity is smaller than that from PYTHIA and HERWIG without baryon junction.

• Ratio of baryon to charge number difference is observed to be larger than 1 using Ru+Ru and Zr+Zr collisions at $\sqrt{s_{NN}} = 200$ GeV.

• Our results disfavor the assertion that valence quarks carry the baryon number.
Backup slides
Photon interactions in ultra-peripheral heavy ion collisions

- Ultra-relativistic, high-$Z$ nuclei produce highly Lorentz-contracted EM fields.

- Equivalent Photon Approximation (EPA): EM fields can be quantized as a flux of quasi-real photons.
  - C. F. von Weizsacker, Z. Phys. 88, 612 (1934)
  - E. J. Williams, Phys. Rev. 45, 729 (1934)
  - X. Wang, et al, PRC 107, 044906 (2023)

Figure from D. Brandenburg WWND 2020
Defining $\gamma A$ and $AA$ event classes

Most photonuclear events have low multiplicity, consistent with very peripheral $Au + Au$ collisions.

Using 60 – 80% peripheral collisions as a baseline and to estimate behavior of peripheral background.
Vanishing baryon stopping at LHC energies

- $\bar{p}/p$ ratio is consistent with 1 for midrapidity Pb + Pb, $\sqrt{s_{NN}} = 2.76$ TeV.
- About 0.8 for Au + Au, $\sqrt{s_{NN}} = 200$ GeV.

Baryon stopping at lower energies
Baryon stopping at Lower Energies

\[ \sqrt{s_{NN}} = 3 \text{ GeV} \]

2/(N_{part}) dN/dy_{p-p}(y=0)

Central A+A collisions

Fit: \( 1.1 \exp(-0.61 \delta y) \)

STAR Preliminary

Nicole Lewis, CFNS Seminar

35
Y-Shaped baryon flux-tube in lattice QCD

• Some lattice calculations have suggested the formation of a Y-shaped color flux tube among the three quarks at long distances

• Still under investigation

String Junction model

- **3D hybrid model:**
  GLAUBER + MUSIC + URQMD Model

- **String Junction** where the baryon charge of the string can fluctuate towards the center of the string with tuning parameter $\lambda_B$
  - $\lambda_B = 0.2$ reproduces the $dN/dy$ of net-protons at STAR
  
  C. Shen and B. Schenke, PRC 105, 064905 (2022)

Plot from Wenbin Zhao, BES-Tea Seminar 2022
Systematic uncertainties for isobar analysis

- Pions, Kaons and proton High and Low:  
  - High: spectrum*(1 + err) from Yang.  
  - Log: spectrum*(1-err).  
- pT > 0.55 or 0.56:  
  - Change pT/A threshold for extrapolation.  
- Levy, Exp and Tsallis:  
  - Function used for extrapolation.  
- IndT, PDMSepT:  
  - Default setting on Blast-wave requires particle anti-particle pair to have same temperature.  
  - IndT: each particle can have different temperature.  
  - PDMSepT: mesons (Kaons and Pions) need to have identical T.  
- VaryCut:  
  - nHitsFit >= 20, nHitsDeDx >= 15.  
- D MSq tight/wide:  
  - Fit range for D mass-square changes.  
    - Tight: 2.5 < M^2 < 4.5.  
    - Wide: 2.1 < M^2 < 4.9.  
    - Default: 2.3 < M^2 < 4.7.  
- P KnockOut High/Low: err from Yang.  
- D KnockOut nar: PID with \[ \left| \frac{1}{\beta_{TPC}} - \frac{1}{\beta_{TOR}} \right| < 0.03 \].  
- D KnockOut ExpBKG: use exponential instead of Log-Gaus background.
## Percentage systematic uncertainty by source

<table>
<thead>
<tr>
<th>Source</th>
<th>0 - 10 %</th>
<th>10 - 20 %</th>
<th>20 - 40%</th>
<th>40 - 60 %</th>
<th>60 - 80 %</th>
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</thead>
<tbody>
<tr>
<td>Signal Extraction</td>
<td>0.17</td>
<td>0.01</td>
<td>0.17</td>
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<tr>
<td>Extrapolation</td>
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<td>2.46</td>
<td>2.49</td>
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<td>6.25</td>
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<tr>
<td>Vary nHits</td>
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<td>D MSq fit</td>
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<td>0</td>
<td>0.52</td>
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<tr>
<td>Knock-out variation</td>
<td>1.22</td>
<td>1.19</td>
<td>1.47</td>
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<td>2.97</td>
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<tr>
<td>All</td>
<td>4.87</td>
<td>2.73</td>
<td>3.07</td>
<td>5.04</td>
<td>6.92</td>
</tr>
</tbody>
</table>
Net-Charge and Net-Baryon at $|y| < 1.0$, Predicted by UrQMD

![Graph showing the net-charge and net-baryon distribution with fit formula $\frac{dQ}{dy} = a x (\frac{dB}{dy})^n$.](image)
Photonuclear event selection: using rapidity gaps


For data collected in 2017, Au + Au collisions at $\sqrt{s_{NN}} = 54.4$ GeV, trigger did not require coincidence in both sides of the detector.


