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Centrality dependence of multistrangeness production in high-energy heavy-ion collisions

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Abstract. We compare the experimental data on yields of protons, strange Λ's, and multistrange baryons (Ξ, Ω), and antibaryons production on nuclear targets, and the experimental ratios of multistrange to strange antibaryon production, at the energy region from SPS up to LHC, with the corresponding results of the Quark-Gluon String Model calculations. In the case of heavy nucleus collisions, the experimental dependence of the $\overline{\Xi}^+/\overline{\Lambda}$, and $\overline{\Omega}^+/\overline{\Lambda}$ ratios, on the centrality of the collision, shows a manifest violation of quark combinatorial rules.

1 Introduction

We compare [1] the results obtained in the Quark-Gluon String Model (QGSM) formalism, with the corresponding experimental data on yields of p, Λ, Ξ, and Ω baryons, and the corresponding antibaryons, in nucleus-nucleus collisions, for a wide energy region, going from SPS up to LHC ranges. We also consider the ratios of multistrange to strange antihyperon production in nucleus-nucleus collisions with different centralities, at CERN-SPS and RHIC energies.

The QGSM [2–4] is based on the Dual Topological Unitarization (DTU), Regge phenomenology [5], and nonperturbative notions of QCD [6]. In QGSM, high energy interactions are considered as proceeding via the exchange of one or several Pomerons. The cut of at least some of those Pomerons determines the inelastic scattering amplitude of the particle production processes, that occur through the production and subsequent decay of the quark-gluon strings resulting of the cut of the Pomerons.

In the case of interaction with a nuclear target, the Multiple Scattering Theory (Gribov-Glauber Theory) [7] is used. For nucleus-nucleus collisions, the Multiple Scattering Theory allows to consider these interactions as a superposition of independent nucleon-nucleon interactions.

At very high energies, the contribution of enhanced Reggeon diagrams (percolation effects) becomes important, leading to a new effect, the suppression of the inclusive density of secondaries [8] into the central (midrapidity) region. This effect corresponds to a significant fusion of the primarily produced quark-gluon strings.

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The QGSM provides a succesful thorough description of multiparticle production processes in hadron-hadron [9–13], hadron-nucleus [14–16], and nucleus-nucleus [17–20] collisions, for a wide energy region. In particular, the inclusive spectra of charged pions, kaons, nucleons, and Λ hyperons, were correctly described in the cited papers.

The production of multistrange hyperons, Ξ^- (dss), and Ω^- (sss), has special interest in high energy particle and nuclear physics. Since the initial-state colliding projectiles contain no strange valence quarks, all particles in the final state with non-zero strangeness quantum number should have been created in the process of the collision. This makes multistrange baryons a valuable probe in understanding the particle production mechanisms in high energy collisions. A remarkable feature of strangeness production is that the production of each additional strange quark featuring in the secondary baryons, i.e., the production rate of secondary $B(qqs)$ over secondary $B(qqq)$, then of $B(qss)$ over $B(qqs)$, and, finally, of $B(sss)$ over $B(qss)$, is affected by one universal strangeness suppression factor, λ_s:

$$\lambda_s = \frac{B(qqs)}{B(qqq)} = \frac{B(qss)}{B(qqs)} = \frac{B(sss)}{B(qss)} \, , \tag{1}$$

together with some simple quark combinatorics [21, 22].

Let us define:

$$R(\overline{\Xi}^+/\overline{\Lambda}) = \frac{dn}{dy}(A + B \to \overline{\Xi}^+ + X)/\frac{dn}{dy}(A + B \to \overline{\Lambda} + X) \, , \tag{2}$$

$$R(\overline{\Omega}^+/\overline{\Lambda}) = \frac{dn}{dy}(A + B \to \overline{\Omega}^+ + X)/\frac{dn}{dy}(A + B \to \overline{\Lambda} + X) \, . \tag{3}$$

The produced antihyperons, $\overline{\Xi}^+$ and $\overline{\Omega}^+$, contain valence antiquarks newly produced during the collision. The ratios in eqs. (2) and (3) are reasonably described by QGSM when a relatively small number of incident nucleons participate in the collision (nucleon-nucleus collisions, or peripheral nucleus-nucleus collisions).

