Absence of anomalous stopping in heavy ion collisions

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Abstract

We show that the baryon stopping observed in heavy ion collisions both at CERN-SPS and at RHIC can be derived from the one observed in proton-proton collisions. No increase in the size of the baryon junction component is required between small size (pp) and large size (AA) systems.
A huge baryon stopping has been observed in central $Pb\ Pb$ collisions at CERN-SPS by the NA49 collaboration [1]. This stopping cannot be obtained from the standard fragmentation of a diquark. In view of that, several authors [2-4] have introduced a mechanism related to the transfer in rapidity of the string junction (SJ), which carries the baryon number. This mechanism had been considered long time before the CERN heavy ion program started [3, 4]. In ref. [6] it was argued that such a mechanism was required in proton-proton collisions in order to explain the net proton production at mid-rapidities. This has been confirmed recently in ref. [7]. In particular, the NA49 data [8] on the inclusive reaction $\pi + p \rightarrow (p - \bar{p}) + X$ in the pion hemisphere, analysed in [7], show very clearly the necessity of the SJ mechanism. This mechanism will be described in detail in the next section.

In most string models of multiparticle production, in particular the Dual Parton Model (DPM) [9] and the Quark Gluon String Model [10], the net baryon production at mid-rapidities increases with the number of inelastic collisions suffered by the nucleon from which it originates. Indeed, in the case of production via diquark fragmentation, when the number of inelastic collisions increases the diquark gets slower due to energy momentum conservation. Hence, the produced net baryon is also slower. The same increase of stopping with the number of inelastic collisions occurs in the case of production via the SJ mechanism. It is then natural to ask whether the stopping observed in heavy ion collisions, both at CERN-SPS [11] and at RHIC [11, 12] is normal or anomalous. More precisely, from hadron-hadron scattering data we can determine the strength of the component associated to the SJ mechanism. Using this value, one can then compute the net baryon production in heavy ion collisions, where the average number of inelastic collisions per participant is larger. If the data can be reproduced in this way, the observed stopping can be considered normal. If, on the contrary, the heavy ion data can only be explained by increasing the coupling of the SJ component, the observed stopping can be considered anomalous.

In this paper we show that present data can be explained with the same strength of the SJ component in $pp$ and central $AA$ collisions and, thus, they give no indication of anomalous stopping.
**SJ transfer mechanism.** In string models there are three different mechanisms of net baryon production. In the first one, production takes place from the fragmentation of a valence diquark. In this case the baryon junction follows the diquark, which fragments into a leading baryon by picking up a sea quark out of the $q\overline{q}$ pairs produced in the string breaking. The produced net baryon is thus made out of two valence and one sea quarks. This mechanism will be denoted diquark preserving (DP).

In the other two cases the diquark is broken (DB). In one case the string junction travels in rapidity together with a valence quark. The produced net baryon is made out of one valence and two sea quarks. In the other case, the string junction travels in rapidity without any valence quark (gluonic mechanism) and the produced net baryon is made out of three sea quarks.

The important point is to determine the rapidity distribution associated to each of these three mechanisms. In a Regge language this amounts to determining the Regge intercept associated to the exchanged objects: $SJ$, $SJ + q_v$ and $SJ + (qq)_v$. Two different choices for these intercepts have been considered in the literature for the DB mechanisms:

$$\alpha_{SJ}(0) = 1/2 \quad , \quad \alpha_{SJ+q_v}(0) = 0 \quad [5]^2$$

and

$$\alpha_{SJ}(0) = 1 \quad , \quad \alpha_{SJ+q_v}(0) = 1/2 \quad [6].$$

Note the equal spacing in eqs. (1) and (2) due to standard Regge rules: $\alpha_{SJ+q_v}(0) = \alpha_{SJ}(0) + \alpha_\rho(0) - 1$, where $\alpha_\rho(0) = 1/2$.

