Stopping and Baryon Transport in Heavy Ion Reactions

F.Videbæk[1]

[1] Physics Department, Brookhaven National Laboratory, Upton, NY11973, USA

E-mail: `videbaek@bnl.gov`

Abstract. In this report I will give an experimental overview on nuclear stopping in hadron collisions, and relate observations to understanding of baryon transport. Baryon number transport is not only evidenced via net-proton distributions but also by the enhancement of strange baryons near mid-rapidity. Although the focus is on high-energy data obtained from pp and heavy ions from RHIC, relevant data from SPS and ISR will be considered. A discussion how the available data at higher energy relates and gives information on baryon junction, quark-diquark breaking will be made.

1. Introduction

A major goal for relativistic heavy ion reactions is to form hot nuclear matter at energy densities in clear excess over the value ($\approx 1\mathrm{GeV/fm}^3$) predicted from Lattice QCD needed to make the phase transition or cross over to matter dominated by degrees of freedom of quarks and gluons rather than of hadrons. The next goal is to study and quantify the properties to confront those with properties of non-perturbative QCD. Such experiments has been carried out at RHIC with considerable progress and remarkable results from the first 3 years of experiments. Please refer to the white-papers from the 4 experiments in Refs.[1]. The deposited energy is essential to understand the formation of this medium. Because baryon number is conserved, and rapidity distributions are only slightly affected by rescattering in the later stages of the collisions, the measured baryon distribution retains information about energy loss and allows the degree of nuclear stopping to be determined. Such measurements may also help distinguish between different mechanism for transporting baryons to mid-rapidity.

At very low energies $1-15$ AGeV the hadrons preserve their identity with multiple collisions and excitation to resonances being important ingredient in the description of both stopping, transverse momentum spectra as well as strange particle production. At the higher energies partonic degrees become important, and many features can be described using a string picture. At these higher energies it have long be thought that the dominant mechanism for transport of baryon number is that of quark-diquark breaking (of the strings) where the baryon number is carried(associated) with the valence quarks. I.e. the distribution will reflect the distribution $q(x)-\bar{q}(x)$. Such a mechanism is not able to move the net-baryon number over a large range of x . These distribution are flat in x (e^{-y} in rapidity) for a single collision as observed at SPS energies. Already an analysis of the ISR data in pp collisions [2, 3], and later data from HERA that shows a non-zero baryon asymmetry of $\approx 8\%$ in γp reaction at more than 7 units of rapidity from the incident baryon [4] has demonstrated that additional mechanisms with a slower x and rapidity dependence are needed to describe the data. One such mechanism described in the afore mentioned publications is the baryon junction originally proposed in Ref. [5]. The baryon junction can be thought of as a final state where the incident quarks couple to a color decuplet state, or a topological structure where three gluons join in a junction carrying the baryon number with the valence quarks left in high rapidity mesons. This allows the baryon number to be carried to a much lower value of x through a diminished x (or $\sqrt{s_{NN}}$) dependence of the cross section. So even if the probability for such mechanism is small it may become important and possibly dominant at higher energies. It should be mentioned that other mechanism has been proposed in Ref. [6] (parton cascade) and Ref.[7] (diquark breaking) that may also be relevant for baryon transport. Clearly experimental data from both pp and AA are needed if we are to distinguish between these possibilities. In this paper I will review data in pp and AA collisions that sheds light on the issue of baryon transport and will compare data to predictions of models with and without the mechanism of baryon junction included. Some basic ideas comes from Refs.[8, 9]. See a recent paper[10] which has discussion as well as a wealth of references to models relevant to baryon dynamics.

