# THE GLUON EXCHANGE MODEL FOR BARYON STOPPING*

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We propose a new model for a homogeneous description of hadron–hadron, hadron–nucleus, and nucleus–nucleus collisions — the Gluon Exchange Model (GEM). While technically it can be regarded as a generalization of the Dual Parton Model by Capella and Tran Thanh Van, it is fundamentally based on the number of exchanged color octets (gluons) and significantly extends the Fock space of states available for the participating protons and nucleons. In *proton–proton* collisions, we provide an exact description of the final-state proton and neutron spectrum. Unlike the original DPM, GEM successfully describes the proton diffractive peak at high rapidity. In *proton–nucleus* reactions, we propose a statistical scheme for the process of soft color octet (gluon) exchange, based on the assumption that the probability to form an effective diquark will be equal for all the allowed quark pairs. The effective diquark can be formed by two valence, one valence and one sea, or by two sea quarks. Consequently, we calculate the probabilities for the different color configurations, involving diquarks of valence–valence, valence–sea, and sea–sea types. These probabilities depend on the number of exchanged gluons, which results in increasing baryon stopping as a function of the number $N$ of proton–nucleon collisions in the nucleus. As such, the process of transport of baryon number down to low rapidities appears to be governed by the emergence of new color configurations as a function of $N$ rather than by the energy loss of the original valence diquark.

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## 1. Introduction

In the course of the last two years, we gradually introduced a new model for the process of baryon stopping in high-energy collisions — the Gluon Exchange Model [1–5]. The underlying motivation was to obtain better

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and more detailed insight into the mechanism of this process from modern experimental data. A reasonably complete description of the model can be found in the cited works as well as in the slides presented at this conference[1]. In this short note, we only elaborate on the aspect of the model which we think to be the most important for the Quark Matter community, namely the building up of the baryon stopping process through multiple gluon exchange, in collisions involving atomic nuclei. For more details, see also Ref. [5].

## 2. GEM

Technically, the Gluon Exchange Model can be regarded as a generalization of the Dual Parton Model (DPM [6]) in its formulation from Ref. [7]. This implies that the collision proceeds through the exchange of soft gluons (color octets) between the constituent quarks from the participating nucleons and subsequent formation of new color singlets (strings), from constituent quarks belonging to opposite colliding nucleons. The decay (fragmentation) of the latter leads to particle production and to the transport of (net) baryon number towards lower rapidities. There are, however, three main aspects which differentiate our approach from the original (classical) version of DPM:

— the participating nucleons are taken in a properly complete ensemble of Fock states; this implies inclusion of not only *valence* quarks but also *sea* quarks and antiquarks already at the level of proton–proton collisions [2];

— the diquark (important for the process of baryon stopping as it can be regarded as a "local concentration of baryon number on the string"[2]) has a purely *effective* character which implies that it can be formed by any two quarks in a *color antitriplet* state; this leads to the appearance of diquarks (= color antitriplets) composed of two valence, valence-and-sea or sea-and-sea quarks, and even to a no-diquark configuration in a process where the exchange of two gluons brings the nucleon's valence quarks in a symmetric (color decuplet) state. As a consequence of different momentum distributions of valence and sea quarks in the nucleon [2], these different configurations lead to very different baryon stopping in the final state of the collision [3, 5];

— the probabilities for the formation of the different diquark configurations (and consequently, of the corresponding strings) in reactions

[1] https://qm2021.syskonf.pl/timetable

[2] The string fragmentation functions into baryons are adjusted to the experimental $pp$ data [8]. In practice, these experimental data enforce the shape of the latter functions which appear to peak close to diquark rapidity, see Ref. [3].

involving nuclei are computed quantitatively, as resulting from the presence of irreducible representations of SU(3) induced by the process of multiple exchange of the color quantum number [5]; this will be explained in some more detail below.

