Net-Baryon Production in Nucleus-Nucleus Collisions and Rare QGP Events

G.H. Arakelyan\textsuperscript{1}, C. Merino\textsuperscript{2}, and Yu.M. Shabelski\textsuperscript{3}
\textsuperscript{1}A.Alikhanyan National Scientific Laboratory, Yerevan Physics Institut, Yerevan, 0036, Armenia
E-mail: argev@mail.yerphi.am
\textsuperscript{2}Departamento de Física de Partículas, Facultade de Física, and Instituto Galego de Física de Altas Enerxías (IGFAE), Universidade de Santiago de Compostela, 15782 Santiago de Compostela, Galiza-Spain
E-mail: merino@fpaxp1.usc.es
\textsuperscript{3}Petersburg Nuclear Physics Institute, NCR Kurchatov Institute, Gatchina, St.Petersburg 188350, Russia
E-mail: shabelsk@thd.pnpi.spb.ru

Abstract. The experimental data on net proton and net $\Lambda$-hyperon spectra obtained by the NA35 Collaboration, as well as the inclusive densities of $\Lambda$ and $\bar{\Lambda}$ obtained by NA49, NA57, and STAR collaborations, are compared with the predictions of the Quark-Gluon String Model. The contributions of String Junction diffusion, interactions with nuclear clusters, and percolation corrections are accounted for. The level of numerical agreement of the calculations with the experimental data is of about 20–30\%. We also consider the experimental ratios of multistrange to strange antibaryon production. The significant differences between the experimental $\Xi^{+}/\Lambda$ and, especially, $\Omega^{+}/\Lambda$ values and the QGSM predictions can be interpreted as the signal of the existence of an additional source of multistrange antibaryon production.

1. Introduction

The Quark-Gluon String Model (QGSM) \cite{1} is based on the Dual Topological Unitarization, Regge phenomenology, and nonperturbative notions of QCD. This model is successfully used for the description of multiparticle production processes in hadron-hadron \cite{2, 3, 4, 5}, hadron-nucleus \cite{6, 7}, and nucleus-nucleus \cite{8, 9, 10} collisions. In particular, the rapidity dependence of inclusive densities of different secondaries ($\pi^{\pm}$, $K^{\pm}$, $p$, and $\bar{p}$) produced in Pb-Pb collisions at 158 GeV/c per nucleon were reasonably described in reference \cite{10}.

In the QGSM high energy interactions are considered as proceeding via the exchange of one or several Pomerons, and all elastic and inelastic processes result from cutting through or between Pomerons \cite{11}. Inclusive spectra of hadrons are related to the corresponding fragmentation functions of quarks and diquarks, which are constructed using the Reggeon counting rules \cite{12}.

In the case of interaction with nuclear target, the Multiple Scattering Theory (Gribov-Glauber Theory) is used. It allows to consider the interaction with nucleus as the superposition of
interactions with different numbers of target nucleons [13, 14, 15, 16].

Also in the case of nucleus-nucleus collisions the Multiple Scattering Theory allows to consider the interaction as the superposition of separate nucleon-nucleon interactions. Though in this case the analytical summation of all the diagrams is impossible [17], the significant classes of diagrams can be analytically summed up in the so-called rigid target approximation [18] which is used in the present paper.

The significant differences in the yields of baryons and antibaryons in the central (midrapidity) region are present even at high energies. This effect can be explained [4, 5, 19, 20, 21, 22, 23, 24] in QGSM by the special structure of baryons consisting of three valence quarks together with a special configuration of gluon field, called String Junction [25, 26, 27, 28].

One additional contribution comes from the coherent interaction of a projectile with multiquark clusters inside the nuclei. The existence of these interactions is confirmed by the presence, with not such a small probability, of a cumulative effect [29]. These contributions were incorporated into the QGSM in [30, 31], and they allow to describe a number of experimental facts.

At very high energies the contribution of the enhancement Reggeon diagrams (percolation effects) becomes important, what leads to a new phenomenological effect, the suppression of the inclusive density of secondaries [32] into the average central (midrapidity) region. This corresponds to a significant fusion of the produced quark-gluon strings. In the energy limit when the probability of this fusions is very large, one should expect the appearance of a new state of matter, the Quark-Gluon Plasma(QGP). However, the process of QGP production can already occur with small probability at a not so high energy.

In this paper we present [33] the description of \( p, \bar{p}, \Lambda, \) and \( \bar{\Lambda} \) production on nuclear targets at CERN SpS and RHIC energies. We also consider [34] the ratios of multistrange to strange antihyperon production in nucleon-nucleus and in nucleus-nucleus collisions.