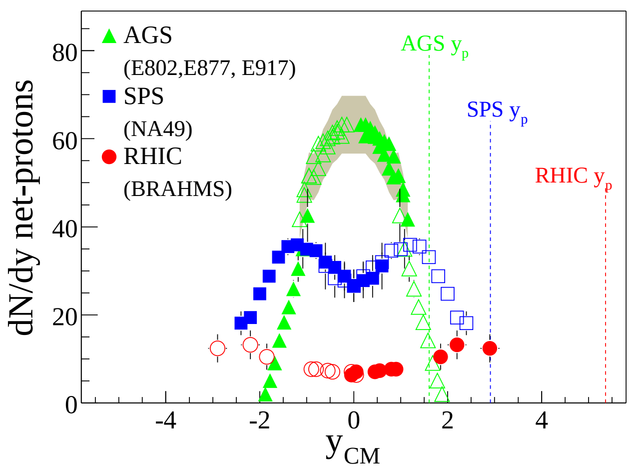

Figure 1. Rapidity density of net protons (i.e. number of protons minus number of antiprotons) measured at AGS, SPS, and RHIC for central collisions.

2. Experimental Considerations

The stopping in nuclear collisions can be estimated from the rapidity loss experienced by the baryons in the colliding nuclei. If incoming baryons have rapidity, y_b in the C.M. system and the average rapidity

$$< y >= \int_0^{y_b} y \frac{dN}{dy} dy / \int_0^{y_b} \frac{dN}{dy} dy \tag{1}$$

after the collision, the average rapidity loss is $\delta y = y_b - <y>$ [8, 9]. Here dN/dy denotes the number of net-baryons (number of baryons minus number of antibaryons) per unit of rapidity. In the case of full stopping δy approaches y_b. Thus, the distributions of dN/dy should be known from mid-rapidity to beam rapidity. Usually the measurements are for protons, in some cases for Λs while rarely have the neutrons been measured. To get the net baryon distributions corrections and extrapolations have to be made. At SIS energies rather detailed measurements have been obtained at 0.4 AGeV and 1.5 AGeV [11]. The clever use of medium mass beams with different

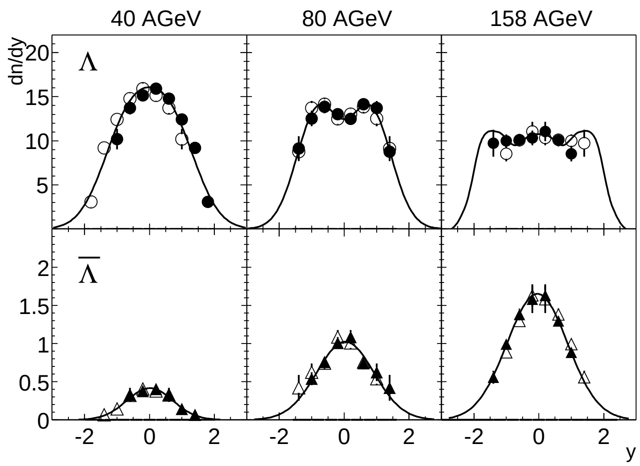

Figure 2. Rapidity distributions of Λ and $\bar{\Lambda}$ at 40, 80 , and 158 AGeV beam energy. The figure is from Ref.[16].

isospin content has shown that already at 1.5 AGeV the system is not fully stopped, but has a small degree of transparency.

At AGS energies the number of produced antiprotons is very small and the net-baryon distribution is similar to the proton distribution [12, 13, 14]. The net-proton rapidity distribution is centered around $y = 0$ and is rather narrow (Fig.1 The rapidity loss is about 1 for a beam rapidity of ≈ 1.6 . At CERN-SPS energies ($\sqrt{s_{NN}} = 17\ GeV, 158AGeV$ Pb+ Pb reactions) the rapidity loss is 1.75 for a beam rapidity of 2.9 [15], about the same relative rapidity loss as at the AGS.

At SPS another feature is visible (see Fig. 1). The net proton rapidity distribution shows a double 'hump' with a dip around $y = 0$. This shape results from the finite rapidity loss of the colliding nuclei and the finite width of each of the humps, which reflect the rapidity distributions of the protons after the collisions. This picture suggests that the reaction at the SPS is beginning to be transparent in the sense that fewer of the original baryons are found at midrapidity after the collisions, in contrast to the situation at lower energies. The net-Λ distributions on the other hand do not show this bump. The data from NA49 [16] displayed in Fig.2 show a rather flat distribution. This is certainly in part due to the higher inelasticity required to produced strange baryons. Also these data shows that at SPS the hyperon production is significant and must be considered for the net baryon distributions. A ratios of $\frac{\Lambda}{p}$ of ~ 0.4 is observed at SPS.