In Ref. [2], we presented the success of GEM in obtaining the exact description of proton and neutron spectra in *pp* collisions at CERN SPS energies, including the "diffractive" proton peak at high rapidity which we explained by a single gluon exchange between the valence quarks from one and the sea quark–antiquark pair from the other proton. In multiple proton–nucleon collisions in *pA* reactions, this latter process is strongly suppressed leading to the disappearance of the diffractive peak, as explained therein. For the corresponding process of multiple gluon exchange, we consider two separate cases where (1) a single soft gluon exchange brings the valence quarks of the projectile proton into the color octet state and the remaining $N-1$ gluons coupling to sea quarks remain independent, and (2) two gluons bring the valence quarks of the proton into the symmetric color decuplet state, while the remaining $N-2$ gluons coupling to sea quarks remain independent. The complexity (and dimension) of the obtained color representations for the projectile constituent quarks increases rapidly with $N$. As an example, below we list the latter for the dominant case (1) for 1, 2, and 6 proton–nucleon collisions:

$$\begin{aligned}
1:&\ \ \underset{\sim}{8} = (2,1,0)\\
2:&\ \ \underset{\sim}{8}\otimes\underset{\sim}{3} = (3,1,0)\oplus(2,2,0)\oplus(2,1,1)\\
6:&\ \ \underset{\sim}{8}\otimes\underset{\sim}{3}^5 = (7,1,0)\oplus 5\cdot(6,2,0)\oplus 5\cdot(6,1,1)\oplus 9\cdot(5,3,0)\oplus 20\cdot(5,2,1)\oplus\\
&\qquad\qquad 5\cdot(4,4,0)\oplus 25\cdot(4,3,1)\oplus 20\cdot(4,2,2)\oplus 16\cdot(3,3,2)
\end{aligned} \tag{1}$$

In the above, $(m_1, m_2, m_3)$ corresponds to an irreducible representation given by a Young tableau with three rows of length $m_1$, $m_2$, and $m_3$, see Ref. [5] for more details. Importantly, as explained therein, we postulate a purely *statistical scheme* for valence–valence, valence–sea and sea–sea diquark formation: for each irreducible representation, the probabilities to form an effective diquark are equal for all allowed pairs of quarks. The relation between (1) and (2) remains a free parameter in the present version of our model, but the analysis of SPS experimental data [8, 9] suggests a strong dominance ($\sim 95\%$) of the "color octet" configuration (1) which we will focus upon in the remaining part of this note.

## 3. Baryon stopping as a function of the number of collisions

Figure 1 shows the $N$-dependence of net proton distributions in $pA$ reactions, resulting from our calculation and put in comparison with SPS experimental data. Panels (a) and (c) correspond to the calculation made for exactly 2 and 6 collisions and panel (b) is based on a Glauber calculation published elsewhere [10]. The break-up of the total distribution into contributions from the formation of valence–valence (VV) as well as effective valence–sea (VS), and sea–sea (SS) diquarks is also included in the figure. In the framework of GEM, the process of baryon stopping as a function of $N$ appears as governed by the emergence of new color configurations cor-