The number of quark-gluon strings (cut pomerons) in nucleus-nucleus collisions increases with the centrality of the collision, but if the secondaries are independently produced in a single quark-gluon string, the ratio of yields of different particles should not depend on the centrality.

2 Comparison of QGSM calculations with experimental data

2.1 Fixed Target Energy Data

The experimental data on proton and hyperon productiom were reasonably described in [16]. The data for p+Be and p+Pb collisions were also described in the same reference, but it appears that the value of the strange suppression parameter λ_s=0.25 would have to be slightly increased to get a better comparison with the experimental data. In the present paper we use the value λ_s=0.32, that provides good results for the description of the experimental data in references [23, 24].

In the case of Pb+Pb collisions at 158 GeV/c per nucleon, we compare the experimental data on dn/dy for central collisions ($|\ y\ | \leq 0.5$), measured by NA49 [25–30], NA57 [31, 32], and WA97 [33] collaborations, with the corresponding QGSM predictions.

In Fig. 1 we show the comparison of the QGSM prediction with the experimental data [32] on the dependence of the ratios $\overline{\Omega}^+/\overline{\Lambda}$ (left panel) and $\overline{\Xi}^+$ to $\overline{\Lambda}$ (right panel), on the number of wounded nucleons, N_ω, in Pb+Pb collisions at 158 GeV/c per nucleon. The number of

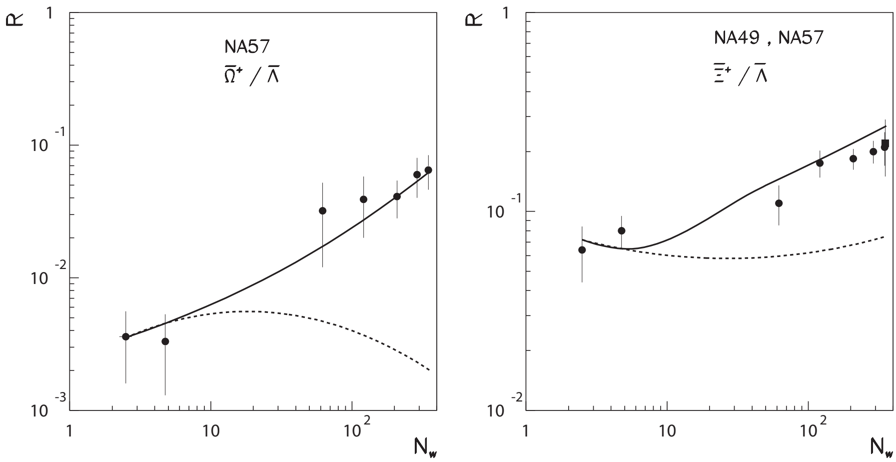

Figure 1. Ratios of $\overline{\Omega}^+/\overline{\Lambda}$ (left panel), and of $\overline{\Xi}^+/\overline{\Lambda}$ (right panel) as functions of the number of wounded nucleons, N_w. The experimental data of Pb+Pb collisions for different numbers of wounded nucleons, N_w (different centralities) measured by the NA57 Collaboration (points), and by the NA49 Collaboration (squares) are presented, and compared with the corresponding QGSM predictions.

wounded nucleons, N_ω, is directly related to the centrality of collisions. Thus, small values of N_w correspond to peripheral collisions (large impact parameter), while large values of N_w correspond to central collisions (small impact parameter).

At small values of N_w the ratio is practically equal to that in the cases of p+Be and p+Pb collisions, and all they can be correctly described by the QGSM by using a value the of the strangeness suppression parameter, λ_s=0.32. Then, the experimental ratio increases rather fast with the incresing value of N_w, i.e. when we move from peripheral to central Pb+Pb collisions. This behavior is reasonably reproduced by the full line in Fig. 1, that it has been calculated with the value λ_s=0.32 at its left end, and with larger values of λ_s at its right end (see ref. [1] for details). The results of QGSM calculations with a constant value λ_s=0.32, disregarding of the value of the number of wounded nucleons (centrality), N_ω, are shown in Fig. 1 by dashed lines.

