Baryon Stopping at HERA: Evidence for Gluonic Mechanism

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Abstract

Recent results from the H1 experiment [1] have confirmed the existence of a substantial baryon asymmetry of the proton sea at small $x$ with magnitude predicted in [2]. This is strong support for the idea [3] that baryon number can be transferred by gluons through a large rapidity interval without attenuation. In this paper we calculate the dependence of baryon asymmetry on associated multiplicity of produced hadrons which turns out to be very sensitive to the underlying dynamics. Comparison with data [1] confirms the dominance of the gluonic mechanism of baryon number transfer and excludes any substantial contribution of valence quark exchange.
A sizeable baryon-antibaryon asymmetry in photon-proton interaction was recently observed by the H1 Collaboration for $p/\bar{p}$ with small momentum in the laboratory frame produced in $\gamma p$ collisions at HERA. The preliminary data presented at the Vancouver Conference [1] show that

$$A = 2 \frac{N_p - N_{\bar{p}}}{N_p + N_{\bar{p}}} = (8.0 \pm 1.0 \pm 2.5)\%.$$  \hspace{1cm} (1)

Here $N_p$ and $N_{\bar{p}}$ are the numbers of detected protons and antiprotons respectively.

Obviously, the observed excess of protons is a consequence of the presence of the proton baryon number (BN) in the initial state of the reaction. Nontrivial is, however, the very large rapidity interval of about 8 units between the initial and final protons. One could expect an exponential attenuation of the BN flow over such a long rapidity interval and a vanishing baryon asymmetry. In contrast, a baryon asymmetry $A$ of about 7% was predicted in [2]. The calculations are based on the gluonic mechanism of BN transfer first suggested in [3]. This mechanism provides a rapidity independent probability of BN stopping, which is natural for gluonic exchanges.

In topological classification [4] BN is associated with the string junction for a star-shaped string configuration in the baryon. Therefore, baryon stopping is stopping of the string junction. It is argued in [4] that at asymptotic energies the string junction alone is stopped without valence quarks, i.e. only gluonic fields are involved. This establishes a correspondence to our gluonic mechanism of BN stopping.

Another mechanism of baryon stopping also suggested and calculated within pQCD in [3] is associated with a probability to find in the proton a low-$x$ valence quark accompanied by the string junction. The dependence of BN transfer on the rapidity interval $\Delta y$ is proportional to $\exp(-\Delta y/2)$ since it is related to the well known $x$-distribution of valence quarks dictated by Regge phenomenology [5]. Evaluated in pQCD [3] this mechanism well explains both the magnitude and energy dependence of baryon asymmetry observed at central rapidity in $pp$ collisions at the ISR [12]-[14]. The contribution of the asymptotic gluonic mechanism calculated in [2] is too small to show up at such a small rapidity interval $\Delta y \leq 4$. 

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The source of baryon asymmetry can be understood in the parton model \[2\]. In the infinite momentum frame of the proton one can attribute a partonic interpretation to the carrier of BN, the string junction, since it carries a fraction of the proton momentum \[3\]. In the rest frame of the proton all the partons in the initial state of the $\gamma p$ interaction belong to the photon. Obviously, the parton distribution of the photon is BN symmetric. However, the interaction with the proton target breaks up this symmetry due to the possibility of annihilation of anti-BN in the projectile parton cloud of the photon with BN of the proton. This leads to a nonzero BN asymmetry in the final state. The rapidity distribution of the produced net BN is related to the energy behaviour of the annihilation cross section.

The annihilation cross section at very high energies was predicted to be nearly energy independent, in nonperturbative \[4\] and perturbative \[5, 6, 7\] approaches. In both cases the magnitude was predicted to be $\sigma_{\text{ann}}(\bar{p}p) \approx 1 - 2 \text{ mb}$. Such a contribution was indeed found in the analysis \[8, 9\] of data on multiplicity distribution in $pp$ and $\bar{p}p$ collision. The corresponding cross section $\sigma_{\text{ann}}(\bar{p}p) \approx 1.5 \pm 0.1 \text{ mb}$ agrees well with the theoretical expectation. This asymptotic mechanism of annihilation results in a rapidity independent BN transfer according to the above partonic picture. Its contribution to baryon asymmetry was estimated in \[2\].

Experimental data for $\bar{p}p$ annihilation are available only at low energy up to 12 GeV. In this energy range the annihilation cross section is much larger that the asymptotic value 1.5 mb and decreases with energy approximately as $s^{-1/2}$. This is to be explained by the preasymptotic mechanism corresponding to the exchange of a valence quark accompanied with the string junction. This assignment explains in a natural way the energy dependence of annihilation, moreover, a parameter-free evaluation of the cross section \[10\] is also in a good agreement with the data.

The same preasymptotic mechanism nicely explains \[3\] the energy dependence and the absolute value for the cross section of net BN production in the central rapidity region in $pp$ collisions at ISR. Baryon stopping in heavy ion collisions measured at the SPS is also well explained by this mechanism \[13, 16\] without free parameters.
This valence quark-exchange contribution to BN transfer in $\gamma p$ collisions was also calculated in [2]. It turns out that the rapidity interval between the initial and final protons in the experiment [1] is not large enough to exclude possibility of this contribution. Both, the gluonic and quark exchange mechanisms are estimated in [2] to give about the same asymmetry at rapidity $\eta = 0$ (see Fig. 5 in [2]) and are able to explain the data within uncertainty of calculations. One needs more detailed information to discriminate between the two mechanisms.