Experimentally, there is ample evidence for the existence of a component with intercept 1/2 in hadron-hadron scattering [7]. In these data there is no room for a component with intercept 1 [3]. Net baryon production in heavy ion collisions, both at CERN-SPS and RHIC, also requires a DB mechanism with intercept 1/2 [2-4, 13]

\[^2\text{One of the authors of ref. [5] (G.V.) considers presently the choice (2) as very natural (G. Veneziano, private communication).}\

\[^3\text{With the possible exception [14] of preliminary HERA data [14]. See also ref. [15] for a discussion on this point.}\

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Moreover, the values of the ratios $B/B$ measured at RHIC indicate that the corresponding net baryon is (dominantly) made out of one valence and two sea quarks [10]. This clearly favors possibility (2), which will be used throughout this paper. This probably indicates that the gluonic SJ component has a coupling too small to manifest itself at present energies, where the pre-asymptotic component $SJ + q_v$ with intercept $1/2$ dominates [3].

Let us turn next to the DP mechanism $SJ + (qq)_v$, i.e. the conventional diquark (plus SJ) fragmentation. Its intercept corresponds to the so-called baryonium exchange, whose intercept is known experimentally to be $-1.5 \pm 0.5$. We will use this experimental value in what follows. Note that, according to the usual Regge rules, this intercept should have equal spacing with respect to the ones in (1) and (2), i.e. should have intercept $-1/2$ in case (1) and 0 in case (2). The same Regge rules allow to relate these intercepts to the intercept of the nucleon trajectory, $\alpha_N(0)$ [4] [18] [19]. Thus, $\alpha_{SJ+(qq)_v}(0) = -1/2$, (0) corresponds to $\alpha_N(0) = 0$ (1/4), whereas the experimental value $\alpha_{SJ+(qq)_v}(0) = -1.5 \pm 0.5$ correspond to $\alpha_N(0) = -\frac{1}{2} \pm \frac{1}{4}$. These discrepancies are probably related to spin effects responsible for the different intercepts of $N$ and $\Delta$ trajectories.

**The model.** Our model for net baryon production consists of two different components associated to the two mechanisms described above. A conventional (DP) component corresponding to the fragmentation of a valence diquark and a DB component in which the SJ follows one of the two valence quarks of the broken diquark. As discussed above, in the first case the baryon is made out of two valence and one sea quarks and is mostly produced in the fragmentation region. In the second case, it is made out of two sea and one valence quarks. This second component

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4Note, however, that a non-zero value of net omegas has been observed in $hA$ collisions [17]. This requires a non-vanishing contribution in which the net baryon is made out of three sea quarks. However, its effect in $AA$ collisions is probably very small since, in this case, the produced net omegas are almost entirely due to final state interaction [15] [16].

5Note also that in QGSM a value $\alpha_{SJ+q_v}(0) = -1$ is used [18] [19], obtained from the experimental value $\alpha_{SJ+(qq)_v}(0) = -1.5$, using the 1/2 Regge spacing rule mentioned above. In this case a component with intercept 1/2 corresponds to the gluonic SJ exchange and the 1/2 – equal – spacing rule is broken between $\alpha_{SJ}(0) = 1/2$ and $\alpha_{SJ+q_v}(0) = -1$. 

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gives the dominant contribution at mid-rapidities. In DPM, QGSM and most string models the hadron spectra of the individual strings are obtained as convolutions of momentum distribution and fragmentation functions. However, in the case of net baryon production it is natural to assume that its rapidity distribution is essentially the one of the SJ, which is given by its Regge intercept. In this way we are led to the following model\footnote{Note that eq. (3) ensures exact baryon number conservation. This conservation is not so easy to enforce when a convolution of momentum distribution and fragmentation functions is performed. However, eq. (3) does not keep track of the fact that the string in which the net baryon is produced has a valence quark at the opposite end. The average value of the rapidity of the latter is about 1.5 units from the maximal value of the rapidity of the proton to which it belongs. Consequently, eq. (3) can not be used to compute the net baryon contribution at the end of phase space in the opposite hemisphere. However, this is of no consequence for the results on the total net baryon distribution in $pp$ or $AA$ collisions since the contribution to the fragmentation region of a nucleon from the nucleon on the opposite side is very small as compared to the one from the same side.} for the net baryon production out of a single baryon

\[
\frac{dN_{\mu}(y)}{dy} = aC^{DB}_\nu Z_+^{1-\alpha_{SJ}(qq_p)}(y) (1 - Z_+)^{\mu(b)-3/2+n_{sq}(\alpha_p(0)-\alpha_{\phi}(0))} + (1-a)C^{DP}_\nu Z_+^{1-\alpha_{SJ}(qq_p)}(y) (1 - Z_+)^{\mu(b)-3/2+c+n_{sq}(\alpha_p(0)-\alpha_{\phi}(0))}
\]  