Let us define, for the collision of projectil A (nucleon or nucleus) with a nuclear target B:

\[
R(\Xi^+ / \bar{\Lambda}) = \frac{dn}{dy}(A + B \rightarrow \Xi^+ + X)/\frac{dn}{dy}(A + B \rightarrow \bar{\Lambda} + X),
\]

\[
R(\Omega^+ / \bar{\Lambda}) = \frac{dn}{dy}(A + B \rightarrow \Omega^+ + X)/\frac{dn}{dy}(A + B \rightarrow \bar{\Lambda} + X).
\]

The produced antihyperons, \( \Xi^+ \) and \( \Omega^+ \), contain valence antiquarks newly produced during the collision. The ratios in equations 1 and 2 are reasonably described by QGSM in the cases when a not very large number of incident nucleons participate in the collision (nucleon-nucleus or peripheral nucleus-nucleus collisions).

The number of quark-gluon strings (cut pomerons) in nucleus-nucleus collisions increases with centrality. If the secondaries are produced independently in every quark-gluon string, the ratio of yields of different particles should not depend on centrality. However, experimentally the enhancement of the yield of \( \Xi^+ \) is stronger than that of \( \bar{\Lambda} \), and for \( \Omega^+ + \bar{\Omega}^+ \) the enhancement is also stronger than for \( \Xi^+ \) (e.g. see [35]). This means that an additional source of multistrange hyperons appears from collective interactions of several strings, and this additional source can be considered as a QGP state effect.

2. Baryon/antibaryon asymmetry in the QGSM

2.1. General approach

The QGSM [1, 2, 3] allows one to make quantitative predictions for different features of multiparticle production, in particular, for the inclusive densities of different secondaries, both in the central and in the beam fragmentation regions.
In QGSM, each exchanged Pomeron corresponds to a cylindrical diagram, and thus, when cutting one Pomeron, two showers of secondaries are produced. The inclusive spectrum of a secondary hadron \( h \) is then determined by the convolution of the diquark, valence quark, and sea quark distributions, \( u(x, n) \), in the incident particles, with the fragmentation functions, \( G^h(x) \), of quarks and diquarks into the secondary hadron \( h \). In the case of multipomeron exchange \((n > 1)\), a new contribution from sea quarks-antiquarks appears. Both the distributions and the fragmentation functions are constructed using the Reggeon counting rules [12]. The average number of exchanged Pomerons \((n)_{pp}\) slowly increases with the energy. The details of the model are presented in [1, 2, 3, 19]. The values of the Pomeron parameters have been taken from [3].

For a nucleon target, the inclusive rapidity, \( y \), or Feynman-\( x \), \( x_F \), spectrum of a secondary hadron \( h \) has the form [1]:

\[
\frac{dn}{dy} = \frac{x_F}{\sigma_{inel}} \cdot \frac{d\sigma}{dx_F} = \sum_{n=1}^{\infty} w_n \cdot \phi_n^h(x) + w_D \cdot \phi_D^h(x) ,
\]

(3)

where the functions \( \phi_n^h(x) \) determine the contribution of diagrams with \( n \) cut Pomerons, \( w_n \) is the relative weight of this diagram, and the term \( w_D \cdot \phi_D^h(x) \) accounts for the contribution of diffraction dissociation processes.

In the case of \( pp \) collisions:

\[
\phi_n^h(x) = f_{qq}^h(x_+, n) \cdot f_q^h(x_-, n) + f_q^h(x_+, n) \cdot f_{qq}^h(x_-, n) + 2(n - 1) \cdot f_s^h(x_+, n) \cdot f_s^h(x_-, n) ,
\]

(4)

\[ x_\pm = \frac{1}{2} \sqrt{\frac{4m^2}{s} + x^2 \pm x} , \]

(5)

where \( f_{qq}, f_q, \) and \( f_s \) correspond to the contributions of diquarks, valence quarks, and sea quarks, respectively.

These contributions are determined by the convolution of the diquark and quark distributions with the fragmentation functions, e.g.,

\[
f_q^h(x_+, n) = \int_{x_+}^1 u_q(x_1, n) \cdot G_q^h(x_+/x_1) dx_1 .
\]

(6)

In the calculation of the inclusive spectra of secondaries produced in \( pA \) collisions we should consider the possibility of one or several Pomeron cuts in each of the \( \nu \) blobs of proton-nucleon inelastic interactions. It is essential to take into account all diagrams with every possible Pomeron configuration and its corresponding permutations. The diquark and quark distributions and the fragmentation functions are the same as in the case of \( pN \) interaction.