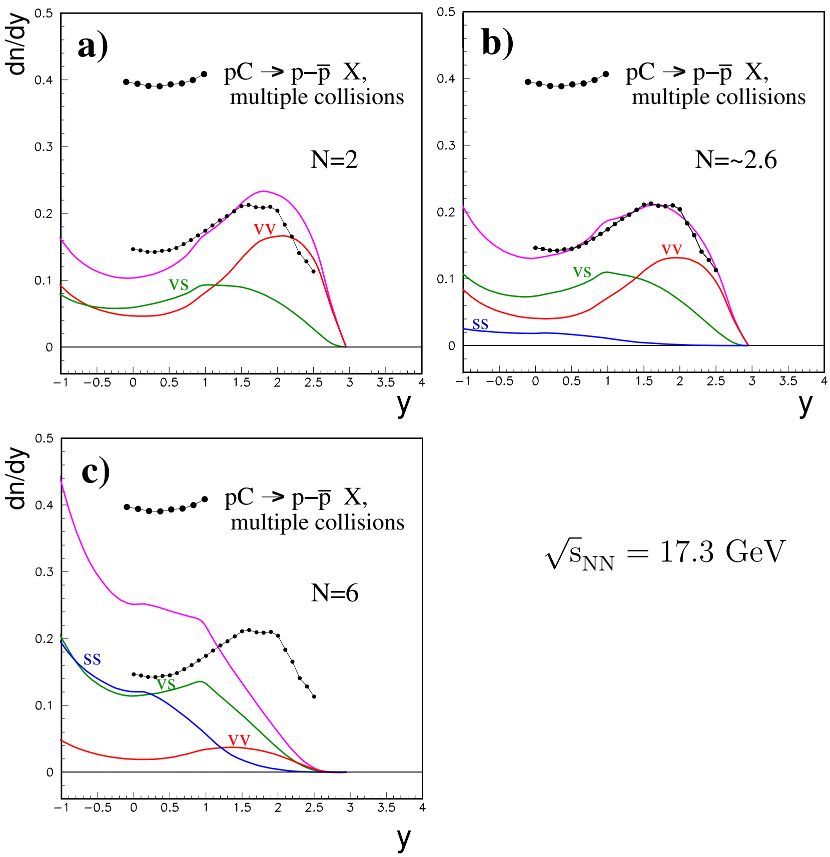


Fig. 1. Rapidity distribution of net protons in $p$C reactions in which the projectile proton undergoes multiple collisions with carbon target nucleons, obtained from the NA49 experiment [8, 9] and compared to our GEM calculations assuming 100% color octet exchange (case (1), as described in the text). The contributions from the VV, VS, and SS configurations are indicated in the plots. Redrawn from Ref. [5].

responding to these three different types of diquarks, each characterized by a different momentum distribution. As such, for $N = 2$ proton–nucleon collisions, the net proton spectrum is being shared by the original valence–valence configuration inherited from $pp$ reactions and the — much softer — effective valence–sea diquark. The softest sea–sea configuration becomes available only at $N = 3$ collisions but the probability of its formation rapidly increases with $N$, so that it appears responsible for 38% of final-state baryons at $N = 6$ (we note that the latter value of $N$ roughly corresponds to the central $p$Pb reaction, at SPS energies).

## 4. Discussion

Our study shortly reported in this note demonstrates, in our view, the potential of multiple soft gluon exchanges involving sea quarks in providing a better understanding of baryon-stopping phenomena observed in high-energy nucleon and nuclear collisions. The emergence of the new color configurations, connected to the formation of effective valence–sea and sea–sea diquarks, provides a mechanism for the transport of the initial baryon number down to low rapidities which is far more powerful than the sole energy loss of the original valence–valence diquark from the incoming proton or nucleon (we note that the relative strength of the two mechanisms can be judged directly from Fig. 1, by comparison of the $N$-dependence of the shape of the original VV contribution to the proton spectrum, *versus* the emergence of the VS and SS contributions).

The latter emergence of new color configurations in the multiple collision process ($\rightarrow$ $pA$ and $AA$ reactions) comes out not as an *ad hoc* addition to the model but on the contrary, as a natural consequence of the building up of increasingly complex color representations resulting from multiple exchanges of the latter quantum number[3]. The statistical scheme assumed for (equal) probabilites of diquark formation from all allowed pairs of quarks evidently awaits further verification with experimental data, preferably on collisions involving heavy nuclei. Notwithstanding, we note that this simplest quantitative scheme provides a satisfactory description of proton and neutron production in $p$C reactions [9] which we consider as most detailed data set of this type at the CERN SPS. Consequently, this implies a homogeneous description of baryon rapidity distributions in $pp$ and $pA$ collisions including the proton diffractive peak, see Refs. [2, 5]. Further implications of the multiple gluon exchange process, like *e.g.* the disintegration of the diquark by bringing the three valence quarks of the proton/nucleon into the symmetric color decuplet state, have also been elaborated upon in Refs. [1–5] and remain under study.

[3] The differences between our approach and that by Capella *et al.* based on the concept of string junction by Rossi and Veneziano [11–13] were addressed in our works [3, 5].

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