Novel Mechanism of Nucleon Stopping in Heavy Ion Collisions

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Abstract
When a diquark does not fragment directly but breaks in such a way that only one of its quarks gets into the produced baryon, the latter is produced closer to mid rapidities. The relative size of this diquark breaking component increases quite fast with increasing energy. We show that at a given energy it also increases with the atomic mass number and with the centrality of the collision and that it allows to explain the rapidity distribution of the net baryon number ($p-\bar{p}$) in SS central collisions. Predictions for $Pb-Pb$ collisions are presented.
In most string models particle production in a $pp$ collision occurs mainly in the form of two diquark-quark strings. There is strong experimental evidence \[1\] that with a large probability the diquark acts as a single entity and fragments directly into a leading baryon. Since the diquark is fast in average, taking a large fraction of the incoming proton momentum, the produced baryon will be in the proton fragmentation region. Moreover, it is easy to see that the corresponding baryon spectrum at $y^* \sim 0$ decreases, quite fast with energy - roughly as $s^{-1} \[1\]-\[3\]$. A diquark breaking component in which only one of two quarks gets into the produced baryon is of course present. This component produces baryons at smaller values of $y^*$ and the produced baryon distribution at $y^* \sim 0$ only decreases like $s^{-1/4} \[3\]$. In the Dual Parton Model (DPM) and Quark Gluon String Model (QGSM) such a component is not explicitly taken into account \[2\], \[4\]. However, it has been shown by Kopeliovich and Zakharov \[3\] that the energy dependence of $d\sigma/dy$ at $y^* = 0$ for the difference $p$ minus $\bar{p}$ measured by two different collaborations \[5\], \[6\] in the ISR energy range can only be understood with a diquark breaking component of a relative size of about 20 % which has to be introduced in the string models as a separate component. The authors of ref. \[3\] have also proposed an interpretation of the diquark breaking component as a result of a color exchange which converts the diquark from a $\{\bar{3}\}$ to a $\{6\}$ color state. While this is an attractive mechanism, it may not be the only one. If to assume that the relative longitudinal momenta of the quarks inside the diquark may be substantially different, a diquark breaking with excitation of a high-mass state could also result in the baryon production at mid rapidities.

In the present work we do not specify the origin of the diquark breaking component and do not attempt to compute its size theoretically (for a calculation in perturbative QCD see ref. \[3\]). Following the phenomenological analysis in ref. \[3\] we determine the latter from experiment. Also, we concentrate ourselves to present CERN energies of $\sqrt{s} \sim 20$ GeV and make only some comments about our expectations for RHIC or LHC energies. We shall show that in heavy ion collisions the relative size of the diquark breaking component increases with atomic mass number and with the centrality of the collision. We show that in central $SS$ collision the rapidity distribution of the difference $p-\bar{p}$ - which in DPM has a sharp dip at mid rapidities \[2\] not present in the data \[6\] - is consistent with experiment after introducing the diquark breaking component - with relative size determined from $pp$ data as explained above. The corresponding distributions for central $Pb-Pb$ collisions at present CERN energies can then be computed, and are given as a prediction of our diquark breaking mechanism.
In DPM, the dominant component in $pp$ scattering is the two string configuration depicted in fig. 1. Here the diquark fragments directly into a final state baryon. The rapidity distribution $dN/dy$ of a hadron in a string is obtained from a convolution of the momentum distribution and fragmentation functions [1]. All formulas and parameters relative to baryon production in nucleon-nucleon collision are given in refs. [2] and [4]. The corresponding results will be denoted $dN_{DP}/dy$ (where $DP$ stands for diquark preserving). As mentioned above there is also the possibility that the diquark breaks in the way depicted in fig. 2. In this case the baryon rapidity distribution follows that of the valence quark and thus the baryon is slower than in the $DP$ component of fig. 1. We then have

$$
\frac{dN_{DB}}{dy}(y) = \frac{C}{2} \left[ \tilde{\rho}_{qv}(y) + \tilde{\rho}_{qv}(-y) \right],
$$

(1)

where $DB$ stands for diquark breaking and $\tilde{\rho}_{qv}(y)$ is the valence quark rapidity distribution. This function and the value of the constant $C$ are given below. Obviously, in the final formula, the $DB$ component has to be weighted by the ratio $\sigma_{DB}/\sigma_{in}$ of the $DB$ over the inelastic cross-section.