(3)

where $n_{sq}$ is the number of strange quarks in the hyperon $\alpha_p(0) = 1/2$ $\alpha_{\phi}(0) = 0$, $Z_+ = (e^{y-y_{max}})$, $y_{max}$ is the maximal value of the baryon rapidity and $\mu(b)$ is the average number of inelastic collisions suffered by the baryon at fixed impact parameter $b$\footnote{Actually the number of inelastic collisions is distributed. However, the distribution is rather narrow and no significant numerical difference has been observed by taking the average value, as in eqs. (3).}. The constants $C\nu$ are obtained from the normalization to unity of each term. The small $Z$ behaviour is controled by the corresponding intercept. The factor $(1 - Z_+)^{\mu(b)-3/2}$ is obtained by requiring that the $Z$-fractions of all quarks at the ends of the strings, other than the one in which the baryon is produced, go to zero\footnote{Note that eq. (3) ensures exact baryon number conservation. This conservation is not so easy to enforce when a convolution of momentum distribution and fragmentation functions is performed. However, eq. (3) does not keep track of the fact that the string in which the net baryon is produced has a valence quark at the opposite end. The average value of the rapidity of the latter is about 1.5 units from the maximal value of the rapidity of the proton to which it belongs. Consequently, eq. (3) can not be used to compute the net baryon contribution at the end of phase space in the opposite hemisphere. However, this is of no consequence for the results on the total net baryon distribution in $pp$ or $AA$ collisions since the contribution to the fragmentation region of a nucleon from the nucleon on the opposite side is very small as compared to the one from the same side.}. Following conventional Regge rules\cite{15, 19, 7} an extra $\alpha_p(0) = \alpha_{\phi}(0) = 1/2$ is added to the power of $1 - Z_+$ for each strange quark in the hyperon.

The fraction, $a$, of the DB breaking component is treated as a free parameter. The same for the parameter $c$ in the DP component – which has to be determined from the shape of the (non-diffractive) proton inclusive cross-section in the baryon
fragmentation region. In the case of $AA$ collisions the value of $\mu(b)$ is given by $\mu(b) = k\nu(b)$ with $\nu(b) = n(b)/n_A(b)$, where $n(b)$ and $n_A(b)$ are the average number of binary collisions and of participant of nucleus $A$ and $k$ is the average number of inelastic collisions in $pp$. At SPS energies $k = 1.4$ and at RHIC $k = 2$ [21].

Related models have been proposed in [3] and [15]. The results for heavy ion collisions are rather similar to the ones obtained from Eq. (3). However, in these models there is some increase in the size of the DB component with the number of inelastic collisions – suggesting an anomalous stopping. In a very recent paper [21] it is found that anomalous stopping is also needed in the model of ref. [7].

**Quark counting rules.** Eqs. (3) do not allow to determine the relative densities of the different baryon species. In order to do so we use simple quark counting rules [15], [16]. Let us denote the strangeness suppression factor by $S/L$, with $2L + S = 1$. Baryons produced out of one valence and two sea quarks, which is the case for the DB component, are given the relative weights $I_2 = 2L^2 : 2L^2 : 4LS : S^2 / 2 : S^2 / 2$ for $p, n, \Lambda + \Sigma, \Xi^0$ and $\Xi^-$, respectively. The various coefficients of $I_2$ are obtained from the power expansion of $(2L + S)^2$. For baryons made out of two valence and one sea quark, which is the case for the DP component, the corresponding weights are given by $I_1 = L : L : S$ for $p, n$ and $\Lambda + \Sigma$, respectively. In the calculation we use $S = 0.1$ ($S/L = 0.22$) as in ref. [14]. The above weights apply to the case where the number of valence $u$ and $d$ quarks is the same. In the case of an incoming proton they have to be modified in a straightforward way. For example, in the DB (DP) component, the weight for the production of a net proton is changed from $2L^2(L)$ into $7L^2/3 (4L/3)$. Likewise the modification due to the fact that about 60% of the nucleons of the nucleus are neutrons is straightforward.