The total number of exchanged Pomerons becomes as large as

\[
\langle n \rangle_{pA} \sim \langle \nu \rangle_{pA} \cdot \langle n \rangle_{pN} ,
\]

(7)

where \( \langle \nu \rangle_{pA} \) is the average number of inelastic collisions inside the nucleus (about 4 for heavy nuclei at SpS energies).

The condition that the absorptive parts of the hadron-nucleus amplitude are determined by the combination of the absorptive parts of the hadron-nucleon amplitudes is basically satisfied [13, 14, 15, 16].

In the case of a nucleus-nucleus collision, in the fragmentation region of projectile we use the approach [8, 9, 10], where the beam of independent nucleons of the projectile interact with the target nucleus, what corresponds to the rigid target approximation [18] of Glauber Theory. In the target fragmentation region, on the contrary, the beam of independent target nucleons interact with the projectile nucleus, these two results coinciding in the central region. The corrections for energy conservation play here a very important role if the initial energy is not very high. This approach was used in [10] for the successfull description of \( \pi^\pm, K^\pm, p, \) and \( \bar{p} \) produced in Pb-Pb collisions at 158 GeV per nucleon.
2.2. String Junction contribution

In the string models, baryons are considered as configurations consisting of three connected strings (related to three valence quarks), called String Junction (SJ) \[25, 26, 27, 28\], this picture leading to some quite general phenomenological predictions.

The production of a baryon-antibaryon pair in the central region usually occurs via \(SJ-SJ\) pair production (SJ has upper color indices, whereas anti-SJ (\(\overline{S J}\)) has lower indices), which then combines with sea quarks and sea antiquarks into a \(B\overline{B}\) pair \[27, 36\], as it is shown in figure 1a.

**Figure 1.** QGSM diagrams describing secondary baryon production: (a) usual \(B\overline{B}\) central production with production of new SJ pair; (b) initial SJ together with two valence quarks and one sea quark; (c) initial SJ together with one valence quark and two sea quarks; (d) initial SJ together with three sea quarks.

However, in the processes with incident baryons another possibility to produce a secondary baryon in the central region, called SJ diffusion, exist. The quantitative description of the baryon number transfer due to SJ diffusion in rapidity space was obtained in \[19\] and following papers \[4, 5, 20, 21, 22, 24\].

In the QGSM the differences in the spectra of secondary baryons and antibaryons appear for processes which present SJ diffusion in rapidity space. These differences only vanish rather slowly when the energy increases.

To obtain the net baryon charge, and according to reference \[19\], we consider three different possibilities. The first one is the fragmentation of the diquark giving rise to a leading baryon (figure 1b). A second possibility is to produce a leading meson in the first break-up of the string and a baryon in a subsequent break-up \[12, 37\] (figure 1c). In these two first cases the baryon number transfer is possible only for short distances in rapidity. In the third case, shown in figure 1d, both initial valence quarks recombine with sea antiquarks into mesons, \(M\), while a secondary baryon is formed by the SJ together with three sea quarks \[5, 19, 38\].

The fragmentation functions for the secondary baryon \(B\) production corresponding to the three processes shown in figures 1b, 1c, and 1d can be written as follows (see \[19\] for more
where $a_N$ is the normalization parameter, and $v_{Bqq}^B$, $v_{Bqs}^B$, $v_{Bss}^B$ are the relative probabilities for different baryons production that can be found by simple quark combinatorics [39, 40]. These probabilities depend on the strangeness suppression factor $S/L$, and we use $S/L=0.32$ following [41]. The contribution of the graph in figure 1d has in QGSM a coefficient $\varepsilon$ which determines the small probability for such a baryon number transfer.

The fraction $z$ of the incident baryon energy carried by the secondary baryon decreases from figure 1b to figure 1d. Only the processes in figure 1d can contribute to the inclusive spectra in the central region at high energies if the value of the intercept of the SJ exchange Regge-trajectory, $\alpha_{SJ}$, is large enough. The analysis in [24] gives a value of $\alpha_{SJ} = 0.5 \pm 0.1$, that is in agreement with the ALICE Collaboration result, $\alpha_{SJ} \sim 0.5$ [42], obtained at LHC. In the calculations of these effects we use the following values of the parameters [24]:

$$\alpha_{SJ} = 0.5 \text{ and } \varepsilon = 0.0757.$$  

(11)

2.3. Contribution from interaction with clusters

In the case of interaction with a nuclear target some secondaries can be produced in the kinematical region forbidden for the interaction with a free nucleon. Such processes are called the cumulative ones, the simplest example being the production of secondary nucleons in the backward hemisphere in the laboratory frame.

