Experimental findings on the Gluon Topology from BES-I and Isobar data

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- baryon number carrier
- Three experimental approaches at RHIC
- Earlier theory and experiment work on pp and ep
- Implication for fluctuations and future perspectives


INT 20r-1c Chirality and Criticality, 2023
Baryon Number (B) Carrier

• Textbook picture of a proton
  • Lightest baryon with strictly conserved baryon number
  • Each valence quark carries 1/3 of baryon number
  • Proton lifetime >10^{34} years
  • Quarks are connected by gluons

• Alternative picture of a proton
  • Proposed at the Dawn of QCD in 1970s
  • A Y-shaped gluon junction topology carries baryon number (B=1)
  • The topology number is the strictly conserved number
  • Quarks do not carry baryon number
  • Valence quarks are connected to the end of the junction

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Model implementations of baryons at RHIC

• Many of the models used for heavy-ion collisions at RHIC (HIJING, AMPT, UrQMD) have implemented a nonperturbative baryon stopping mechanism

• Baryon Stopping
  • Theorized to be an effective mechanism of stopping baryons in $pp$ and $AA$


• Specific rapidity dependence is predicted:

\[ p = \sim e^{-\alpha_B y} \]
\[ \alpha_B \sim = 0.5 \]

2003 RBRC Workshop on “Baryon Dynamics at RHIC”

“Science, however, is never conducted as a popularity contest...” --- Michio Kaku

BUT citations ARE
Measurements of quark electric charges

Scattering cross section $\sigma \propto e_q^2$

$(2/3)^2 + (1/3)^2 + (1/3)^2 = 2/3$

$(2/3)^2 + (2/3)^2 + (1/3)^2 = 1$

$(1/3)^2 + (1/3)^2 + (1/3)^2 = 1/3$

Figure 53.2: World data on the total cross section of $e^+e^- \rightarrow \text{hadrons}$ and the ratio $R(s) = \sigma(e^+e^- \rightarrow \mu^+\mu^-, s)/\sigma(e^+e^- \rightarrow \mu^+\mu^-, s)$. $\sigma(e^+e^- \rightarrow \text{hadrons}, s)$ is the experimental cross section corrected for initial state radiation and electron-positron vertex loops, $\sigma(e^+e^- \rightarrow \mu^+\mu^-, s) = 4\pi\alpha^2(s)/3s$. Data errors are total below 2 GeV and statistical above 2 GeV. The curves are an educative guide: the broken one (green) is a naive quark-parton model.
Measurements of quark baryon number?

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• Neither of these postulations has been verified experimentally

Quark Distribution and Charge Transport

Quark components at low-\(x\) is proportional to valence quarks

What we know

\[ \frac{Q}{B^*Z/A} \text{ ratio in UrQMD} \to 1 \text{ for large } A \]

\(\sqrt{s_{NN}} = 200\text{GeV, } y_{l1} < 1.0\)

\[\frac{dQ}{dy} / (Z/A) / (dB/dy)\]

\(x f(x, \mu^2 = 10 \text{GeV}^2)\)

PDG

MSHT20NNLO

g/10

\(u, \bar{u}\)

\(c, \bar{c}\)

\(s, \bar{s}\)

\(d, \bar{d}\)
Three approaches toward tracking the origin of the baryon number

1. **STAR Method:**
   Charge (Q) stopping vs baryon (B) stopping:
   if valence quarks carry Q and B, Q=B at middle rapidity

2. **Kharzeev-STAR Method:**
   If gluon topology (J) carries B as one unit, it should show scaling according to Regge theory
   \[ p = e^{-\alpha_B \Delta y} \]
   \[ \alpha_B \sim 0.5 \]

3. **Artru Method:**
   In γ+Au collision, rapidity asymmetry can reveal the origin

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Proposed to use double ratio in Zr+Zr and Ru+Ru isobar collisions to cancel all the detector effects, the signal is at the level of \(10^{-3}\)
Double ratios between Ru+Ru and Zr+Zr collisions

- The double ratios of $\pi^+/\pi^-$ and $p/\bar{p}$ are larger than 1. Due to extra charge in Ru?
- The double ratios of $K^-/K^+$ is consistent with unity within uncertainties.

