Strangeness enhancement from strong color fields at RHIC

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In ultra-relativistic heavy ion collisions, early stage multiple scatterings may lead to an increase of the color electric field strength. Consequently, particle production - especially heavy quark (and di-quark) production - is greatly enhanced according to the Schwinger mechanism. We test this idea via the Ultra-relativistic Quantum Molecular Dynamics model (UrQMD) for Au+Au collisions at the full RHIC energy ($\sqrt{s} = 200$ AGeV). Relative to p+p collisions, a factor of 60, 20 and 7 enhancement respectively, for Ω (sss), Ξ (ss), and Λ, Σ (s) is predicted for a model with increased color electric field strength.

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One of the major goals of the relativistic heavy ion collider (RHIC) at Brookhaven National Laboratory is to explore the phase diagram of hot and dense matter near the quark gluon plasma (QGP) phase transition. The QGP is a state in which the individual hadrons dissolve into a gas of free (or almost free) quarks and gluons in strongly compressed and hot matter (for recent reviews on the topic, we refer to [1,2]). The achievable energy- and baryon densities depend on the extend to which the nuclei are stopped during penetration, thus on centrality and bombarding energy.

Strange particles, especially multi-strange baryons (which have more than one strange quark) carry vital information about the collision dynamics [3–10]. Relative strangeness abundancies have been proposed as a powerful tool for searching the transition from hadronic matter to partonic matter in high energy nuclear collisions [3–5]. Indeed, strangeness enhancement has be observed in heavy ion collisions at all collision energies with different colliding systems.

Recently, measurements by the WA97 and the NA49 collaborations clearly demonstrated the relative enhancement of the (anti-)hyperon yields (Λ, Ξ, Ω) in Pb-Pb collisions as compared to p-Pb collisions [11–16]. The observed enhancement increases with the strangeness content ($|S| = 1, 2, 3$) of the probe under investigation [11–16]. For the ($\Omega^- + \overline{\Omega^-}$)-yield the enhancement factor is as large as 15.

A number of different mechanisms are under debate to understand this strong increase in strangeness production with centrality and beam energy:

- Equilibrated (gluon rich) plasma phase: Chemical and flavour equilibration times are predicted to be shorter in a plasma phase than in a thermally equilibrated hadronic fireball of $T \sim 160\,\mathrm{MeV}$ [3]. Thus, a dominant production mechanism for strangeness in an equilibrated gluon rich plasma phase (Hot glue scenario [17]), might be the production of $s\bar{s}$ pairs via gluon fusion ($gg \to s\bar{s}$) [3]. This might allow for strangeness equilibration within the lifetime of the QGP, resulting in strong strangeness enhancement compared to hadronic scenarios.

- Baryon-junctions: A baryon junction exchange mechanism was proposed to explain valence baryon number transport in nuclear collisions. Recently it was extended to study midrapidity (anti-)hyperon production [18]. It was found that Baryon junction-anti-junction (J anti-J) loops can indeed enhance anti-Lambda, anti-Xi, anti-Omega yields at SPS energies. While this mechanism leads to a reasonable description of central interactions, it can not explain the enhancement in the measured hyperon to anti-hyperon ratios with increasing centrality.

- Diquark breaking and sea-diquarks: A new version of the dual parton model, featuring an improved diquark breaking mechanism has been applied to explain the observed strangeness enhancement at the full SPS energy [19]. Here, the strange- and antibaryon production invokes strings originating from diquark-antidiquark pairs in the nucleon sea to reproduces the observed yields of p and Lambda and their antiparticles. However cascades are underestimated by 50% and Omega's are underestimated by a factor five. Agreement with measured data can only be achieved in this model if additional final state interactions among hadrons are taken into account.

- Strong color fields: Another kind of string-hadronic models employs the Schwinger mechanism [20] of a fragmenting color field (string) directly. However, in central high energy heavy ion collisions the string density can be so high that the color flux tubes overlap [21,22]. Consequently, the superposition of the color electric fields yields an enhanced particle

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production [21,22]. In particular, the heavy flavors and diquarks are dramatically enhanced due to a higher effective string tension [22–24]. Note that the strong color field leads to the enhancement not only of the heavy flavors and diquarks but also enhances the high p_t tail of the transverse momentum distribution of all created particles. However, the changes in the final p_t are rather moderate in AA collisions due to final state interactions [22]. A consistent enhancement of hyperons and anti-protons is necessary to support this scenario. In fact, it has been shown that this approach is consistent with the measured anti-proton and hyperon yields at SPS energies, if rescattering effects are taken into account [25,26].

