BARYON AND ANTIBARYON PRODUCTION IN HADRONIC AND NUCLEAR INTERACTIONS

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Abstract

We introduce a new formulation of the diquark breaking mechanism which describes with no free parameters the huge nuclear stopping observed in central nucleus-nucleus collisions. Supplemented, in the dual parton model, with strings originating from diquark–antidiquark pairs from the nucleon sea, it gives a substantial increase of hyperon and antihyperon yields from $pPb$ to central $PbPb$ collisions. Compared to data, this increase is slightly underestimated for Λ’s and Ξ’s but is five times too small for Ω’s. Introducing final state interactions, a reasonable description of all baryon and antibaryon yields is achieved.

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Enhancement of strange baryon and anti-baryon production in central nucleus-nucleus collisions has been observed experimentally \[1\] \[2\]. In particular, a spectacular enhancement of $\Xi$’s and $\Omega$’s from $pPb$ to central $PbPb$ collisions has been measured \[2\]. This phenomenon has been proposed as a signal of quark gluon plasma formation \[3\]. On the other hand explanations based on string models have also been proposed \[4\]. In ref. \[3\] enhancement of $\Lambda$’s and $\bar{\Lambda}$’s was described in the dual parton model (DPM) \[6\] with final state interaction. An important drawback of \[6\] is the lack of nucleon stopping –which would increase the net baryon yield at mid rapidities. As a consequence a very strong effect due to final state interaction was needed, as well as a rather large value of the fraction of strange quarks in the nucleon sea. A mechanism of nuclear stopping based on diquark breaking (DB) has been known for a long time \[7\]-\[9\]. Recently, it has been introduced in nucleus-nucleus interactions \[10\]-\[11\].

The purpose of this paper is threefold. First, we propose a new formulation of the DB stopping mechanism of \[10\]-\[11\], which allows to describe net baryon stopping without any dynamical parameter governing the DB probability. Second, we show that the DPM with DB and strings with diquarks–antidiquark pairs ($d$-$\bar{d}$) from the sea at their ends, allows to describe most of the observed yields of $\Lambda$, $\bar{\Lambda}$, $\Xi$ and $\bar{\Xi}$ –but significantly underestimates the production of $\Omega$’s and $\bar{\Omega}$’s. Third, using the corresponding baryon densities as initial conditions for final state interaction we achieve a reasonable description of all baryon and antibaryon production\[1\].

**Baryon stopping.** We describe baryon stopping via the mechanism shown in Fig. 1 –the same as Fig. 5 of \[11\]. However, contrary to \[11\] we assume here that there is no dynamical suppression associated to DB –i.e. the weight of the DB diagram of

\[1\] In this paper we concentrate ourselves on the rapidity density. For a calculation of the transverse mass spectra in DPM see \[2\].
Fig. 1 is the same as the conventional DP one of Fig. 2. More precisely, in the case of a single inelastic collision per nucleon (two string configuration), two valence quarks of the nucleon are sitting together at a string end. We assume that they form a sort of compact object which hadronizes in the conventional way (DP mechanism). However, in the presence of several inelastic collisions we assume that the net baryon number (string junction) has equal probability of finding itself in any of them. If it follows the valence diquark (Fig. 2) we have the conventional DP situation. In the other cases it joins with sea quarks producing a much slower baryon (DB mechanism of Fig. 1). The rapidity distribution of the net baryon production $\Delta B = B - \bar{B}$ in $AA$ collisions is then given by

$$
\frac{dN^{AA\rightarrow\Delta B}}{dy}(y) = \frac{\bar{n}_A}{\bar{n}} \left[ \bar{n}_A \left( \frac{dN^{\Delta B}_{DP}}{dy}(y) \right)_{\bar{n}/\bar{n}_A} + (\bar{n} - \bar{n}_A) \left( \frac{dN^{\Delta B}_{DB}}{dy}(y) \right)_{\bar{n}/\bar{n}_A} \right].
$$