From baryon stopping:
$B^*(\Delta Z/A) \approx 2 \times 10^{-3}$

Charge stopping:
$\Delta Q \approx 1 \times 10^{-3}$
Identified hadron spectra to low momentum

Net-charge difference \((\text{Ru}+\text{Ru} - \text{Zr}+\text{Zr})\)

\[
R2_\pi = \frac{(N_{\pi^+}/N_{\pi^-})_{\text{Ru}} \approx \frac{1+(N_{\pi^+}+N_{K^+}+N_\rho)-(N_{\pi^-}+N_{K^-}+N_{\overline{\rho}}))_{\text{Ru}}}{1+(N_{\pi^+}+N_{K^+}+N_\rho)} = 1 + \Delta R_{\text{Ru}} - \Delta R_{\text{Zr}}
\]

\[\Delta Q = \left[ (N_{\pi^+} + N_{K^+} + N_\rho) - (N_{\pi^-} + N_{K^-} + N_{\overline{\rho}}) \right]_{\text{Ru}} - \left[ N_{\pi^-} \right]_{\text{Zr}}\]

- Focus on pion terms,
  
  \[
  (N_{\pi^+} - N_{\pi^-})_{\text{Ru}} - (N_{\pi^+} - N_{\pi^-})_{\text{Zr}} = N_{\pi,\text{Ru}} \times \Delta R_{\text{Ru}} - N_{\pi,Zr} \times \Delta R_{\text{Zr}}
  \]
  
  \[
  \approx N_{\pi}(\Delta R_{\text{Ru}} - \Delta R_{\text{Zr}}) = N_{\pi} \times (R2_\pi - 1)
  \]

- Where \(N_{\pi} = 0.5 \times (N_{\pi^+} + N_{\pi^-})\)
- Therefore, \(\Delta Q = N_{\pi}(R2_\pi - 1) + N_K(R2_K - 1) + N_\rho(R2_\rho - 1)\)
Separate charge and baryon transports

UrQMD matches data on charge stopping better in peripheral; better on baryon stopping in central
overpredicts charge stopping in central; underpredicts baryon stopping in peripheral

Tommy Tsang (KSU) for STAR, APS GHP 2023
Baryon stopping in UrQMD

M. Bleicher, et al., JPG 25 (1999); hep-ph/9909407

\[ z^\pm = t \pm z \quad \text{and} \quad p^\pm = E \pm p \quad . \]  

(33)

The light cone momentum \( p^\pm_{\text{hadron}} \) given to the newly produced hadron is:

\[ p^\pm_{\text{hadron}} = z^\pm_{\text{fraction}} p^\pm_{\text{total}} \quad . \]  

(34)

The fragmentation of a baryonic string reads:

\[ \frac{p^\pm (qgqgq)}{\text{String}} = z^\pm_{\text{fraction}} p^\pm (qqq) + \left( p^\pm - z^\pm_{\text{fraction}} p^\pm \right) \frac{qg}{\text{Baryon String}} \quad . \]  

(35)

The main input is the fragmentation function which yields the probability distribution \( p(z^\pm_{\text{fraction}}, m) \). This function regulates the fraction of energy and momentum given to the produced hadron in the stochastic fragmentation of the color string. For newly produced particles the Field-Feynman function \([11]\):

\[ p(z^\pm_{\text{fraction}}) = \text{constant} \times (1 - z^\pm_{\text{fraction}})^2 \quad , \]  

(36)

is used. \( F(z) \) drops rapidly with increasing \( z \) (Fig. [25]). Therefore, the longitudinal momenta of e.g. produced antibaryons (Fig. [23]) and pions (Fig. [24]) are small (they stick to central rapidities), in line with the experimental data. The rapidity spectra of those particles have a characteristic Gaussian-like shape, in contrast to the baryon spectra in \( pp \), as it is clearly seen in Figure [24].