Usually, the cumulative processes are considered as a result of the coherent interaction of a projectile with a multiquark cluster, i.e. with a group of several nucleons which are at short distances from each other that appears as a fluctuation of the nuclear matter [29, 43].

The inclusive spectra of the secondary hadron $h$ in the central region is determined at high energies by double-Pomeron diagrams [44]. The case of $pp$ collision is shown in figure 2a. In the case of proton-nucleus collisions two different possibilities exist, the interactions with individual target nucleons (figure 2b) and the secondary production on cluster (figure 2c). For nucleus-nucleus collisions there are four possibilities (figures 2d, 2e, 2f, and 2g). The one in figure 2g corresponds to a new process where a secondary hadron is produced by the interaction of two clusters.

It was shown in references [30, 31] that in the case of secondary production from the cluster fragmentation, the inclusive spectra can be calculated in the framework of the QGSM with the same quark and diquark fragmentation functions. The only difference comes from the quark and diquark distributions, $v_q^B(x,n,k)$ and $u_q^cl(x,n,k)$, where $k$ is the number of nucleons in the cluster. The distributions $u_q^cl(x,n,k)$ can also be calculated by using the Reggeon counting rules. All these functions $u_q^cl(x,n,k)$ are normalized to unity, and the function $u_q^cl(x,n)$ does not depend on $k$.

This approach was successfully used in [30, 31] for the description of cumulative particles produced in $hA$ collisions. In the present paper we use it for describing the enhancement of strangeness production on nuclear targets in the central region.

2.4. Inelastic screening (percolation) effects

The QGSM gives a reasonable description [5, 6, 10, 45] of the inclusive spectra of different secondaries produced both in hadron-nucleus and in nucleus-nucleus collisions at energies $\sqrt{s_{NN}}$
Figure 2. Reggeon diagrams for the different possibilities corresponding to the inclusive spectra of a secondary hadron $h$ produced in the central region in (a) $pp$, (b,c) $pA$, and (d–g) $AB$ collisions. Pomerons are shown by wavy lines.

At fixed energies, $\sqrt{s_{NN}} \leq 30–40$ GeV, the nucleus-nucleus interaction can be described as the sum of one-Pomeron and of multipomeron eikonal exchanges. The inelastic processes are then determined by the production of one (figure 3a), or several (figure 3c) multiperipheral ladders, and the corresponding inclusive cross sections are described by the diagrams of figures 3b and 3d.
In accordance with the Parton Model [51, 52], the fusion of multiperipheral ladders shown in figure 3c becomes more and more important with the increase of the energy, resulting in the reduction of the inclusive density of secondaries. Such processes correspond to the enhancement Reggeon diagrams of the type of figure 3d, and to even more complicate ones. All these diagrams are proportional to the squared longitudinal form factors of both colliding nuclei [32]. Following the estimations presented in reference [32], the RHIC energies are just of the order of magnitude needed to observe this effect.

Unfortunately, all quantitative estimations are model dependent, since the numerical weight of the contribution of the multipomeron diagrams is rather unclear due to the many unknown vertices in these diagrams. However, the number of unknown parameters can be reduced in some models, and, as an example, in reference [32] the Schwimmer model [53] was used for the numerical calculations.

Another possibility to estimate the contribution of the diagrams with Pomeron interaction comes [54, 55, 56, 57, 58] from Percolation Theory. The percolation approach and its previous version, the String Fusion Model [59, 60, 61], predicted the multiplicity suppression seen at RHIC energies, long before any RHIC data were measured. New calculations of inclusive densities and multiplicities in percolation theory both in $pp$ [62, 63], and in heavy ion collisions [63, 64], are in good agreement with the experimental data in a wide energy region.

In order to account for the percolation (inelastic screening) effects in the QGSM, it is technically more simple [23] to consider the maximal number of Pomerons $n_{\text{max}}$ emitted by one nucleon in the central region that can be cut. These cut Pomerons lead to the different final states. Then the contributions of all diagrams with $n \leq n_{\text{max}}$ are accounted for as at lower energies. The larger number of Pomerons $n > n_{\text{max}}$ can also be emitted obeying the unitarity constraint, but due to the fusion in the final state (at the quark-gluon string stage), the cut of $n > n_{\text{max}}$ Pomerons results in the same final state as the cut of $n_{\text{max}}$ Pomerons.

