Baryon Stopping In relativistic Heavy Ion Collisions -
Expectations and Reality at RHIC

F. Videbæk
Physics Department
Brookhaven National Laboratory
Reasons for interest in Baryons Stopping in AA and Particular at RHIC

Aim at RHIC to
• Achieve small baryon chemical potential.
• High energy densities as manifested by large particle densities in central region.

What has been learned?
Surprise that
• $P$-bar/p considerably $< 1$ also in contrast to predictions.
Net-Baryons vs. energy

Net-Baryons = N(Baryons) - N(antiBaryons) at given rapidity

Net-Baryons as extracted from Net-protons > (some) models.

Should we be surprised?

What does earlier measurements tell us?

Is there something we have missed
Outline

• Energy loss; stopping definitions.
• Background;
  – Stopping mechanisms
  – pp, pA data and interpretation.
• Stopping in AA
  – Systematic from SIS to SPS
  – Model expectations (simple)
• Summary of higher energy data including RHIC results
  – P-bar/p systematic;
  – Net protons
  – Net Lambda’s
Nuclear Energy Loss

- What are we trying to observe
  - Initial projectile, target at $Y_{beam}$, $Y_{target}$ can interact in either a transparent or opaque way (stopped).
  - Additionally produced particles emerge a mid rapidity
- Aim to describe process in greater detail
Baryon Stopping

- Stopping has been of interest in long term since it is the prerequisite for the creation of a hot and dense system.
- Early pp, and pA data lay the foundation for understanding.
- The systematic was established by the analysis of Busza and Goldhaber [Phys.Lett.139B,235(1984)] based on FNAL data, and by the model evaluation of Date, Gyulassy and Hufner.
- Many models that describe high energy relativistic reaction at energies where string description are appropriate have assumed the primary mechanism for baryon transport is qq-q string breaking.
- At very high energy other mechanism will take over; one of those proposed is baryon gluon junctions.
Schematic picture of baryons, string breaking and junctions
A few words on mechanism

- Di-quark-quark breaking corresponds to having the baryon number associated with the valence quarks. This will describe the basic behavior of pp at lower energy.
- The junction can carry the baryon number in the gluonic junction containing many low energy gluons; this will be increasing important at higher energy due to time-contraction of the projectile/targets at high energy.
- Described in many papers of which results will be used later.
  - GCRossi and G.veniziano NPB123(77)507
  - D.Kharzeev PhysLettB378(96) 1497.
Projectile Stopping/Fragmentation

Usage of \( x \) for studying stopping/fragmentation.

Provides more detail on high-momentum region.

Definition of \( x \)

\[
x_F = \frac{p_L^*}{p_L^*}_{\text{max}} \quad (-1 < x_F < 1)
\]

\( \frac{d\text{n}}{dy} \propto x \frac{d\text{n}}{dx} \); 

If \( \frac{d\text{n}}{dx} \) is flat => rapidity distributions are \( \frac{d\text{n}}{dy} = e^{-y} \)
Modern pp, pA data

• Very nice and complete data has emerged from experiments at AGS (E910, E941) and SPS (NA49) on pp and pA data.
• Data selected and presented vs. #grey tracks ie. Target protons related to #collisions of incoming proton.
• Data also exists for pp->nX supplementing the pp data.
SPS pp, pA

- Subtract target component.
- Most central pA completely stopped.
- Average collisions ? ~3.1
pA→nX

Neutron $x_F$ distributions nearly identical to protons for $\nu > 1$. 

![Graph showing neutron and proton $x_F$ distributions](image)
A-A stopping  
Ni+Ni from SIS

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**FOPI results from 1-2 AGeV**

*Phys Rev C57, 244(98)*

Not isotropic

Incomplete stopping and/or Longitudinal expansion.

Evaluate

\[ dy = y_B - \frac{1}{2} \int_0^1 y \frac{dn}{dy} \]

As an estimate for rapidity loss (lower limit)
AA at AGS energies

Data from several AGS experiments E866, E917, E877, E895.

The system systematic shows a continuous development of stopping, but never reaching more than about \(<dy>\sim1.02\).

Still more than 40% of all protons show up in the middle 1/3 of the rapidity interval.

PRC 57,R466(98); PRC 50,1024(95)
Energy dependence at AGS

The E917, the last experiment of the series E802/E859/E866 performed measurements at several energies 2,4,6,8 E.A GeV.

The proton distribution data demonstrates a slowly increasing width with energy, and still incomplete stopping at 6,8, and 10.8 A.GeV.

Central Pb-Pb from Na49

Data from NA49 for Pb-Pb at 158 A.GeV/c
\textit{Phys.ReV.Lett.82,2473(99)} show again considerable and much larger $<dy>$ than at AGS. For Pb the dy-loss is $1.75 \pm 0.05$ and for SS $1.63 \pm 0.16$.

Relative though to the available rapidity the $<?y>/y_{cm}$ is constant.
Energy systematic

The near constant dy/y$_{\text{cm}}$ was first described by OH/FV, but recently enhanced by adding data from FOPI by N.Hermann in Annu. Sci.Part.Rev.(99) 49,581.

To this plot are added the recent data from AGS experiment E917.

At No energy is complete stopping achieved. (thermal isotropic Boltzman distribution) – as described by the green curve.

Another representation of the same data showing the ‘increase’ in dy for AA, while pp is approximately constant.