The proton is on average less stopped, since it is build up from the leading diquark in the string (leading particle effect). Fig. [24] compares the \( x_F \) distribution of protons and \( \Lambda \)'s for the Feynman scaling variable \( x_F = 2p_T/\sqrt{s} \) measured in \( pp \) reactions at 205 GeV/c. The data on leading baryons can only be reproduced when a modified fragmentation function is used for the leading baryons (cf. Fig. [24], dashed curve). This leading baryon fragmentation function is of Gaussian form:

\[ p(z^\pm_{\text{fraction}}) = \text{constant} \times \exp \left[ -\frac{(z^\pm_{\text{fraction}} - b)^2}{2a^2} \right] \quad , \]  

(37)

with parameters \( a = 0.275 \) and \( b = 0.42 \).
Ratio of baryon over charge transports

- **Experimental data:**
  More baryon transported to C.O.M than charge by about a factor of 2

- **Model simulations:**
  Less baryon transported to C.O.M frame than charge

- **Pure geometry:**
  with neutron skin predicts the right centrality dependence (Trento)

**STAR Preliminary**
Isobar (Ru + Ru, Zr + Zr)
\( \sqrt{s_{NN}} = 200 \text{ GeV}, l_{yl} < 0.5 \)
The average close to beam rapidity (limiting Fragmentation) does not reflect the “tail” at high rapidity.
Quantifying baryon number transport

• RHIC Beam Energy Scan (BES-I) span large range of rapidity shift

• Exponential with slope of $\alpha_B = 0.61 \pm 0.03$

• Consistent with the baryon junction transport by gluons: $\alpha_B \sim 0.5 + \Delta$
  $\Delta \sim 0.1$


![Graph showing exponential fit and data points for baryon number transport in various experiments.](image-url)
Quantifying baryon number transport

• Striking scaling for all centralities and collision beam energies from central A+A to p+p

• Expect slope to change if stopping is through multiple scattering of quarks

• New heavy-ion simulation requires baryon junction to match data

What do we know about e+p collisions?

- RHIC nuclear energy is at a sweet spot
  - U+U, Au+Au, O+O, Cu+Au, Cu+Cu, He3+Au, d+Au, p+Au, p+p
- LHC and HERA energy are too high with small baryon excess (<1%)
- Isobar collisions at EIC with low Q² and low-p_t PID to study the charge and baryon transports

Artru & Mekhfi, NPA 1991
“unpolarized and polarized electroproduction of fast baryons

Figure 1. Main mechanisms of electroproduction of fast baryons.

The first mechanism dominates in the region (see Fig. 2)

\[ Y < Y_C \approx \beta^{-1} \ln(\beta/b) \]  

\( Y_C \) corresponds to \( \Delta_4 \) in Ref.1. The second one dominates for \( Y > Y_C \). In this talk I will show that both mechanisms can reveal interesting features of hadronic physics (I shall consider only events with low transverse momenta).

Slope \( \beta \sim 1 \) at \( y=2.5 \)

Figure 2. Rapidity spectrum: (a) of the migration mechanism, (b) of the pair creation mechanism.
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Measurement of the Baryon-Antibaryon Asymmetry in Photoproduction at HERA
C. Adloff et al. (H1 Collaboration), ICHEP 1998

Baryon stopping at HERA: Evidence for gluonic mechanism
Boris Kopeliovich (Heidelberg, Max Planck Inst. and Dubna, JINR), Bogdan Povh (Heidelberg, Max Planck Inst.)
What do we know about $\mu+p$ collisions

Same plot, opposite conclusion!

Benchouk (EMC), ISMD1984

At this point it should be noted that, if they were significantly contributing, protons coming from scattering on diquark clusters (higher twist) would also present such behaviours as those of Figs. 2 and 3d. However those protons must exhibit a strong decrease with $Q^2$, which is obviously not the case as shown by Fig. 4 and their contribution to our sample can be excluded.

EMC, PLB 103 (1981) 388; last cited in 1992

Fredriksson, “Hello Diquark, Goodbye Gluon!”, Moriond 1984

Fig. 3 - Ratio of proton (antiproton) multiplicity to the overall positive (negative) multiplicity in $\mu p$ scattering according to Ref. 7 (EMC). Part of the difference between $p$ and $\bar{p}$ might be explained by the diquark process in the upper reaction, while large-$Q^2$ events come from knocked-out quarks, as shown in the lower reaction. The two processes give rise to completely different $p$-$\bar{p}$ correlations.

Fig. 4 - The ratio of the proton (antiproton) multiplicity to the overall positive (negative) hadron multiplicity as a function of $Q^2$ for $W^2 > 100$ GeV$^2$ and $x_B > 0.2$. 