(1)

Here $\bar{n}_A$ is the average number of participants in each nucleus and $\bar{n}$ the average number of collisions. $dN_{DP}/dy$ is given by the conventional DP hadronization mechanism and $dN_{DB}/dy$ is the rapidity density given by the DB component—which behaves \([7, 9, 10]\) as $\exp\left[-\frac{1}{2}|y_{\Delta B} - y_{Max}|\right]$. Both distributions depend, due to energy-conservation, on the average number of collisions per nucleon $n/n_A \approx \bar{n}/\bar{n}_A$. Note that for $\bar{n} = \bar{n}_A$, only the DP component is present and we recover the usual scaling in the number of participants. Baryon number conservation implies that both DP and DB rapidity distributions are normalized in such a way that their integral over $y$ is equal to two. Following \([11]\) we have

\[This is the behaviour in the original work \([7]\) and is used by all authors at present energies \([10, 11]\). However, a flat behaviour in $y$ at high energies has been proposed in \([3, 8]\). This has very important consequences for the net baryon number at $y^* \sim 0$ at LHC \([11]\). A new component consisting on a diquark which contains a quark from the nucleon sea also has been introduced in \([13]\). However, in this case the diquark hadronizes as a valence diquark producing baryons mainly in the fragmentation regions.\]
\[ \frac{dN^{\Delta B}_{DB}}{dy}(y) = C_{n/n_A} \left(Z_{+}^{1/2}(1 - Z_{+})^{\gamma_{n/n_A}} + Z_{-}^{1/2}(1 - Z_{-})^{\gamma_{n/n_A}} \right) \]

where \( Z_{\pm} = \exp(\pm y - y_{max}) \). The same shape will be used for all baryon species.

Two different ansätze for the power \( \gamma \) were proposed in [11]—which give for central PbPb collisions \((\bar{n}/n_A \sim 4)\) a value of \(dN^{\Delta B}_{DB}/dy\) at \(y^* \sim 0\) in the range 0.5 to 0.60.

In order to reproduce the data of the NA49 collaboration [1] for \(B-\bar{B}\) at \(y^* = 0\), we need a value 0.48. Our analysis will concentrate on mid-rapidities and this value will be used throughout this paper.

Eq. (1) also applies to \(pp\) collisions putting \(n = n_A = 1\). However, this applies only at low energies where the two string configuration dominates. At high energies the second term in (1) is present and increases the net baryon stopping. Unfortunately, the only available data at ISR do not allow to either confirm or rule out the presence of the DB component. However, the effect of this component is quite important in \(pA\) collisions where the \(pPb\) data of [1] confirm its presence (see below). In DPM, the extension of eq. (1) to \(pA\) collisions is straightforward. A good approximation to the exact formula, valid at \(y^* = 0\), is

\[ \frac{dN^{pA\rightarrow\Delta B}}{dy}(0) = \bar{n} \frac{dN^{pp\rightarrow\Delta B}}{dy}(0) + \frac{1}{2} \left( \frac{dN^{\Delta B}}{dy}(0) \right)_{\bar{n}}. \]

Here \(\bar{n} = A \sigma_{pp}/\sigma_{pA}\) and \((dN^{\Delta B}/dy)_{\bar{n}}\) is given by eq. (1) with \(n_A = 1\). Eq. (3) is self-evident. On the nucleus side we have \(\bar{n}\) diquarks which hadronizes as in \(pp\) collisions (the average number of collisions per nucleon at present energies is close to one in both cases). On the proton side, we have one diquark which hadronizes as in \(AA\) collisions. (The average number of collisions of this nucleon in \(pPb\) and in central \(PbPb\) collisions is practically the same). Eq. (3) is very useful since it gives the rapidity density of the net baryon in \(pPb\), in terms of the same quantities which appear in \(PbPb\) (eq. (1)) plus the corresponding one for \(pp\).
**B-B pair production.** Following \[5, 12\] the rapidity distributions of antibaryons in AA collisions is given by

\[
\frac{dN_{AA \rightarrow \bar{B}}}{dy}(y) = \bar{n}_A \left( \frac{dN_{\text{string}}^B}{dy}(y) \right)_{\bar{n}/\bar{n}_A} + (\bar{n} - \bar{n}_A) \left( \frac{dN_{\text{sea}}^B}{dy}(y) \right)_{\bar{n}/\bar{n}_A} .
\]