As a tool for our investigation of heavy ion reactions at RHIC the Ultra-relativistic Quantum Molecular Dynamics model (UrQMD 1.2) is applied [27]. UrQMD is a microscopic transport approach based on the covariant propagation of constituent quarks and diquarks accompanied by mesonic and baryonic degrees of freedom. It simulates multiple interactions of ingoing and newly produced particles, the excitation and fragmentation of color strings and the formation and decay of hadronic resonances. At RHIC energies, the treatment of subhadronic degrees of freedom is of major importance. In the UrQMD model, these degrees of freedom enter via the introduction of a formation time for hadrons produced in the fragmentation of strings [28–30]. The leading hadrons of the fragmenting strings contain the valence-quarks of the original excited hadron. In UrQMD they are allowed to interact even during their formation time, with a reduced cross section defined by the additive quark model, thus accounting for the original valence quarks contained in that hadron [27]. Those leading hadrons therefore represent a simplified picture of the leading (di)quarks of the fragmenting string. Newly produced (di)quarks do, in the present model, not interact until they have coalesced into hadrons – however, they contribute to the energy density of the system. For further details about the UrQMD model, the reader is referred to Ref. [27].

In the following two different scenarios will be explored in order to study the speculation of a string tension increase in heavy ion collision at RHIC energies: UrQMD calculations with the standard color flux tube break-up mechanism (i.e. a string tension $\kappa = 1$ GeV/fm) will be contrasted by UrQMD simulations with an in-medium κ increased to 3 GeV/fm. According to the implemented Schwinger mechanism for the string fragmentation (m denoting the ((di-)quark masses)

$$\gamma_X = \frac{P(X\overline{X})}{P(q\bar{q})} = \exp\left(-\frac{\pi(m_X^2 - m_q^2)}{\kappa}\right) \quad , \qquad (1)$$

this results in an enhancement of the strangeness and diquark production probabilities to $\gamma_s = 0.72$ and $\gamma_{qq} = 0.46$ (for $\kappa = 3$ GeV/fm) compared to $\gamma_s = 0.37$ and $\gamma_{qq} = 0.093$ for $\kappa = 1$ GeV/fm. Note that a decrease of the (di-)quark masses due to chiral symmetry restoration may lead to a similar enhancement as the $\kappa = 3$ GeV/fm scenario.

Fig. 1 depicts the particle rapidity distributions (a, b) and ratios from Au+Au (b = 2 fm) to p+p collisions (c, d) at the RHIC full energy $\sqrt{s} = 200$AGeV. The symbols denote: $\Omega^- + \overline{\Omega^-}$ (full circles), $\Xi^- + \overline{\Xi^-}$ (full triangles), $\Sigma^0 + \overline{\Sigma^0}$ (reversed triangle), $\Lambda^0 + \overline{\Lambda^0}$ (full square) and anti-protons (open circles). (a) shows the rapidity distributions with string tension $\kappa = 1$GeV/fm; (b) shows the same as (a) with $\kappa = 3$GeV/fm. (c) depicts the ratio $R(y) = \frac{\frac{dN}{dy}^{\rm Au}(y)/A_{\rm part}}{\frac{dN}{dy}^{\rm pp}(y)/2}$ of the particle yields per participant from central AA collisions over that of the p+p collisions with $\kappa = 1$GeV/fm; (d) same as (c), however with $\kappa = 3$GeV/fm for Au+Au.

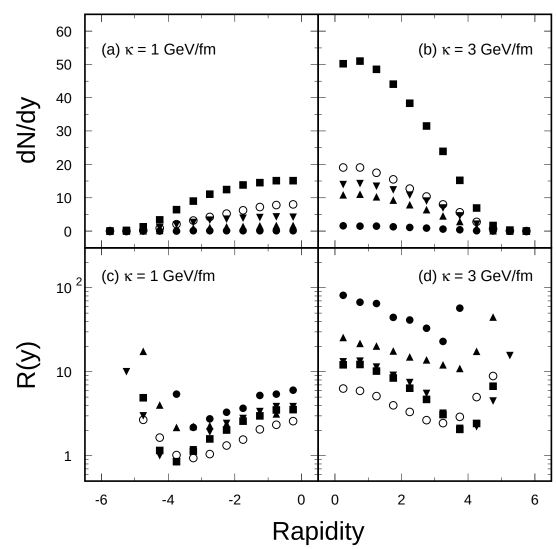

FIG. 1. Particle rapidity distributions and ratios from Au+Au (b = 2 fm) and p+p collisions at the RHIC full energy $\sqrt{s} = 200$AGeV. (a) Rapidity distributions with string energy density $\kappa = 1$GeV/fm^3; (b) same as (a) with $\kappa = 3$GeV/fm^3; (c) ratio $R(y) = \frac{\frac{dN}{dy}^{\rm Au}(y)/A_{\rm part}}{\frac{dN}{dy}^{\rm pp}(y)/2}$ of the particle yields per participant from central nuclear collisions over that of the p+p collisions with $\kappa = 1$GeV/fm; (d) same as (c) with $\kappa = 3$GeV/fm. $\Omega^- + \overline{\Omega^-}$ (full circles), $\Xi^- + \overline{\Xi^-}$ (full triangles), $\Sigma^0 + \overline{\Sigma^0}$ (reversed triangles), $\Lambda^0 + \overline{\Lambda^0}$ (full squares) and anti-protons (open circles).