BRAHMS has measured the net proton rapidity distribution at RHIC in the interval $y = 0-3$ for central $(0-10\%)$ Au+Au collisions at $\sqrt{s_{NN}} = 200$GeV. Details of the analysis can be found in [9]. The results are displayed in Fig.1. The distribution measured at RHIC is both qualitatively and quantitatively very different from those at lower energies indicating a significantly different system is formed near mid-rapidity. At RHIC the Λ production is even more crucial for estimation of the net-baryon yield as well as correct for in the measured proton and anti-proton yields. A detailed discussion can be found in [9]. The ratio $\frac{\Lambda}{p}$ of ~ 0.9 was observed by STAR and PHENIX near midrapidity[17, 18]. The BRAHMS analysis presented assumes that the measured ratios at mid-rapidity is representative for all measured rapidities up to 3.

The net number of protons per unit of rapidity around $y = 0$ is only about 7 and the distribution is flat over at least the ± 1 unit of rapidity. The distribution rises in the rapidity range $y = 2-3$ to an average $dN/dy \approx 12$. Baryon conservation in the reactions can be exploited to set limits on the relative rapidity loss and the energy per baryon at RHIC. This is illustrated in Fig. 3, which in the insert shows two possible distributions whose integral areas correspond to the number of baryons present in the overlap between the colliding nuclei. From such distributions one can deduce a set of upper and lower limits for the rapidity loss at RHIC. Since not all baryons are measured with the bulk of these in the rapidity interval 3-5.4 these assumptions have to be made for these. The limits shown in the figure includes estimates of these effects [9] for different extrapolations. The conclusion is that the absolute rapidity loss at RHIC ($\delta y = 2.05 \pm 0.17$) is slightly larger than at SPS. The value is close to expectations from extrapolations of pA data at lower energies [19, 20]. In fact the relative rapidity loss is significantly reduced as compared to an extrapolation of the low energy systematic [8].

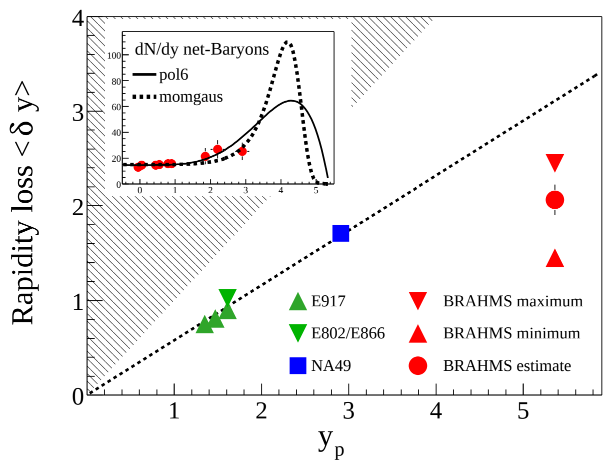

Figure 3. Average rapidity loss as deduced from net-proton distributions vs. beam rapidity. The straight line is the linear extrapolation from Ref.[8] for constant relative rapidity loss. Insert: two possible net-baryon distributions (Gaussian in p_T and 6'th order polynomial) respecting baryon number conservation.

Also from these distribution one can estimate the average energy loss of the colliding nuclei. We find this to be about 73 ± 6 GeV per nucleon, but still with a significant uncertainty if the extreme limits are assumed. The same limits on the relative rapidity loss gives a range of energy loss per baryon of 47 GeV $< E <$ 85 GeV.