**Numerical results.** A good description of the data on the rapidity distribution of $pp \rightarrow p - \bar{p} + X$ both at $\sqrt{s} = 17.2$ GeV [22] and $\sqrt{s} = 27.4$ GeV [23] is obtained from eq. (3) with $a = 0.4$, $c = 1$, $\alpha_{SJJ+(q\bar{q})} = 1/2$ and $\alpha_{SJJ+(q\bar{q})} = -1$. The results are shown in Table 1 at three different energies, and compared with the data [22, 23]. As we see the agreement is reasonable. We have also checked that eq. (3) reproduces the preliminary data of the NA49 collaboration on $pp \rightarrow p - \bar{p} + X$ [24] and $\pi p \rightarrow p - \bar{p} + X$. 

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As well as the ones on $pp \rightarrow \Lambda - \bar{\Lambda} + X$ \cite{19}. For comparison with the nucleus-nucleus results, all values in Table 1 have been scaled by the number of participants pairs in central $Pb Pb$ and $Au Au$ collisions ($n_A = 175$). As it is well known, a pronounced minimum is present at $y^* = 0$. There is also a substantial decrease of the mid-rapidity yields with increasing energy. Also, the mid-rapidity distributions get flatter with increasing energy since the net proton peaks are shifted towards the fragmentation regions.

It is now possible to compute the corresponding net baryon production in heavy ion collisions and to check whether or not the data can be described with eq. \cite{8} using the same set of parameters.

The results for net proton ($p - \bar{p}$) and net baryon ($B - \bar{B}$) production in central $Pb Pb$ collisions at $\sqrt{s} = 17.2$ GeV and central $Au Au$ collisions at $\sqrt{s} = 130$ GeV are given in Table 2. The centrality is defined by the average number of participants $- n_{\text{part}} = 350$ in both cases. Experimental results \cite{1,11} are given in brackets.

The comparison of column 2 with the $pp$ results in Table 1 at the same energy, shows the well known change in the shape of the rapidity distribution between $pp$ and central $Pb Pb$ collisions. The minimum at $y^* = 0$ is much less pronounced in $Pb Pb$ and the net proton peaks in the $pp$ fragmentation regions are shifted to $y^* \sim \pm 1.5$. More interesting are the results in columns 4 and 5 which contain the predictions at RHIC (where data are only available at $y^* \sim 0$). We see that the shape of the rapidity distribution is very different from the one at SPS. (At RHIC the value at $y^* = 0$ is smaller than at SPS by a factor 3, whereas at $y^* = 2$ the decrease is only 45 \%). We also see that the peaks at $|y^*| = 1.5$ are not present at RHIC, (i.e. they are shifted to higher values of $|y^*|$).

The main result of our work is the fact that the calculated values in $Pb Pb$ and $Au Au$ collisions are in reasonable agreement with experiment. Actually, the calculated value at RHIC is even higher than the experimental value\cite{8}. This has been achieved using the same parameters as in $pp$ collisions. In particular, there is

\footnote{It has been shown in \cite{15,16} that final state interaction is crucial in order to obtain the observed enhancement of strange baryons both at SPS and RHIC. Due to strangeness conservation, this produces a small decrease of the net proton yield – while the net baryon yield is not changed. This decrease is maximal at $y^* = 0$, where it is of 14 \% at RHIC \cite{16}. The computed value for $Au Au \rightarrow p - \bar{p}$ is thus reduced from 8.0 to 7.0 – in better agreement with experiment.}
no need to increase the value of the parameter $a$, which determines the strength of the SJ component.