Let us now turn to a nucleon-nucleus ($NA$) collision. Here we can also have a $DP$ and $DB$ components. In the case of a double inelastic collision they are depicted in figs. 3 and 4, respectively. In the $NA$ case (as well as in a $NN$ configuration involving at least four strings) it is also possible to have a configuration as the one depicted in fig. 5 in which the baryon number is associated to a gluon or sea quark of the incoming nucleon. For the moment we disregard such a configuration but shall come back to it later on. Let us now split
the nucleon-nucleon (NN) cross-section into its diquark preserving and diquark breaking components \( \sigma_{in} = \sigma_{DP} + \sigma_{DB} \). We assume that once the diquark has been destroyed in a collision with one nucleon of the nucleus it cannot be reconstructed in further collisions with other nucleons of the nucleus. The \( NA \) cross-section involving \( n \) inelastic \( NN \) collisions is then given by

\[
\sigma_{DB,n}^{NA}(b) = \binom{A}{n} \sum_{i=1}^{n} \binom{n}{i} \sigma_{DB}^{i} \sigma_{DP}^{n-i} T_A^n(b) [1 - \sigma_{in} T_A(b)]^{A-n} \cdot \tag{2}
\]

Figure 3: Diquark preserving component for nucleon-nucleus scattering for two inelastic collisions.

Figure 4: Same as fig. 3 for the diquark breaking component.

Figure 5: Same as fig. 4 but here the produced baryon has the rapidity distribution of a sea quark.
Here $T_A(b)$ is the standard nuclear profile function at impact parameter $b$, normalized to unity. In (2) we have replaced the usual factor $\sigma_{in}^n T_A^n$ corresponding to the cross-section for $n$ inelastic collisions by the product $\sum_{i=1}^n \binom{n}{i} \sigma_{DB} \sigma_{DP}^{n-1} T_A^n = (\sigma_{in}^n - \sigma_{DP}^n) T_A^n(b)$. Indeed only the term $\sigma_{DP}^n T_A^n$ will contribute to the diquark preserving cross-section. Summing in $n$ we have

$$\sigma_{DB}^{NA}(b) = \sum_{n=1}^{A} \sigma_{DB,n}^{NA}(b) = 1 - [1 - \sigma_{DB} T_A(b)]^A .$$

Eq. (3) shows that the diquark preserving cross-section belongs to a class of process which has only self-absorption (or self-shadowing). Obviously

$$\sigma_{DP}^{NA}(b) = \sigma_{in}^{NA}(b) - \sigma_{DB}^{NA}(b) .$$

Since $\sigma_{DB} < \sigma_{in}$, it is clear from (3) and (4) that $\sigma_{DB}^{NA}$ increases faster with $A$ than $\sigma_{DP}^{NA}$. Actually, when $\sigma_{DB}$ is sufficiently small to neglect in (3) second and higher powers of $\sigma_{DB}$, $\sigma_{DB}^{NA}$ will increase linearly with $A$. This proves the result stated above that the relative size of the $DB$ component increases with increasing $A$. The result can be easily generalized to an $AB$ collision. We have

$$\sigma_{AB}^{DB}(b) = 1 - (1 - \sigma_{DB} T_{AB}(b))^{AB} .$$

where $T_{AB}(\vec{b}) = \int d^2 s \ T_A(\vec{s}) \ T_B(\vec{b} - \vec{s})$. For $\sigma_{DB}$ sufficiently small we get from (5), after integration in impact parameter, $\sigma_{AB}^{DB} = AB \sigma_{DB}$.