Here \(dN_{\text{string}}/dy\) denotes the conventional pair production resulting from \(d-\bar{d}\) production in the string breaking process. At present energies the \(q-\bar{q}\) strings have too little energy for baryon pair production; practically all their production occurs in \(qq-\bar{q}\) strings, hence the scaling in the number of participants. This gives a much too small antibaryon yield. For this reason we have introduced \[5, 12\] the second term in (4) which corresponds to pair production in strings with a \(d\) or \(\bar{d}\) from the nucleon sea at one of their ends. The average number of \(d-\bar{d}\) pairs scales as \(\bar{n}-\bar{n}_A\). Note that for \(dN_{\text{string}}/dy \sim dN_{\text{sea}}/dy\), the scaling in the number of participants is converted into a scaling in the number of collisions.

For \(pA\) collisions the equivalent of expression (3), valid at \(y^* = 0\), is

\[
\frac{dN_{pA \rightarrow \bar{B}}}{dy}(0) = \frac{\bar{n}}{2} \frac{dN_{pp \rightarrow \bar{B}}}{dy}(0) + \frac{1}{2} \left( \frac{dN_{BB}}{dy}(0) \right)_{\bar{n}} .
\]

Here \(\bar{n} = A \sigma_{pp}/\sigma_{pA}\) and \((dN_{BB}/dy)_{\bar{n}}\) is given by eq. (4) with \(n_A = 1\).

**Numerical results.** Let us concentrate first on the non-conventional contributions (second terms in eqs. (1-3) and (4-5))—which are numerically very important since they contain the factor \(\bar{n}-\bar{n}_A\). Actually, \(dN_{\text{sea}}/dy\) has been computed in [5]. However, as stated there, there is a huge uncertainty on its absolute normalization. In view of that, we are going to determine it from \(pA\) data. Since data [2] for multi-strange hyperons are only available in the rapidity range \(-0.5 < y^* < 0.5\) we shall restrict our analysis to this region.
Turning to the relative yields of the different baryon species, we note that in $dN_{\text{sea}}^B/\text{d}y$ the baryons and antibaryons are produced from three sea quarks. Therefore the factors controlling the relative yields are: $4L^3, 4L^3, 12L^2S, 3LS^2, 3LS^2$ and $S^3$ for $p, n, \Lambda + \Sigma, \Xi^0, \Xi^-$ and $\Omega$, respectively. Moreover, we use for both baryons and antibaryons the conventional relation $\Sigma^+ + \Sigma^- = 0.6\Lambda$, which is obtained after resonance decay. We take $L = 0.435$ and $S = 0.13$. In this way the strangeness suppression factor has the conventional value $S/L = 0.3$ and the sum of all baryon yields add up to $(2L + S)^3 = 1$. However, this fixes only the relative normalization of the various (anti) baryon species—and there is one free parameter which provides the absolute normalization which is fixed by the data. The obtained values are given in Table I.