Obviously, for small values of N_w, both curves coincide, but when N_w increases the full line also increases in agreement with the data, while the dashed line is practically constant, with exception of small corrections mainly connected to energy conservation. This dashed line shows a very significant disagreement with the experimenatl data at large values of N_w. The difference between the full and the dashed lines for the ratio $\overline{\Omega}^+/\overline{\Lambda}$ in a very central event is of about one order of magnitude. Such a large difference comes from the fact that the cross section for $\overline{\Omega}$ production is proportional to $\lambda_s{}^3$.

This behaviour in which the value of the strangeness suppression factor λ_s increases with the value of N_w (centrality), indicates that the simple quark combinatorial rules are not valid for central collisions of heavy nuclei.

2.2 STAR Collaboration Data

Now we consider the experimental data on midrapidity densities of protons and hyperons in Au+Au measured at RHIC by the STAR [34–37] Collaboration at $\sqrt{s}$ = 62.4 GeV, and we compare them with the results of the corresponding QGSM calculations. One can appreciate that, in general, the agreement of the QGSM predictions with the experimental data in this energy region is quite reasonable.

Again, we see here that the value of λ_s for multistrange hyperon production is larger than for the case of Λ and $\overline{\Lambda}$ production. Now this difference is not so large as it is for collisions at lower fixed-target energies, in what it seems an indication that the violation of the quark combinatorial rules becomes less important for high energy collisions.

In Fig. 2 we present the comparison of the QGSM predictions with experimental data on the N_ω dependence of the ratios $\overline{\Omega}^+/\overline{\Lambda}$ (left panel), and $\overline{\Xi}^+/\overline{\Lambda}$ (right panel), measured by the STAR Collaboration in the midrapidity region, at $\sqrt{s}$ = 62.4 GeV. Similarly as in Fig. 1, the left end of the full line here was calculated with a value λ_s=0.32, while for the right end larger values of λ_s were used (see [1]). The dashed line was calculated with a constant value of λ_s=0.32.

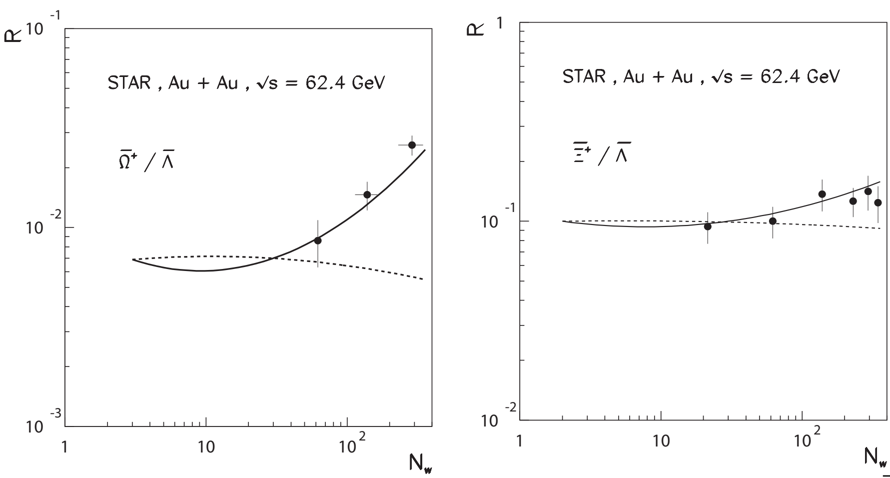

Figure 2. The experimental points obtained by the STAR Collaboration on the ratios of $\overline{\Omega}^+/\overline{\Lambda}$ (left panel), and $\overline{\Xi}^+$ to $\overline{\Lambda}$ (right panel), in Au+Au collisions at $\sqrt{s}$ = 62.4 GeV, at different centralities, as a function of the number of wounded nucleons, N_w, together with the results of the corresponding QGSM calculations (solid curves).

The same calculations for the ratio of $\overline{\Xi}^+/\overline{\Lambda}$ in Cu+Cu collisions at $\sqrt{s}$ = 200 GeV [38] show again that the violation of the quark combinatorial rules decreses with the growth of the energy of the collision, the difference between the full and dashed lines being of the order of the experimental error bars, at $\sqrt{s}$ = 200 GeV.