In order to compute the nucleon rapidity distribution we only need to specify the values of $\sigma_{DB}$ as well as the value $C_{NN}$ of the constant $C$ in (1) for an $NN$ collision, as well as the function $\tilde{\rho}_{q_s}(y) \equiv Z \rho_{q_s}^n(Z)$ in (1). Here $Z = e^{-\Delta y}$, $\Delta y = y - Y_{MAX}$. The function $\rho_{q_s}^n(Z)$ is explicitly given in DPM and QGSM and depends on the number $n$ of inelastic collisions suffered by the nucleon ($n = 1$ in Figs. 1 and 2 and $n = 2$ in Figs. 3-5). Indeed, in these models the nucleon splits into $2n$ components (valence quark, diquark and $n - 1$ gluons or $q_s-\bar{q}_s$ pairs) and the joint moment distribution is written as a product of the $2n$ factors controlling the $Z \sim 0$ behaviour of the $2n$ constituents times $\delta(1 - \sum_{i=1}^{2n} Z_i)$. In QGSM, where both valence and sea quarks have (at the energies considered here), the same $Z^{-1/2}$ behaviour, one has

$$\rho^n(Z_1, \cdots Z_{2n}) = C_n \ Z_1^{-1/2} \ Z_2^{-1/2} \cdots \ Z_{2n-1}^{-1/2} \ Z_{2n}^{1.5} \ Z_{2n+1}^{1.5} \ \delta \left( 1 - \sum_{i=1}^{2n} Z_i \right)$$
where $Z_{2n}$ corresponds to the diquark and the constant $C_n$ is determined from the normalization to unity. In this case one gets by integrating over all variables except the valence quark one

$$\tilde{\rho}_{q_v}^n(y) \equiv Z \, \rho_{q_v}^n(Z) = C_n \, Z^{1/2}(1 - Z)^{n+1/2} \, .$$

(6)

In DPM, on the other hand, one assumes a $\bar{Z}^{-1}$ behaviour for the sea quark with $\bar{Z} = \sqrt{Z^2 + \mu^2/s}$. This only changes the effective power of $(1 - Z)$ in (6) and we have checked that at present energies the differences are only of a few per cent.

The quark momentum distribution in (6) is also appropriate for the diquark breaking case when the latter takes place via the color exchange mechanism described in ref. \[3\]. Indeed, in this case the diquark, while changing its color, retains essentially its momentum. However, in the case of diquark breaking via longitudinal momentum transfer, where the two quarks in the diquark are separated, the number of independent constituents is now $2n + 1$ (see figs. 2 and 4 for the cases $n = 1$ and $n = 2$ respectively). Moreover, the $X$-value of one of the quarks has to be larger than $Z$ - i.e. the momentum fraction of the quark carrying the baryon number.

One then has instead of (6)

$$\tilde{\rho}_{q_v}^n(y) \equiv Z \, \rho_{q_v}^n(Z) = C'_n \, Z^{1/2} \int_{Z}^{1-Z} \frac{dX}{\sqrt{X}} (1 - X - Z)^{n-1/2} \, .$$

(7)

In the numerical calculations we have used eq. (7). We have checked that using (6) the changes in our results are at most of the order of 10%.

For the constant $C$ in eq. (1) we take, in the case of a $NN$ collision, $C = 0.84$. The factor 0.84 originates as follows. In $NN$ collision we produce a net baryon number equal to 2 with equal number of protons and neutrons. Moreover, at the present energies we know that the number of $\Lambda/\Sigma^0$ is about 0.1 \[10\], while the number $\Sigma^\pm$ is about 0.06 \[7\]. For the diquark splitting component of figs. 2 and 4, however, the production of strange baryons is twice as large as in the case of direct diquark fragmentation since the $s$-quark can be created in either side of the valence quark. (In the component depicted in fig. 5 the production of strange baryons would be enhanced by a factor 3). Therefore from baryon number conservation the average multiplicity of either protons and neutrons will be 1 - 0.1 - 0.06 = 0.84 (remember that $\tilde{\rho}_{q_v}^n(y)$ is normalized to unity).