3. Particle Ratios

Ratios of baryon to anti-baryons also give information on baryon transport albeit indirectly since it depends on both transport and baryon pair-production. In particular the fraction $p/\bar{p} - 1$ is the relative fraction of transported vs. produced protons. At RHIC several experiments have measured properties of the particle ratios. It is found that the centrality dependence of $\bar{p}/p$ is weak [21, 22, 23], the p_{T}-dependence up to several GeV/c is flat, and the ratios of anti-neutrons to neutrons was deduced from measurements of $\bar{d}/d$ [24] and found to be consistent with that of protons. In the following I will discuss results on $\bar{p}/p$ from PHOBOS on collision geometry and centrality dependence and from BRAHMS on rapidity dependence both being compared to models.

The particle ratios near mid-rapidity has been measured in d+Au, Au+Au and pp collisions by the PHOBOS collaboration[25, 26]. The $\bar{p}/p$ ratios in d-Au are very close to that observed in pp collisions ($\bar{p}/p \simeq 0.84$) while larger than what is seen in AuAu collisions ($\bar{p}/p \simeq 0.76$). This indicates that a larger fraction of baryon are transported to mid-rapidity in Au-Au collisions than in pp and d-Au collisions. This is consistent with the expectation of additional scattering in the heavy ion system. The surprising observation is that when the d-Au system is studied versus centrality, or rather the mean number of collisions $<\nu>$ estimated from a Glauber description is consistent with no dependence. This is shown in Fig.4 taken from their publication. This is in contrast to results from calculations of HIJING [27], AMPT[28] and RQMD[29] model that all predict a significant decrease of $\bar{p}/p$ with $<\nu>$. Such behavior arises naturally in the picture where multiple collisions cause increasing stopping and baryon transport, but is apparently not born out by the data from RHIC.

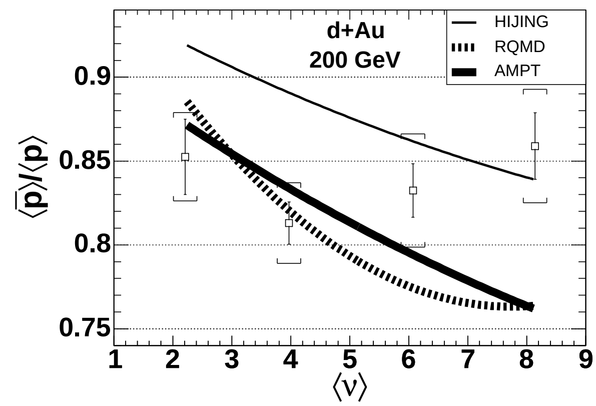

Figure 4. Ratios of anti-proton to proton as function of centrality in d-Au collisions at $\sqrt{s_{NN}} = 200\text{GeV}$. The figure is from the Phobos Collaboration [25]

BRAHMS has recently presented measurements and analysis of $p/\bar{p}$ ratios in pp collisions at 200 GeV as function of rapidity [30]. Figure 5 shows the resulting ratios of antiparticle to particle yields as a function of rapidity (left panel). For the ratios there is a clear midrapidity plateau and subsequent decrease with rapidity. This $\bar{p}/p$ ratio would implies that at midrapidity 12% of the protons carry baryon number that has been transported from the beam region at $y = 5.3$. It has been shown (see Ref.[31]) that one may need to correct for isospin effects before generalizing these results from $p + p$ to hadron–hadron collisions. At $y < 1.5$ the Au+Au ratios for the 20% most central collisions reported in [32] are noticeably similar to the present results. The kaon (not shown) and proton ratios remain consistent with the Au+Au results over our entire acceptance range. This is surprising in view of the different dynamics one might expect for the two systems. The ratio starts to decrease above $y = 1.5$, indicating a transition from the string breaking dominated regime at midrapidity to the fragmentation region. Though results for pp and AuAu looks similar in term of rapidity dependence there is a difference at mid-rapidity with the $\bar{p}/p$ values being lower in pp, as also shown by the PHOBOS results discussed above.

The right panel of Fig. 5 shows the present data and data from NA27 at $\sqrt{s} = 27.5$ GeV [34] (open triangles) shifted by the respective beam rapidities. Overlaying the two datasets we observe the ratios to be independent of the incident beam energy when viewed from the rest frame of one of the protons in the area where our rapidity region overlaps with he other experiment. This is consistent with the idea of limiting fragmentation that has also been observed for charged hadrons in nucleus–nucleus collisions [33, 35, 36]. We also note a transition in behavior at $y - y_b = -4$, indicative of a boundary between the midrapidity and fragmentation regions.