The QGSM fragmentation formalism allows one to calculate the integrated over $p_T$ spectra of different secondaries as the functions of rapidity and $x_F$. The number of strings that can be used for the secondary production should increase with the initial energy [65]. The contribution coming from the coherent interaction of two nuclear clusters [31] has been estimated following [33] to be not larger than (20−30)%.

In this frame, we obtain a reasonable agreement with the experimental data on the inclusive spectra of secondaries produced in $d+Au$ collisions at RHIC energy [23] with a value $n_{\text{max}} = 13$, and in $p+Pb$ collisions at LHC energy [66] with the value $n_{\text{max}} = 23$.

However, in nucleus-nucleus collisions, even at not very high energies (e.g., see [35]), the yield of $\Xi^+$ is more strongly enhanced than that of $\overline{\Lambda}$, and also the yield of $\Omega^- + \overline{\Omega}^+$ shows a stronger enhancement than the yield of $\Xi^+$. This means that one additional source of multistrange hyperons must be at work from collective interactions of several strings.

At intermediate energies, we can think of rare situations when a few strings overlap in a small volume. This can be possibly considered as a QGP state effect. This can occur when the density of produced quark-gluon strings is several times larger than its average value.

When we consider central Pb+Pb collisions, we see that the experimental data on the ratios in equations 1 and 2 are in disagreement with the standard QGSM predictions. The experimental ratios show very strong energy dependences as a function of centrality in the CERN SpSRHIC energy interval. To account for this effect, we can assume that some new contribution for multistrange antihyperon formation appears in this case. For example, the three strange antiquarks needed for the formation of $\overline{\Omega}^+$ could be taken at some energies out of three different quark-gluon strings, and not from the fragmentation of the same string. This could be possible if the multiplicity of newly produced strange-antistrange pairs would decreases with the number of pairs faster than, say, a Poissonian distribution. This new contribution is not included in the standard QGSM scheme, and it can be identified as a QGP formation signature.
3. Numerical results

3.1. Net baryon spectra

We present the QGSM results for $dn/dy$ of net proton ($p - \bar{p}$) and net $\Lambda$-hyperon ($\Lambda - \bar{\Lambda}$) productions at 200 GeV per nucleon both in proton-nucleus and in nucleus-nucleus collisions, and their comparison to the corresponding experimental data by the NA35 Collaboration [67]. The absolute normalization of $dn/dy$ in all cases is determined by the data of proton and antiproton production in $pp$ collisions at similar energies.

In the case of net proton production in $p - ^{32}\text{S}$ collisions, the QGSM calculations are in reasonable agreement with the experimental data. In the case of $p - ^{197}\text{Au}$ collisions the number of net protons is too small at small rapidities, what can be explained by the influence of the target fragmentation region. The nuclear cluster contribution, which is important mainly in the beam fragmentation region, seems to be too large.

In the case of net $\Lambda$-hyperon production the experimental error bars are rather large, and one can talk of general semiquantitative agreement of the QGSM calculations with the data.

For the sulphur $^{32}\text{S}$ beam shown in figure 4, the theoretical calculations are in reasonable agreement with the data for net proton production, whereas the data on net $\Lambda$-hyperon production are systematically higher than all calculated curves. In any case, though, all

Figure 4. Net proton $p - \bar{p}$ (upper panels) and net $\Lambda$-hyperon $\Lambda - \bar{\Lambda}$ (lower panels) production in $^{32}\text{S} - ^{32}\text{S}$ (left panels) and in $^{32}\text{S} - ^{197}\text{Au}$ (right panels) collisions at 200 GeV per nucleon. Solid curves show the QGSM calculations with both SJ and cluster contributions, dashed curves with SJ contributions but without the cluster ones, and dotted curves without both SJ and cluster contributions.
disagreements are not large than \( \sim 30\% \).

The data of the NA35 Collaboration [67] are compatible with the results of the NA44 Collaboration [68].

### 3.2. Production in midrapidity region

The NA49 Collaboration obtained experimental data [69, 70] for yields of \( \Lambda \) and \( \Xi^{+} \) hyperons, and for \( \Xi^{+} \) in midrapidity region \((|y| < 0.4 \text{ for } \Lambda \text{ and } \Xi, \text{ and } |y| < 0.5 \text{ for } \Xi^{+}\)) in the central C+C, Si+Si, and Pb+Pb collisions (5% centrality for \( \Lambda \) and 10% centrality for \( \Xi^{+} \)), at 158 GeV per nucleon.