Significant difference between pp and AA.
Multichain Model
S.Date,M.Gyulassy&H.Sumyahi, PRD32,619(85)

This model is a semi-phenomenological model that was successfully used to describe pA dynamics and stopping from pp. At the time no AA data at high energy was available.

Assumptions
Separation of geometry from dynamics pp->pA->AB
Independent projectile and target fragmentation.
Glauber probabilities for $n$ interactions.
Multiple collision dynamics depends only on $x$ and assumes simple scaling for subsequent interactions.

\[
\text{fraction } x_i = \alpha_i (1+\alpha)^i \\
\frac{dN}{dy} = \sum_{BA} P_{m,n} Q_{mn}(x) \\
\text{where there the probability densities can be derived}
\]

\[
Q_n(x) = \int_{x'} F_n(x/x') f_p(x') \, dx' \\
F_n \text{ depends only on } \alpha \text{ and } n
\]

\[
\text{the physics is contained in fragmentation function } f_p(x) = x
\]
Estimates for \( y/y_{beam} \)

\(~100,120 \text{ GeV/c fixed target.}\)

Calculation of average dy loss for pA yielded an alpha value of ~3.

Data from ~100,120 GeV/c fixed target. This was applied to AA for the full energy range.

S. Date et al
Predictions from this model.

The energy losses are comparable to observed values.
The net proton values at RHIC also close to \( \exp(-11) \).

The model which describes the lower energies quite well predicts a rising \( \Delta y \) that seems to level off.

Values higher than Hijing 1.36 which has di-quark string fragmentation.
This model is not a microscopic model but phenomenological describing \( pA \rightarrow AA \).
Thus, much of the AA physics is already present in \( pA \).
Net Baryon and Rapidity Loss systematic at higher energies.

- Proton, antiproton ratios from pp.
- RHIC data mainly from $s = 130$, and 200 GeV.
- Net Baryon numbers have been measured/deduced by STAR, Phenix.
Energy Dependence of p-bar/p

- The first data showed P-bar/p ~ 0.6-0.7. (STAR, BRAHMS, PHENIX, and PHOBOS) at \( y \sim 0 \). The graph shows a survey of this ratio for AA and pp data.

The first order isospin correction of the pp data it is possible under the assumption that NN->pp-barX has the same cross-section as pp->p-pbarX (pair production) to correct the ratios from pp collisions.

This show the fast increase in p/pbar ratio at \( s \sim 20 \) indicating the beginning of transparency.

- Additionally, the AA has a smaller ratio at a given energy equivalent to stopping than pp.
A detailed view of pp data from baryon junction point of view.

Kharzeev had proposed to use pp to look at the contribution from baryon junctions to stopping in pp.

The prediction from QCD is that at $y \sim 0$ this component is

$$? \sim s^{?/2-0.25} \quad \text{where } ? \text{ is a small } \sim 0.08;$$

The dn/dy for p and p-bar at $y \sim 0$ from R803 at ISR is shown as well as the Net protons.

The pp data has some sensitivity to this component-

The 200 GeV data from RHIC will be valuable in this regard.
Net proton and ?’s

- Net protons from STAR, Phenix (130GeV)
- Is ~ 2 over Hijing prediction, but close to value from Multichain model.
- Protons includes mostly hyperons decay protons.

The ?’s carries a significant part of the baryon number.
~5/(10+Neutrons)
Can be as much as 25%.
Na49.

*Half Width ~2 units*

Brahms 200 GeV preliminary

*Half Width ~5 units.*

At RHIC a wider region of ~ 0.8-1.0 exists with ~ constant ratio while at lower energy a rapid change is seen. RHIC does though not show a very wide rapidity region with nearly constant properties (plateau)
Conventional string models

The hijing string fragmentation model that has been successful in describing over all multiplicities do fail on baryon distributions. Dominated by quark-diquark breaking. This is shown here for the Brahms 130 GeV data.
Can the data be understood from other models?

Comparison with model calculations (AMPT) that includes additional description of the scattering process; a string model, partonic cascade modification to string breaking (popcorn) mechanism and re-scattering in hadronic phase.

$n^? \leftrightarrow NN$ channels simulated by $?$ and $?$ 2-body channels.

In particular the re-scattering is important for keeping

\[Au-Au \ 200 \ GeV; \text{ Brahms preliminary}\]
Baryon Junctions at RHIC

- A prediction was made by Vance and Gyulassy (98) using the description by Kharzeev implemented within Hijing/B.
- Strong proton stopping as well as enhanced strange baryon production.
- Brahms measurements at higher rapidities ($y \sim 0-3$) will address in near future.
Summary

- Data for baryon exists systematically as a function of centrality, number of collisions, and collision energy form SIS to RHIC. The development of rapidity loss and net baryons at mid rapidity with energy and systems from pA to AA seems rather smooth.

- The q-qq string fragmentation models that predicts an e^{-y} behavior of stopped protons, do not describe heavy ion data.

- A mechanism as baryon junctions is promising in describing features at higher energies, and may also describe the large production of strange and multi strange baryons observed at RHIC and SPS. This may well be present already in pA and pp collisions as deduced from the smooth behavior.

- The field of relativistic heavy ion collisions has already given much insight into understanding of soft hadronic processes and will hopefully result in understanding on perturbative QCD.
The spokesperson and his experiment

E802/866 spectrometer

May 24, 2002  NBI Heavy Ion Symposium
Brahms

‘former’ Professor Ole and the last Experiment
THE END