2.3 LHC experimental Data

In Table 1 we consider the experimental data on p, $\overline{p}$, and Ξ^-, $\overline{\Xi}^+$, Ω^-, $\overline{\Omega}^+$ production in central Pb+Pb collisions at $\sqrt{s}$ = 2.76 Tev, and of $p + \overline{p}$ production in central Pb+Pb collisions at $\sqrt{s}$ = 5.02 Tev, measured by the ALICE Collaboration [39–41], at the CERN LHC.

The value of the strangeness suppression parameter λ_s needed for a correct description of Ξ^- and $\overline{\Xi}^+$ production at LHC is smaller than at RHIC energies, and it coincides with the standard value λ_s=0.32. In the case of Ω^- and $\overline{\Omega}^+$ production at LHC, the value of λ_s also decreases with respect to the RHIC energy range. Thus, the unusually large values of λ_s that correspond to central Pb+Pb collisions at 158 GeV/c per nucleon, monotonically decrease with the increase of the initial energy of the collision.

Thus, the experimental data on strange and multistrange particle production show that the value of the strangeness suppression factor to be taken in QGSM to correctly describe those experimental data, is lower at RHIC and LHC energy ranges, than at SPS (i.e. a smaller enhancement of strangeness production at RHIC and LHC, when compared with that at SPS).

Table 1. Experimental data on dn/dy by the ALICE Collaboration of p, $\bar{p}$ central production at $\sqrt{s}$ = 2.76 TeV [39], of p+$\bar{p}$ central production at $\sqrt{s}$ = 5.02 TeV [41], Ξ^-, and of Ξ^-, $\overline{\Xi}^+$, Ω^-, and $\overline{\Omega}^+$ production in central Pb+Pb collisions at $\sqrt{s}$ = 2.76 TeV per nucleon [40], and the comparison with the results of the corresponding QGSM calculations.

Process	$\sqrt{s}$ (TeV)	Centrality	dn/dy (Exp. Data)	dn/dy (QGSM)	λ_s
Pb+Pb $\to p$	2.76	0–5%	34 ± 3	34.604	0,32
Pb+Pb $\to \overline{p}$	2.76	0–5%	33 ± 3	33.898	
Pb+Pb $\to p + \overline{p}$	5.02	0–5%	74.56 ± 0.06 ± 3.75	77.71	0,32
Pb+Pb $\to \Xi^-$	2.76	0–10%	3.34 ± 0.06 ± 0.24	3.357	0,32
Pb+Pb $\to \overline{\Xi}^+$	2.76	0–10%	3.28 ± 0.06 ± 0.23	3.317	
Pb+Pb $\to \Omega^-$	2.76	0–10%	0, 58 ± 0.04 ± 0.09	0.606	0.38
Pb+Pb $\to \overline{\Omega}^+$	2.76	0–10%	0, 60 ± 0.05 ± 0.09	0,601	

3 Conclusion

We consider the production of hyperons in collisions on nuclear targets, in the framework of the QGSM formalism, and we find that the experimental data on multistrange hyperon and antihyperon production in p-nucleus and in peripheral nucleus-nucleus collisions can be reasonably described in the QGSM framework, by using for all baryons the same standard value of the strange suppression parameter λ_s=0.32, while to get a correct description in QGSM of multistrange hyperon and antihyperon production in central Pb+Pb collisions in the midrapidity region, a larger value of λ_s is needed.

In particular, one can see that the experimental probability of multistrange hyperon production in Pb+Pb collisions increases monotonically with the number of wounded nucleons, N_w, i.e. when going from peripheral to very central nucleus-nucleus collisions. A similar situation occurs in the case of Au+Au collisions at RHIC energies, though the effect is not so pronounced.

As a matter of fact, the experimental data on the production of hyperons in central collisions of heavy nuclei show a very significant violation, essentially large at CERN-SPS energies $\sqrt{s}$ = 17.3 GeV, of simple quark combinatorial rules, this violation decreasing with the growth of the initial energy of the collision. On the contrary, the corresponding data in proton-nucleus and in peripheral nucleus-nucleus collisions are in agreement with the quark combinatorics theoretical description, by considering one universal and constant strangeness suppression factor.

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