To interpret these results further, we confront predictions from theoretical models of hadron-hadron collisions with the data. The curves in the left panel of Figure 5 compare our results to the predictions of two such calculations, PYTHIA Ver. 6.303 [37] and HIJING/B [38], using the same p_{T} range as the present analysis. Both models give a good description of the pion data and for kaons at midrapidity. Also, PYTHIA clearly overestimates the $\bar{p}/p$ ratios. This is a well–known problem since PYTHIA employs only quark–diquark breaking of the initial protons.

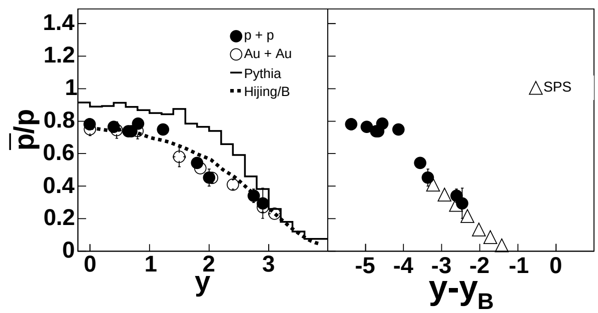

Figure 5. Left: $\bar{p}/p$ from p+p at $\sqrt{s_{NN}}$(solid) points compared with Au+Au [32] (open points), and predictions from PYTHIA [37] (solid histogram) and HIJING/B [38] (thick dashed line). Right ratios shifted by y_b compared with data from NA27 (triangles) at $\sqrt{s_{NN}}$=27.5 GeV [34].

The baryon junction scenario, incorporated as a model prediction in the HIJING/B event generator [38], is shown as the dashed lines in Fig. 5, exhibit a much better agreement with the data both in terms of overall magnitude and the width of the distribution. In Ref. [39] the author shows that baryon stopping in $p + p$ and Au+Au collisions at SPS and RHIC energies can be described using the same parameters for the baryon junction couplings, and predict that at RHIC the shapes of the rapidity distributions for $p+p$ and Au+Au will be similar for $|y| < 2$. The similarity of $\bar{p}/p$ in $p + p$ and $A + A$ up to $|y| < 3$ supports this prediction.

4. Model comparisons to Au-Au collisions at RHIC

In the following section comparisons to models at RHIC energies will be made. A large number of studies have been carried out both at lower energies and shows that the cascade mechanism via multiple collisions and resonances excitation is dominant at SIS and AGS energies. Though, already at SPS energies the stopping neither by cascade model nor by string models. In Ref.[38] the baryon junction mechanism was introduce to enhance stopping over what a conventional string description would give and achieved a satisfactory description of the NA49 net-proton data. In this paper there is also a prediction for RHIC which in fact over estimates the actual later measurements of protons and Λs.

In the left panel Fig. 6 the net-baryons measured by BRAHMS are compared to 3 models. The HIJING[27] model (full drawn curve) where the main mechanism for baryon transport is $q - qq$ string breaking result in a net-baryon yield at mid-rapidity slightly lower than the data, and with a mean rapidity loss of 1.7 being at the low end of the allowed range. The AMPT model (light line) on the other hand results in a much higher yield at mid-rapidity, still compatible with the data, but a mean rapidity loss at the upper end of the range. This model [28] includes the socalled popcorn mechanism to describe baryon - antibaryon production with parameters adjusted to described the NA49 data from SPS. The larger difference between the models are at the higher rapidities where the data are still lacking. The models results in significant different energy per baryon in the final state of 38 and 22 GeV, respectively. On the figure is also shown the calculation of the parton cascade description [6] (dashed points). This particular model should only be compared with data near mid-rapidity, since the spectator baryons that are left within a few units of beam rapidity are not explicitely dealt with in this model. In conclusion several models do in fact describe the measurements at RHIC energies, but the conventional string breaking description does underestimate the baryon transport to mid-rapidity.