A reasonable agreement with the QGSM predictions can be seen for secondary \( \Lambda \) and \( \Xi^{+} \), but the calculated yields of \( \Xi^{+} \) are significantly smaller than those measured by the NA49 Collaboration.

On the other hand, the NA57 Collaboration obtained the experimental data [71] for \( \Lambda \), \( \Xi^{+} \), and \( \Omega^{+} \) yields in midrapidity region \(|y| < 0.5\) in the minimum bias \( p+Be \) and \( p+Pb \) interactions, and in central (5% centrality) \( Pb+Pb \) collisions at 158 GeV per nucleon.

Unfortunately, the data by the NA49 and NA57 Collaborations are not compatible, the values of \( dn/dy \) for different hyperons measured by one collaboration being far outside the error bars of the corresponding values published by the other collaboration for the same centrality. This is probably due to different experimental event selection.

Here again one can see that the calculated yields of \( \Lambda \) and \( \Xi^{+} \) are in agreement with experimental data on the level of 20−30\% accuracy. Inclusive densities of \( \Xi^{+} \) hyperons are reasonably reproduced for the cases of \( p+Be \) and \( p+Pb \) collisions, but are several times underestimated in the case of central \( Pb+Pb \) interactions. For \( \Omega^{+} \) production in central \( Pb+Pb \) collisions, the disagreement is larger than one order of magnitude. The reason to discuss the production of antihyperons in these processes is that since a large baryon charge already exists in the initial state, some hyperons can be produced via the final state interaction of any baryon with a strange meson, but, on the contrary, the production of multistrange antihyperon production would be a signal of the production of several strange antiquarks in some small space-time volume.

At the LHC energy \( \sqrt{s_{NN}} = 3 \text{ TeV} \), the numerical QGSM predictions we obtain for \( dn/dy \) in the cases of midrapidity production of \( \Lambda \) and \( \Xi^{+} \) in central \( Pb+Pb \) collisions are 36.2 and 35.6, respectively.

### 3.3. Ratios of multistrange to strange antihyperon production

These effects are more evidently seen in Fig. 5, where the experimental ratios of \( \Omega^{+}/\Lambda \) and \( \Xi^{+}/\Lambda \) as functions of the number of participating nucleons, \( N_w \), together with the corresponding QGSM results, shown by solid curves. The first two left points in every panel correspond to \( p+Be \) and \( p+Pb \) collisions, and the other points correspond to \( Pb+Pb \) interactions with different centralities.

We consider the disagreement of the QGSM results with the experimental values as a signal of the quantitatively large new contribution of \( \Omega^{+} \) and \( \Xi^{+} \) production to the inclusive cross section. This new contribution could appear when strange antiquarks are taken from different Pomerons (quark-gluon strings), in some collective interaction that can be seen as at the origin of Quark-Gluon Plasma formation.

Thus, the selection of events with \( \Xi^{+} \), and especially with \( \Omega^{+} \) production, would allow the definition of a sample enriched by Quark-Gluon Plasma formation events, and such a sample could be compared to a sample of events where only \( \Lambda \) hyperons are produced, to unravel QGP definite features.
Figure 5. Ratios of $\Omega^+$ to $\Lambda$ (left panel), and of $\Xi^+$ to $\Lambda$ (right panel) as functions of the number of wounded nucleons, $N_w$. The experimental data for p+Be, p+Pb, and for Pb+Pb with different centralities measured by the NA57 Collaboration (points) and by the NA49 Collaboration (squares) are presented, together with the corresponding QGSM results, shown by solid curves.

Hyperon production at higher energies in midrapidity region was also measured at RHIC by the STAR Collaboration [72, 73] for Au + Au and Cu+Cu collisions at $\sqrt{s_{NN}} = 62.4$ GeV and 200 GeV.

The experimental ratios of $\Omega^+$ to $\Lambda$ obtained by the STAR Collaboration remain larger than the QGSM predictions at high centralities, and, so, the new mechanism by which the three strange antiquarks needed for $\Omega^+$ formation are taken from different Pomerons is still important, though its relative contribution decreases in comparison with CERN SpS energies.

On the other hand, the experimental ratios of $\Xi^+$ to $\Lambda$ are now in agreement with the QGSM model calculations, probably meaning that the production of $\Xi^+$ inside one only Pomeron becomes more effective at this energy than the possibility of taking two strange antiquarks from different Pomerons. This trend is confirmed by the STAR Collaboration data [73] at $\sqrt{s_{NN}} = 200$ GeV.