Finally we take $\sigma_{in} = 32$ mb and from ref. \[3\] $\sigma_{DB} = 7$ mb\[\dagger\].

\[\dagger\] Actually, two values of $\sigma_{DB}$, dependent on the form of the proton wave function, are quoted in \[3\]. The lower one, describes well the experimental data on the energy dependence of $(dN/dy)^p - (dN/dy)^\bar{p}$.
We are now ready to compute the nucleon rapidity distribution in \(NN\) and \(AB\) collisions. We concentrate on the difference \(\Delta p = p - \bar{p}\) which has been measured by the NA35 collaboration in peripheral and central \(SS\) collisions [7]. It is given by

\[
\frac{dN_{NN \to \Delta p}}{dy}(y) = \left(1 - \frac{\sigma_{DB}}{\sigma_{in}}\right) \frac{dN_{DP \to \Delta p}}{dy}(y) + \frac{\sigma_{DB}}{\sigma_{in}} \frac{dN_{DB \to \Delta p}}{dy}(y) .
\]  

(8)

Here \(dN_{DB}/dy\) is given by eqs. (1) and (7), with \(n = 1\), while \(dN_{DP}/dy\) has been computed in ref. [4] (all formulae and numerical constants are the ones given there).

Likewise in an \(AA\) collision we have

\[
\frac{dN_{AA \to \Delta p}}{dy}(y) = \left(\bar{n}_A - \bar{n}^{DB}_A\right) \left[\frac{dN_{DP \to \Delta p}}{dy}(y)\right]_{n=\bar{n}/\bar{n}_A} + \bar{n}^{DB}_A \left[\frac{dN_{DB \to \Delta p}}{dy}(y)\right]_{n=\bar{n}/\bar{n}_A} .
\]  

(9)

where

\[
\bar{n}^{DB}_A(b) = A \left(1 - \sigma_{DB} T_{AA}(b)\right) / \sigma^{DB}_{AA}(b)
\]

and \(\bar{n}_A\) has the same expression except that \(\sigma_{DB}\) is replaced by \(\sigma_{in}\) - both in the numerator and in the denominator. Eq. (9) is easily generalized for the case of collision of different nuclei A and B. Distribution function \(dN_{DB}/dy\) in (9) is given by eqs. (1) and (7) with \(n = \bar{n}/\bar{n}_A\), i.e. the average number of collisions per participant nucleon. Again \(dN_{DP}/dy\) is the one computed in ref. [4]. For central collisions, \(\bar{n}_A\) and \(\bar{n}^{DB}_A\) in (9) have to be computed for \(b \sim 0\).

Note that by construction eqs. (8) and (9) reproduce the rapidity distributions of ref. [4] for \(\sigma_{DB} = 0\). The extra nucleon stopping for \(\sigma_{DB} \neq 0\) is due to the fact that \(\bar{n}^{DB}_A\) increases much faster than \(\bar{n}_A\) with increasing \(A\) - and to the different shapes of \(DP\) and \(DB\) rapidity distributions. The former has a pronounced dip at \(y^* \sim 0\), while the latter is concentrated at mid rapidities.

The results for peripheral and central \(SS\) collisions at CERN energies are shown in fig. 6 and compared with the data from the experiment NA35 [7]. We also show the results obtained with \(\sigma_{DB} = 0\) [4]. We see that the dramatic dip present in the latter case for central \(SS\) collision has been largely filled in by the contribution of the \(DB\) component in agreement with experiment. The prediction for a central \(Pb-Pb\) collision is also shown. In this case the dip is converted into a broad plateau.

at \(y^* \sim 0\), (line II in fig. 3 of that reference). This line is obtained from our eq. (1), when weighted by \(\sigma_{DB}/\sigma_{in}\) with \(\sigma_{DB} \sim 6 \div 7\) mb. In the notations of ref. [3] this line corresponds to \(\sigma_{DB} = 3.5\) mb/K with \(K \sim 0.5\). In the following we shall use the value \(\sigma_{DB} = 7\) mb. (Using \(\sigma_{DB} = 6\) mb the changes in our results are less than 5 %).
We conclude with two remarks on strange baryon production and on the extrapolation of our results to much higher energies. Concerning the first, we have already explained that the ratio of strange over non-strange baryons is twice as large in the $DB$ component as in the $DP$ one: the corresponding $\Lambda$ enhancement is, however, rather small. We obtain an