The situation is quite different for the new component $dN_{\text{DB}}^B/\text{d}y$. Here net baryon conservation fixes the absolute normalization and therefore there is in principle no free parameter—since the strangeness suppression factors are the same as above. However, it turns out that proceeding in this way the strange baryon yields in $pA$ are overestimated—especially $\Xi$’s and $\Omega$’s. A possible explanation of this fact is that, at present energies, it may happen that the baryon is not formed out of three sea quarks as in Fig. 1, but, due to lack of phase space, the valence quark at the string end is picked up instead§. In this case, the relative yields of $\Lambda$’s of $\Xi$’s will be reduced and that of $\Omega$’s will be zero. In any case, we take here a phenomenological attitude. We determine the strange net baryon yields at $y^* = 0$ from the data. We have thus three free parameters $\Lambda-\bar{\Lambda}$, $\Xi^-\Xi^+$ and $\Omega-\bar{\Omega}$—plus a forth parameter for the absolute normalization of antibaryons as discussed above. We arrive in this way to the values listed in Table I.

§Nevertheless, the factors given above should apply at very high energy. They give a ratio $\Xi/\Lambda + \Sigma \sim 0.3$ in agreement with Tevatron [14] and SPS collider [15] data.
Finally, the conventional components $dN_{DP}/dy$ and $dN_{string}/dy$ have been obtained in two different ways: using the formalism of ref. [5] and using the QGSM Monte Carlo without string fusion. In the former case, the obtained values are given in Table I. It should be noted that the contribution of these conventional components to the final results is significantly smaller than the one of the new components, since the latter are proportional to $\bar{n} - \bar{n}_A$.

With the values given in Tables I we obtain the results shown in Figs. 3 and 4. The $pA$ data are well reproduced for all baryon species. In $PbPb$, the $p + \bar{p}$ and most of the $\Lambda + \bar{\Lambda}$ yield are reproduced. However, the $\Xi^- + \bar{\Xi}^+$ yield is somewhat underestimated and the $\Omega + \bar{\Omega}$ one is five times smaller than the measured one.

In an attempt to solve this problem, we use our expressions (1) and (4) as initial baryon densities for final state interaction. We consider the following channels

$$\pi N \rightarrow K\Lambda, \quad \pi N \rightarrow K\Sigma, \quad \pi\Lambda \rightarrow K\Xi, \quad \pi\Sigma \rightarrow K\Xi, \quad \pi\Xi \rightarrow K\Omega,$$

plus the corresponding ones for antiparticles. The final state interaction is treated

The parameters of this Monte Carlo, which produced too many strange baryons in $pp$ collisions, have been tuned up, and its results in $pp$ collisions are now in agreement with the calculations of [5] and with the experimental data (see Table 1 in [5]).

A qualitatively similar result has been obtained in [18]. This paper, which was appeared after completion of the present work, is based on a different realization of baryon stopping and uses a junction-antijunction exchange mechanism for baryon pair production. It does not include final state interaction.

As a technical point, one should notice that some of the charge combinations in (1) are not possible or have negligibly small cross-sections. The latter correspond to quark diagrams with three quark lines (baryon exchange) in the $t$-channel. They have not been included. All reactions corresponding to quark diagrams with light quark annihilation and $s-s$ production have been included with identical cross-section. We have neglected all strangeness exchange reactions $\pi\Lambda \rightarrow KN$, etc. Although, at threshold, the cross-sections are larger than those of the non-strangeness exchange reactions (6), this is no longer the case for the averaged cross-sections $<\sigma>$ (see [3]). Channels (3) are thus dominant due to the relations $\rho_N > \rho_\Lambda > \rho_\Xi > \rho_\Omega$ between baryon densities.
in the same way as in ref. [19, 20]. The products of densities in (6) are taken at fixed values of $\vec{b}$ and $\vec{s}$. For the baryon densities, the dependence on these variables is contained in the geometrical factors $\tilde{n}_A$ and $\tilde{n}$ in eqs. (1) and (4). They are computed in the Glauber model with Saxon-Woods profiles. The pion densities and the initial and final times are the same as in [19, 20]. The only difference resides in the fact that, in the case of $J/\psi$ suppression, there is a single channel and the $J/\psi$ appears both in the initial and final state. In this case, the differential equations for the gain and loss of particles can be solved analytically and a simple exponential form is obtained. In the present case, the gain and loss differential equations for the solution of the coupled channels (6) has to be obtained numerically. We have only one free parameter: the cross-section $< \sigma >$ averaged over the momentum distribution of the incoming particles which is taken to be the same for all reactions (the relative velocity between the interacting particles is included in $< \sigma >$). We take $< \sigma > = 0.14$ fm. (A comparable value has been obtained in [3]). It is clear that the relative enhancement of the various baryon and antibaryon yields resulting from the interactions (6) will be the largest for $\Omega$’s and the smallest for $\Lambda$’s. This is due to the fact that $\Lambda$’s are produced in some reactions and destroyed in others. On the contrary $\Omega$’s are produced and never destroyed. The results are shown in Figs. 3 and 4. A reasonable description of all baryon and antibaryon is obtained. However, the ratio $\Omega + \bar{\Omega}/\Xi^- + \bar{\Xi}^+$ in $PbPb$ collisions is slightly underestimated.