Recently before this conference, the ALICE Collaboration has also published [74] results on the mid-rapiditiy anti-baryon to baryon ratios in $pp$ collisions at $\sqrt{s} = 0.9, 2.76,$ and $7$ TeV.

4. Conclusion
The QGSM provides a reasonable description of nucleon and $\Lambda$, as well as their antiparticles, production in nucleon-nucleus and nucleus-nucleus collisions at high energies. The level of numerical accuracy is of about 20–30%. Part of the uncertainty is connected to discrepancies among the different experimental data.

Inclusive densities of $\Xi^+$ hyperons are reasonably reproduced for the cases of p+Be and p+Pb collisions [71], but they are several times underestimated in the case of central Pb+Pb interactions [71]. For $\Omega^+$ production in central Pb+Pb collisions the disagreement is larger than one order of magnitude.

In nucleus-nucleus collisions, the number of quark-gluon strings (cut pomerons) increases with centrality. If the secondaries are independently produced in each quark-gluon string, the ratio of yields of different particles should not depend on centrality. However, it is experimentally clear
(e.g. see [35], and figure 5) that the yield of $\Xi^-$ is more strongly enhanced than that of $\bar{\Lambda}$, the same as the yield of $\Omega^- + \Xi^+$ is more enhanced than that of $\Xi^+$. This shows that an additional source of multistrange hyperons originated by the collective interactions of several strings must also play an actile role, and then this additional source of multistrange hyperons can possibly be considered as a QGP signature.

If this scenario in which collective effects among different quark-gluon strings help in explaining the energy dependence from CERN SpS to RHIC of the production ratios of $\Omega^+ / \Lambda$ and of $\Xi^+ / \Xi$ would be confirmed, one could not expect a significant dependence of these ratios on centrality (see figure 5), neither significant differences of these ratios at LHC energies from the QGSM predictions, the expected values being $R(\Omega^+ / \Lambda) \sim 0.14$ and $R(\Xi^+ / \Xi) \sim 0.014$.

A situation similar to the one shown in figures 5 can appear at LHC in Pb+Pb collisions in the midrapidity region for charmed antibaryon production, that is, for the ratios $\Sigma_c^- = \bar{c}s\bar{s}$ to $\bar{\Lambda}_c$, and $\Xi_c^- = \bar{c}s\bar{s}$ to $\bar{\Lambda}_c$.

In summary, we can assume that the considered Quark-Gluon Plasma formation events are rather rare, but at the same time they can be clearly identified by a well-defined selection trigger. At CERN SpS energy, such a trigger can be the $\Omega^+$ production in central Au+Au collisions, where a strong centrality dependence of the ratio $\Omega^+ / \Lambda$ is apparent (see figure 5a).

Acknowledgements

We want to thank Olga Piskunova for giving us the possibility to participate and contribute to this workshop. We are grateful to A.B. Kaidalov for useful discussions and comments. We also thank M. Poghosyan for his comments during this conference. This paper was supported by Ministerio de Economía y Competitividad of Spain (FPA2011-22776), the Spanish Consolider-Ingenio 2010 Programme CPAN (CSD2007-00042), by Xunta de Galicia, Spain (2011/PC043), by the State Committee of Science of the Republic of Armenia (Grant-13-1C023), and, partially, by grant RSGSS-3628.2008.2.