![Graph showing rapidity distribution of the $p-\bar{p}$ difference in AA collisions at $\sqrt{s} = 20$ GeV.](image)

**Figure 6:** Rapidity distribution of the $p-\bar{p}$ difference in AA collisions at $\sqrt{s} = 20$ GeV. The thick dashed curve corresponds to the diquark preserving mechanism of ref. [4] for central SS collision. The thick solid curve shows the result of our calculations including the diquark breaking component for central SS collision. The full circles are the data points from [7].

The same for peripheral SS collisions is shown by the thin solid and dashed curves and the square points. Here the theoretical curves are for $NN$ collisions, normalized to the data.

The dotted curve shows our prediction for central $Pb-Pb$ collision scaled down by a factor $1/5$. It corresponds to nucleon minus antinucleon - rather than to proton minus antiproton.
extra Λ average multiplicity of 1.1 in central SS and 13 in central Pb-Pb (with extra $y^* = 0$
 densities of 0.3 and 3.8, respectively). As discussed in ref. [4] the existing data require final
state interactions such as $\pi + N \rightarrow K + \Lambda$. The results obtained with the nucleon rapidity
 distributions computed above are close to the ones obtained in ref. [4], where some extra
stopping had been arbitrarily introduced (see full lines in fig. 3 of ref. [4]). More precisely
the Λ distribution in central SS is increased by about 10 % as compared to the one given
in [4], and the one for central Pb-Pb collisions is increased by about 15 % at $y^* \sim 0$ but is
narrower than the one given in [4].

Finally, we turn to the $DB$ component in fig. 5 which has not been considered so far. As
emphasized in ref. [3], in this component the baryon number follows the distribution of a sea
quark or gluon and would lead to a baryon distribution flat in rapidity and independent of
energy at very high energies. At present CERN energies, however, such a component would
produce essentially no change in our results. Indeed, as discussed above, a sea quark has an
$\bar{Z}^{-1}$ distribution in DPM, and we have checked numerically that at the energies considered
here this distribution differs by less than 10 % from the one of a valence quark. However,
at energies of RHIC and especially LHC this component would provide an interesting and
efficient mechanism of nucleon stopping. As discussed above it would also be efficient in
producing strange baryons at mid-rapidities. Actually two extreme scenarios may be con-
considered: 1) the component depicted in fig. 5 is strongly suppressed for some dynamical
reason and can be neglected and 2) at RHIC energies and beyond, this component is the
dominant part of $DB$ - and is independent of $s$. In both cases the $DP$ component at $y^* \sim 0$,
which falls roughly as $s^{-1}$, is already negligible at RHIC energies. As for the $DB$ one, it
falls in the first scenario as $s^{-1/4}$ giving a $y^* \sim 0$ net baryon number, $p-\bar{p}$, of 10 at RHIC
and 2 at LHC. In the second scenario, one gets a net baryon number at $y^* \sim 0$ of 10 at both
RHIC and LHC, which is about 30 % of the one predicted at 160 GeV/c (see fig. 6).

Finalizing this work we learned that D. Kharzeev has just published paper [11] on a
similar subject, and we would like to compare our results. The very observation of [11] that
gluons can trace baryon number was already done in [3], and in addition the cross section
was evaluated. We disagree with [11], however, on the rapidity dependence for the gluonic
mechanism of baryon number flow. Solid arguments presented in [12, 13] (see also [14])
and in the present paper prove that this mechanism is rapidity independent. However, this
point is not important for phenomenology at present energies since the data [1, 3, 4] are
dominated by the preasymptotic mechanism of a valence quark exchange accompanied with
the diquark destruction (exchange of a valence quark together with the string junction in
terms of topological expansion [13]). Finally, in contrast to [11], we have presented a full calculation of baryon stopping in AA collisions.

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