In conclusion, we have introduced a two component model for net baryon production in $pp$, $pA$ and $AA$ collisions. One component corresponds to the conventional diquark fragmentation mechanism and produces baryons mostly in the fragmentation regions. The other component is associated with the mechanism of transfer in rapidity of the baryon junction and gives the dominant contribution at mid-rapidities. The model allows to compute the net baryon rapidity distribution for the different baryon species and for all centralities at any given energy. The model contains two free parameters – the most important one being the parameter $a$ which determines the relative strength (40 %) of the baryon junction component. We have shown that the same set of parameters allows to describe the data on net proton production in $pp$ and $AA$ collisions. This leads to the conclusion that no anomalous stopping has been observed in heavy ion collisions.

| $y^*$ | $pp \rightarrow p - \bar{p}$ at $\sqrt{s} = 17.2$ GeV | $pp \rightarrow p - \bar{p}$ at $\sqrt{s} = 27.4$ GeV | $pp \rightarrow p - \bar{p}$ at $\sqrt{s} = 130$ GeV |
|-------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| 0     | 9.2                                           | 6.5                                           | 3.6                                           |
| 1     | 15.0                                          | 9.3                                           | 4.2                                           |
|       | [16.1 ± 1.8]                                 | [9.6 ± 0.9]                                   |                                               |
| 1.5   | 25.8                                          | 14.6                                          | 5.1                                           |
|       | [24.1 ± 1.4]                                 | [15.4 ± 0.9]                                  |                                               |
| 2     | 47.1                                          | 26.2                                          | 6.8                                           |
|       | [45.4 ± 1.4]                                 | [27.7 ± 0.9]                                  |                                               |

Table 1. Calculated values of the rapidity distribution of $pp \rightarrow p - \bar{p} + X$ at $\sqrt{s} = 17.2$ GeV and 27.4 GeV ($k = 1.4$) and $\sqrt{s} = 130$ GeV ($k = 2$). The data in the second column are from ref. [22]. (In order to convert $d\sigma/dy$ into $dN/dy$ a value of $\sigma = 30$ mb has been used). The data at $\sqrt{s} = 27.4$ GeV are from ref. [23], as presented in [1]. Following [1], and for comparison with the nucleus-nucleus results, all values in Table 1 have been scaled by $n_A = 175$ – the number of participant pairs.
in central \( \text{Pb Pb} \) and \( \text{Au Au} \) collisions.

| \( y^* \) | \( \text{Pb Pb} \rightarrow p - \overline{p} \) \( \sqrt{s} = 17.2 \text{ GeV} \) | \( \text{Pb Pb} \rightarrow B - \overline{B} \) \( \sqrt{s} = 17.2 \text{ GeV} \) | \( \text{Au Au} \rightarrow p - \overline{p} \) \( \sqrt{s} = 130 \text{ GeV} \) | \( \text{Au Au} \rightarrow B - \overline{B} \) \( \sqrt{s} = 130 \text{ GeV} \) |
|-------|------------------|------------------|------------------|------------------|
| 0     | 23.0             | 58.5              | 8.0              | 20.9             |
|       | [26.7 ± 3.7]     | [67.7 ± 7.3]      | [5.6 ± 0.9 ± 24\%] |                  |
| 1     | 32.3             | 79.7              | 8.6              | 22.6             |
|       | [34.9 ± 1.5]     | [84.7 ± 3.5]      |                  |                  |
| 1.5   | 36.3             | 87.0              | 12.3             | 31.5             |
|       | [34.4 ± 1.7]     | [80.0 ± 3.9]      |                  |                  |
| 2     | 25.3             | 57.15             | 17.3             | 43.4             |
|       | [24.7 ± 1.5]     | [56.1 ± 3.1]      |                  |                  |

**Table 2.** Calculated values of the rapidity distribution \( dN/dy \) for central \( \text{Pb Pb} \rightarrow p - \overline{p} + X \) and \( \text{Pb Pb} \rightarrow B - \overline{B} + X \) at \( \sqrt{s} = 17.2 \text{ GeV} \) \( (k = 1.4) \) and central \( \text{Au Au} \rightarrow p - \overline{p} + X \) and \( \text{Au Au} \rightarrow B - \overline{B} + X \) at \( \sqrt{s} = 130 \text{ GeV} \) \( (k = 2) \). The centrality has been defined by the number of participant pairs \( (n_A = 175 \text{ at both energies}) \) and \( \nu = n/n_A = 4.5 \) \( (5.0) \) at SPS (RHIC). Data are from refs. [1] and [11].

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