Feb 18, 2005
Diquark Lund model predicts a flavor dependence of backward proton production (20%) while data shows little-to-no dependence

Fig. 5a-d. Average multiplicities from the H$_2$ (full circles) and the D$_2$ target (open circles) vs. W for backward protons a, backward antiprotons b. The histograms show the Lund model predictions (full line: H$_2$ target, dashed line: D$_2$ target, full line only where both are the same)

the Lund model (JETSET62) predicts a higher yield of backward going protons from hydrogen than from deuterium, an effect which is less pronounced in the data.

Total citations: 19
Photonuclear Events Are Selected With Rapidity Gaps

Similar technique used by LHC photonuclear measurements:

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

- Selection of photon+Au collisions from Au+Au at 54.4GeV ultra-peripheral collisions
- Antiproton shows flat rapidity distribution
- Proton shows the characteristic asymmetry increase toward nucleus side
- Slope is closer to the slope of the beam energy dependence
- PYTHIA shows much larger slope

Nicole Lewis (BNL) for STAR, DIS2023
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   \( \alpha_B = 0.61 \)

3. **Artru Method:**
   In \( \gamma + \text{Au} \) collision, rapidity asymmetry can reveal the origin
   \( \alpha_B(\text{A} + \text{A}) = 0.61 < \alpha_B(\gamma + \text{A}) = 1.1 < \alpha_B(\text{PYTHIA}) \)
What do we know about pp collisions?

ALICE, PRL105 (2010)

\[ \sqrt{s} \text{ [GeV]} \]

\[
\begin{array}{|c|c|}
\hline
\Delta y & \bar{p}/p \text{ ratio} \\
\hline
2 & 0.2 \\
3 & 0.4 \\
4 & 0.6 \\
5 & 0.8 \\
6 & 1.0 \\
\hline
\end{array}
\]

HERWIG: net-charge vs. net-baryon transport

Rongrong Ma (BNL)

\[ dN/dy \text{ (y=0)} \]

HERWIG and PYTHIA: \( \alpha_B \approx 1.6-2.5 \)

Negative (\( p/\bar{p} \)) at LHC energy

red curve consistent with \( \alpha_B = 0.6 \)
Bjorken Scaling for quarks

- Scaling at certain $x$ range, quarks behave as point-like particles
- Evolution with $x$ due to gluons
- At DIS (high $Q^2 > 1$ GeV$^2$)

**Figure 18.10:** The proton structure function $F_2^p$ measured in electromagnetic scattering of electrons and positrons on protons, and for electrons/positrons (SLAC, HERMES, JLAB) and muons (BCDMS, E665, NMC) on a fixed target. Statistical and systematic errors added in quadrature are shown. The H1+ZEUS
Conclusions and Perspectives

- Baryon number is a strictly conserved quantum number, keeps the Universe as is

- We did not know what its carrier is; It has not been experimentally verified one way or the other until now

- RHIC Beam Energy Scans provide unique opportunity in studying baryon number transport over large unit of rapidity

- RHIC Isobar collisions provide unique opportunity in studying charge and baryon transport

- Experimental verification of the simplest QCD topology

- Baryon junction (if exists) is a non-perturbative object
- Need small $Q^2$ and low-momentum hadron particle identification

$$Q^2 \leq 1 \text{ GeV}^2$$

$$\pi/k/p \text{ PID } p_t \geq \sim 100 \text{ MeV}$$

- Isobar collisions to measure baryon and charge transport (quark transports), EMC 1987

  $$\text{Zr/Ru; Li}^7/\text{Be}^7$$

- EIC can measure the baryon junction distribution function

- Explore other signatures at EIC
Questions for discussion: what about fluctuations?

Brought up by a student at Chirality workshop in Beijing in 07/2023

Asakawa, Heinz, Muller, PRL 85 (2000) 2072

V. Koch, arXiv:0810.2520

and since all baryons in the hadronic phase have baryon number $|B_{\text{hadronic}}| = 1$ and all quarks have baryon number $|B_{\text{quark}}| = 1/3$ we get for the the ratio of the cumulants the simple results

\[
\begin{align*}
R_{4,2}^B &= 1; \quad \text{hadron phase} \\
R_{4,2}^B &= \frac{1}{9}; \quad \text{QGP}
\end{align*}
\]

Is the statement confirmed by LQCD?
If YES, does it rule out gluon junction or can both scenarios co-exist?
Is this confirmed by experiments?
If YES, how do we reconcile all experimental results?
the simplest QCD topology
B=1