Chun Yuen Tsang, 2023 Annual RHIC and AGS Users’ Meeting 2023
Photonuclear event selection: identifying the single neutron peak

Low multiplicity events collected with ZDC triggers. Cutting on single neutron peak, dominated by $\gamma + A$ events.
Photonuclear event selection: $dN/d\eta$ with and without BBC and VPD Cuts

Normalized by the total amount of tracks per $\eta$ bin
Photonuclear analysis
Estimating background contamination from peripheral collisions

Estimate background contribution utilizing ZDC ADC distributions of peripheral events, 80-100% Centrality.

• Scale down so the tail matches \( \gamma A \)-enriched events, for ADC between 250 and 800.
• Background fraction \( \sim 10\% \).
Analysis procedures for photonuclear events

- **Track cuts:**
  - Must be primary tracks.
  - Must be TOF matched.
  - nHitsFit > 15.
  - DCA < 3 cm.
  - $|\eta| < 0.75$.
  - $p_T > 0.2$ GeV/c.
  - Proton PID: $0.7 < m^2 < 1.06$ GeV/c$^2$.

- **Apply event and track cuts and measure spectra as a function of $m_T - m_p$ and $y$ for:**
  - Photonuclear events.
  - Peripheral $AA$ events with centrality 60-80% to estimate behavior of hadronic peripheral event contamination.
Analysis procedures for photonuclear events

- Correct for:
  - Energy loss.
  - Tracking efficiency.
  - TOF matching efficiency.
  - Knock out protons.
  - Incorrectly reconstructed tracks by fitting \( m^2 \) distribution with student-t function.
  - Contamination from peripheral events.

\[
Y_{p}^{YA-\text{rich}} = \frac{Y_{p}^{YA+AA} - rf \ Y_{p}^{AA}}{1 - rf}
\]

- Fit spectra with a Levi fit function to extract \( dN/dy \).

\( r \) – Peripheral event contamination
\( f \) – Multiplicity factor
Low $p_T$ baryon enhancement in $\gamma A$

- Double ratio: antiparticle/particle in $(\gamma A)/(AA)$.
- $\bar{p}/p < 1$ for $p_T \lesssim 1$ GeV/$c$.
  - Indication of soft baryon stopping in $\gamma A$ collisions.
- Not corrected for efficiency, but largely cancels in the double ratio.
Fitting to PYTHIA data

- **γ + Au-rich points acceptance:**
  \[-4.6 \lesssim y - Y_{beam} \lesssim -3.4\]
- **Central value fit range:**
  \[-4.0 < y - Y_{beam} < -0.81\]
- **Estimate Uncertainty by adjusting fit range:**
  \[-4.0 < y - Y_{beam} < -0.61\]
  \[-4.0 < y - Y_{beam} < -1.01\]
- **Slope:** 2.43 ± 0.30.
- Going to run more events in PYTHIA to have better coverage over our data acceptance.

Exponential Slope: \(f(y - Y_{beam}) = A \exp(b \times (y - Y_{beam}))\)

<table>
<thead>
<tr>
<th>PYTHIA 6.4 - ep 10 × 27 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Q^2 &lt; 0.01 \text{ (GeV/c)}^2), (E_\gamma &lt; 2 \text{ GeV}), (0.4 &lt; p_T &lt; 1.2 \text{ GeV/c})</td>
</tr>
</tbody>
</table>
Virtuality of ultra-peripheral Au + Au

$\sqrt{s_{NN}} = 54$ and 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 $E_\gamma = \gamma_L (\hbar c / R_A) = 0.8 - 2.8$ GeV. The virtuality and transverse momentum are $Q^2 \approx (E_\gamma / \gamma_L)^2 \approx (\hbar c / R_A)^2 = 0.0008$ GeV$^2$. The typical range of the center of mass energy of the photon-nucleon 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 [36]. However, it is

n/p ratio from Hijing all centralities
Thank you