In conclusion, we have introduced a new formulation of the diquark breaking mechanism which describes baryon stopping with a diquark breaking probability equal to one. Incorporated in DPM, together with strings originating from diquark-antidiquark pairs from the nucleon sea and final state interactions we have obtained a reasonable description of all baryon and antibaryon yields at mid-rapidities in $pp$,.
$pPb$ and $PbPb$ collisions.

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Figure Captions

Fig. 1 : Diquark breaking component for nucleon-nucleus scattering and two inelastic collisions.

Fig. 2 : DP component for nucleon-nucleus scattering for two inelastic collisions.

Fig. 3 : Baryon yields for \( pPb \) and \( PbPb \) collisions at 160 GeV per nucleon calculated from eqs. (1-3) using the values in Table 1 before (dotted line) and after (full line) final state interaction. The dashed lines are the results with final state interaction using the Monte-Carlo results [16, 17] for the conventional DP and string breaking components. The data are from the WA 97 collaboration [2].

Fig. 4 : Same as in Fig. 3 for the ratios \( \bar{B}/B \).
Table I : Values of the rapidity densities at $y^* = 0$ in eqs. (1,3-5). The values in the first lower rows are for central PbPb collisions ($\bar{n}_A = 178, \bar{n} = 858$) and those in the last two rows for pp. Three numbers in the first row and one in the second one have been adjusted to the data (see main text).

|                          | $p$     | $\Lambda$ | $\Xi^-$   | $\Omega$ |
|--------------------------|---------|-----------|-----------|-----------|
| $dN^\Delta_B/\text{dy}$ | $1.87 \times 10^{-1}$ | $6.22 \times 10^{-2}$ | $3.26 \times 10^{-3}$ | $2.38 \times 10^{-4}$ |
| $dN^B_{\text{sea}}/\text{dy}$ | $4.36 \times 10^{-3}$ | $2.44 \times 10^{-3}$ | $2.92 \times 10^{-4}$ | $2.91 \times 10^{-5}$ |
| $dN^\Delta_B/\text{dy}$ | $6.90 \times 10^{-2}$ | $1.40 \times 10^{-2}$ | $0$ | $0$ |
| $dN^B_{\text{string}}/\text{dy}$ | $8.50 \times 10^{-3}$ | $2.83 \times 10^{-3}$ | $1.65 \times 10^{-4}$ | $5.05 \times 10^{-6}$ |
| $dN^\Delta_B/\text{dy}$ | $3.60 \times 10^{-2}$ | $7.00 \times 10^{-3}$ | $0$ | $0$ |
| $dN^B_{\text{pp}}/\text{dy}$ | $5.65 \times 10^{-3}$ | $3.30 \times 10^{-4}$ | $1.01 \times 10^{-5}$ | $1.01 \times 10^{-5}$ |
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Figure 3
Figure 4