It worth noting that a nice topological classification for these mechanisms was suggested by Rossi and Veneziano [4]. However, their prediction for the energy dependence has no reasonable justification and is in a severe contradiction with the standard high-energy Regge phenomenology for total cross sections (see discussion in review [11]), therefore we discard it. Particularly, if the difference between $\bar{p}p$ and $pp$ total cross sections is due to annihilation, one has to eliminate the $\omega$ exchange from the elastic $pp$ amplitude, but keep it as the major Reggeon term in the $Kp$ elastic scattering. Another problem arises with relation between $\omega$ and $\rho$ exchanges, since the latter is predicted by quark models to be much smaller than the former in agreement with results of the standard Regge phenomenology. According to Eylon and Harari [17] annihilation is related via unitarity to the Pomeron (at least a substantial part of it, see [11]) and does not contribute to the $\bar{p}p$ and $pp$ total cross section difference.

An important signature of the asymptotic gluonic mechanism is a higher mean multiplicity of produced particles. This is due to three sheet topology of the final state according to classification in [4], which is illustrated in Fig. 1 (left). The gluon is replaced by a sea $\bar{q}q$ pair. The valence quark exchange mechanism also shown in Fig. 1 exhibits a two-sheet (two-string) topology, i.e. the same multiplicity as in the Pomeron. It is easy to see in Fig. 1 that the mean multiplicity of produced particles in the rapidity interval where the baryon asymmetry is measured is $5/4$ times larger for the gluonic mechanism (left) compared to the quark exchange mechanism (right). This fact makes baryon asymmetry dependent on the multiplicity of the produced hadrons.

First of all, we should describe the multiplicity distribution measured in [1]. We use the
standard AGK cutting rules,[18] which relate via unitarity inelastic processes with multi-pomeron exchanges in the elastic amplitude. Keeping only the double-Pomeron corrections the multiplicity distribution normalized to unity reads,

\[
N_n = (1 - 4\delta) \frac{(n)^n}{n!} e^{-\langle n \rangle} + 4\delta \frac{(2\langle n \rangle)^n}{n!} e^{-2\langle n \rangle}.
\]  

(2)

Here \(\langle n \rangle\) is the mean number of produced particles corresponding to one cut pomeron; the parameter \(\delta\) is the weight of the double-pomeron contribution to the total cross section. We use them as free parameters to adjust to the data by eye. The result with \(\langle n \rangle = 5.2\) and \(\delta = 0.02\) is shown in Fig. 2 (left) by full circles. It is remarkable that the value of \(\delta\) is about an order of magnitude smaller than what follows from eikonal model, which is reasonably good for hadronic collisions. We interpret it as suppression of gluons and sea quarks, which are responsible for the multi-pomeron terms, in a photon compared to a hadron. This would also naturally explain a substantially steeper growth with energy of the photon-photon total cross section measured by the L3 collaboration.[19] A further development of this issue goes too far beyond the scope of present paper. Whatever the reason of smallness of \(\delta\) is, it has no effect on our results for multiplicity dependence of baryon asymmetry.

Now we are in position to predict the variation of the baryon asymmetry[1] with asso-
Figure 2: Multiplicity distribution of charged hadrons produced in photon-proton interaction as measured in [1]. The histogram represents the data, the black points are the result of our calculation (left).

Baryon asymmetry as function of multiplicity of charged hadrons. The crosses are the results of measurements in [1]. The solid and dashed curves show our predictions for the gluonic and quark exchange mechanisms respectively (right). See the text for details.

According to the previous discussion we assume that the mean associated multiplicity for net $p$ and $\bar{p}$ contributing to the denominator of (1) are due to production of sea baryon-antibaryon pairs, number of which is proportional to the multiplicity of hadrons. Therefore, the shape of $n$-dependence of $N_p + N_{\bar{p}}$ in (1) is given by (2). The same is true for the numerator in (1), except the mean multiplicity associated with net BN production according to Fig. 1 is larger for the gluonic mechanism. Using (2) we can represent the asymmetry (1) as function of $n$,

$$A_n = A_n \frac{(1 - 4\delta) K^n e^{-(K-1)(n)} + 4\delta (K + 1)^n e^{-K(n)}}{1 + 4\delta(2^n e^{-\langle n \rangle} - 1)}$$

(3)

According to the previous discussion we assume that the mean associated multiplicity for net
BN production (see Fig. [1]) is $K$ times larger than the mean multiplicity in BN symmetric events, where $K = 5/4$ or $K = 1$ for gluonic and quarks exchange mechanisms respectively. The results for $A_n$ are depicted in Fig. [2] (right) by solid ($K = 5/4$) and dashed ($K = 1$) lines. We use $A = 0.07$ as it is predicted in [2]. The data [1] shown by crosses agree well with the assumption that the baryon asymmetry is dominated by the contribution of the gluonic mechanism, but reject any sizeable contribution of the preasymptotic quark exchange mechanism which leads to a constant $A_n$.

Note, that the systematical uncertainty not included in the error bars in Fig. [2] can affect only the overall normalization [1], but does not change the shape of $n$-dependence. The kinematical restrictions imposed by the experimental set up do not affect our calculations, which depend only on parameters $\langle n \rangle$ and $\delta$ measured in the same experiment.

Summarizing, an exciting possibility that baryon number can be transferred by gluons through a large rapidity interval without attenuation [3] is strongly supported by measurements [1] of baryon asymmetry in $\gamma p$ collisions. Although the magnitude of the effect agrees with the prediction made in [2], this fact alone cannot exclude a large contribution of the preasymptotic valence quark exchange mechanism at this rapidity interval $\Delta y \approx 7 - 8$. We have found that the dependence of baryon asymmetry on associated particle multiplicity is extremely sensitive to the underlying mechanism. Comparison with corresponding data from [1] strongly supports dominance of the gluonic mechanism and excludes a large contribution of BN transfer by valence quarks.

Acknowledgements: We are grateful to Andrei Rostovtsev for useful discussions.

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