References

[1] A.B. Kaidalov and K.A. Ter-Martirosyan, Yad. Fiz. 39, 1545 (1984); 40, 211 (1984).
[2] A.B. Kaidalov and O.I. Piskounova, Yad. Fiz. 41, 1278 (1985); Z. Phys. C30, 145 (1986).
[3] Yu.M. Shabelski, Yad. Fiz. 44, 186 (1986).
[4] G.H. Arakelyan, C. Merino, C. Pajares, and Yu.M. Shabelski, Eur. Phys. J. C54, 577 (2008) and hep-ph/0709.3174.
[5] C. Merino, C. Pajares, and Yu.M. Shabelski, Eur. Phys. J. C71, 1652 (2011).
[6] A.B. Kaidalov, K.A. Ter-Martirosyan, and Yu.M. Shabelski, Yad. Fiz. 43, 1282 (1986).
[7] Yu.M. Shabelski, Z. Phys. C38, 569 (1988).
[8] Yu.M. Shabelski, Yad. Fiz. 50, 239 (1989).
[9] Yu.M. Shabelski, Z. Phys. C57, 409 (1993).
[10] J. Dias de Deus and Yu.M. Shabelski, Yad. Fiz. 71, 191 (2008).
[11] V.A. Abramovsky, V.N. Gribov, and O.V. Kancheli, Yad. Fiz. 18, 595 (1973).
[12] A.B. Kaidalov, Sov. J. Nucl. Phys. 45, 902 (1987); Yad. Fiz. 43, 1282 (1986).
[13] Yu.M. Shabelski, Yad. Fiz. 26, 1084 (1977); Nucl. Phys. B132, 491 (1978).
[14] L. Bertocci and D. Treleiani, J. Phys. G3, 147 (1977).
[15] J. Weis, Acta Phys. Polonica B7, 85 (1977).
[16] T. Jaroszewicz et al., Z. Phys. C1, 181 (1979).
[17] V.M. Braun and Yu.M. Shabelski, Int. J. Mod. Phys. A3, 2117 (1988).
[18] G.D. Alkhazov et al., Nucl. Phys. A280, 365 (1977).
[19] G.H. Arakelyan, A. Capella, A.B. Kaidalov, and Yu.M. Shabelski, Eur. Phys. J. C26, 81 (2002) and hep-ph/0103337.
[20] F. Bopp and Yu.M. Shabelski, Yad. Fiz. 68, 2155 (2005) and hep-ph/0406158; Eur. Phys. J. A28, 237 (2006) and hep-ph/0603193.
[21] G.H. Arakelyan, C. Merino, and Yu.M. Shabelski, Yad. Fiz. 69, 911 (2006) and hep-ph/0505100; Phys. Atom. Nucl. 70, 1110 (2007) and hep-ph/0604103; Eur. Phys. J. A31, 519 (2007) and hep-ph/0610264.
[22] O.I. Piskounova, Phys. Atom. Nucl. 70, 1110 (2007) and hep-ph/0604157.
[23] C. Merino, C. Pajares, and Yu.M. Shabelski, Eur. Phys. J. C59, 691 (2009) and arXiv:0802.2195[hep-ph].
[24] C. Merino, M.M. Ryzhinski, and Yu.M. Shabelski, Eur. Phys. J. C62, 491 (2009); Lecture given by Yu.M. Shabelski at The XLIII PNPI Winter School on Physics, St.Petersburg (Russia), February 2009, arXiv:0906.2659[hep-ph].
[25] X. Artru, Nucl. Phys. B85, 442 (1975).
[26] M. Imachi, S. Otsuki, and F. Toyoda, Prog. Theor. Phys. 52, 346 (1974); 54, 280 (1976); 55, 551 (1976).
[27] G.C. Rossi and G. Veneziano, Nucl. Phys. B123, 507 (1977).
[28] D. Kharzeev, Phys. Lett. B378, 238 (1996).
[29] L.L. Frankfurt and M.I. Strikman, Phys. Rep. 76, 215 (1981).
[30] A.V. Efremov et al., Sov. J. Nucl. Phys. 47, 858 (1988).
[31] A.V. Efremov et al., Phys. Atom. Nucl. 57, 874 (1994).
[32] A. Capella, A. Kaidalov, and J. Tran Thanh Van, Heavy Ion Phys. 9, 169 (1999).
[33] G.H. Arakelyan, C. Merino, and Yu.M. Shabelski, arXiv:1305.0388[hep-ph], and accepted for its publication in Phys. Atom. Nucl.
[34] G.H. Arakelyan, C. Merino, and Yu.M. Shabelski, arXiv:1402.6505[hep-ph].
[35] Huan Z. Huang, Phys. Lett. B276, 166 (1992).
[36] H.J. M"ohring, J. Ranft, C. Merino, and C. Pajares, Phys. Rev. D47, 4142 (1993).
[37] N.S. Amelin, M.A. Braun, and C. Pajares, Z. Phys. C63, 507 (1994).
[38] I. Bautista, C. Pajares, and J. Dias de Deus, Nucl. Phys. A882, 44 (2012).
[39] I. Bautista, J. Dias de Deus, G. Milhano, and C. Pajares, Phys. Lett. B715, 230 (2012).
[40] I. Bautista, C. Pajares, G. Milhano, and J. Dias de Deus, Phys. Rev. C86, 034909 (2012).
[41] J. Dias de Deus and C. Pajares, Phys. Lett. B695, 211 (2012) and arXiv:1011.1099[hep-ph].
[42] C. Merino, C. Pajares, and Yu.M. Shabelski, arXiv:1207.6900[hep-ph].