Recently the HIJING/B model was improved in Ref.[10] by taking into account intrinsic k_T motion. The main idea is to see if the baryon junction mechanism is also able to account for the enhanced baryon over meson ratios seen in AA collisions in the intermediate p_{T}-range of 1-4 GeV/c. The model was also compared to the BRAHMS proton and net-proton distributions. The results are available in Ref.[10] as Figs. 4 and 6 and show an overall good description. The authors also calculated the mean rapidity loss to be 1.75 similar to that of the pure HIJING calculation shown in Fig.6 and a mean energy per baryon of 40 GeV. This number are within the experimental values of 2.0 ± 0.2 albeit on the lower range; as a result the mean energy is also considerable large than the value of 26 GeV quoted here albeit as pointed out this experimental has an considerable uncertainty. The model thus does transport additional baryons to mid-rapidity being a candidate for the correct description. Additionaly this transport is an important component in describing the enhancement of baryon over pions observed in the intermediate p_{T} range of 1-5 GeV/c. As stated by the authors it fails in describing the transverse spectra of kaons and Λs. All in all there are indications that the baryon junction picture are important for baryon dynamics at RHIC.

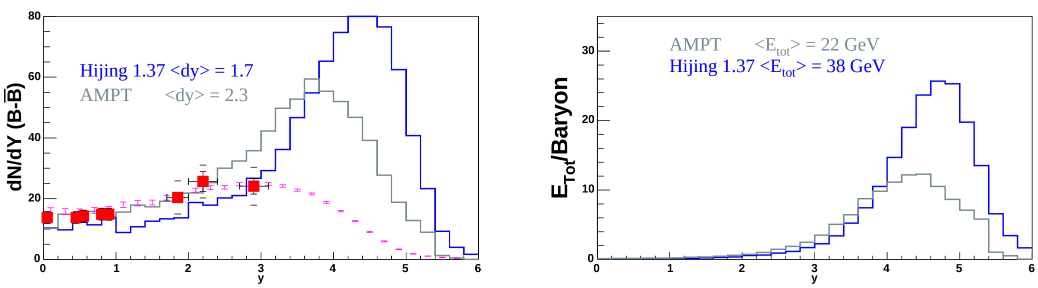

Figure 6. The left panel shows the rapidity density distributions compared to AMPT, HIJING and parton cascade model calculations. The right panels shows the rapidity distributions of energy per baryon.

5. Summary

At the highest energies so far available for heavy ion collisions, namely $\sqrt{s_{NN}} = 200$GeV at RHIC the mean rapidity loss in AA collisions seems to have reach an approximate saturated value of ≈ 2 units. In contract the measurements of net-proton distributions so far do not constrain the mean energy deposited in the collision as well, i.e. the energy that is available for particle production , longitudinal and transverse motion. Evaluation of the data, as well as comparison to models indicate that a likely range of energies are $25 - 37$ GeV/ net-baryon leaving $63 - 75\%$ for production. The analysis of the distributions as well as the $p/\bar{p}$ values < 1 in both pp and AA seem to require additional baryon transport mechanism over quark diquark breaking. The data still leaves open whether this is caused by the baryon junction mechanism, if it can be explained by other of the proposed mechanisms. Such mechanisms as these will in general not decrease the energy per baryon, since only baryon number is transported to mid-rapidity while the energy associated will reside at large rapidities in forward going mesons. Thus the direct connection between stopping of energy and rapidity loss of net-baryons is broken at the higher energies.

The outlook to have some of these questions clarified is encouraging. Not only are there more data to come from RHIC at both $\sqrt{s} = 62.4$ GeV and $\sqrt{s_{NN}} = 200$GeV, but also the upcoming ALICE experiment at LHC will have a distinct possibility to measure the baryon asymmetry in pp and AA collisions with a rapidity loss of up to$\sim 8 - 9.6$ units of rapidity which can help to disentangle the transport processes with different energy dependences.

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