A strong enhancement of the (anti-)hyperon production compared to scaled pp interactions is predicted (cf. (c)). This enhancement is purely due to rescattering between constituent (di-)quarks and hadrons in the medium. If strong color fields, similar to Pb+Pb at SPS [25,26], are present, the model predicts a dramatic enhancement in the multi-strange hadron production, up to a factor of 100 (in case of the Omega) at midrapidity.

The enhancement of the hyperon yields is strongly dependent on the centrality of the events as shown in Fig. 2: (a) shows the particle yields with string tension $\kappa = 1$GeV/fm, while (b) is same as (a) with $\kappa = 3$GeV/fm. Fig. 2(c) shows the ratio $R = \frac{N^{\rm Au}(A_{\rm part})/A_{\rm part}}{N^{\rm pp}/2}$ of the particle yields per participant[1] from central AA collisions over that of the inelastic p+p collisions with $\kappa = 1$GeV/fm. (d) depicts the same as (c) with $\kappa = 3$GeV/fm for Au+Au collisions. The symbols are: $\Omega^- + \overline{\Omega^-}$ (full circles), $\Xi^- + \overline{\Xi^-}$ (full triangles), $\Sigma^0 + \overline{\Sigma^0}$ (reversed triangle), $\Lambda^0 + \overline{\Lambda^0}$ (full square) and anti-protons (open circles).

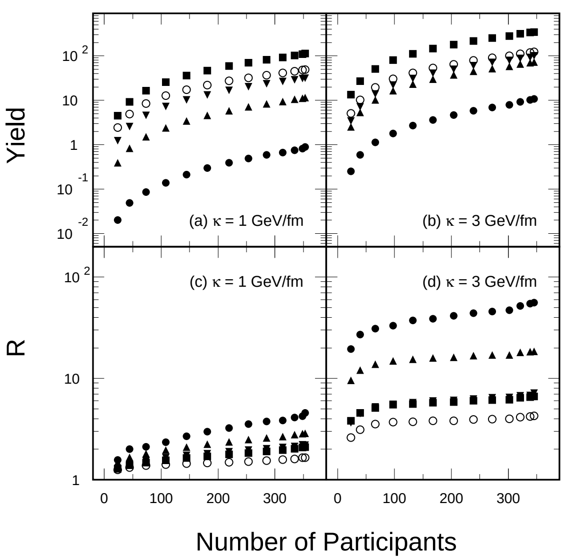

FIG. 2. Particle 4π yields and ratios as a function of number of participants from Au+Au and inelastic p+p collisions at the RHIC full energy $\sqrt{s} = 200$AGeV. (a) yields with string energy density $\kappa = 1$GeV/fm^3; (b) same as (a) with $\kappa = 3$GeV/fm^3; (c) ratio $R = \frac{N^{\rm Au}(A_{\rm part})/A_{\rm part}}{N^{\rm pp}/2}$ of the particle yields per participant from central AA collisions over that of the p+p collisions with $\kappa = 1$GeV/fm^3; (d) same as (c) with $\kappa = 3$GeV/fm^3 for the Au+Au interactions. $\Omega^- + \overline{\Omega^-}$ (full circles), $\Xi^- + \overline{\Xi^-}$ (full triangles), $\Sigma^0 + \overline{\Sigma^0}$ (reversed triangles), $\Lambda^0 + \overline{\Lambda^0}$ (full squares) and anti-protons (open circles).

The 4π yields and ratios as a function of number of participants from Au+Au at the RHIC full energy $\sqrt{s} =$ 200AGeV increase rapidly with centrality (a, b) by two orders of magnitude when going from peripheral ($A_{part} \approx 25$) to central collision. The enhancement itself is most pronounced when scaled with the number of participating nucleons A_{part} and compared to p+p collisions at the RHIC full energy (c, d).

Finally, Fig. 3 depicts an inside view into a central (b=2 fm) Au+Au collision at the full RHIC energy. Open circles show the mass distribution of excited strings. Filled circles and squares represent the probabilities of a $[3]-[\overline{3}]$ string of a given mass to decay into Ωs with $\kappa = 1$ and 3 GeV/fm, respectively. The increase of the string tension to $\kappa = 3$ GeV/fm leads to a strong increase of the Omega production over all inspected string masses (compare full circle with full squares). However, the probability to excite a string with a large mass is strongly suppressed, as can been seen by the exponential decrease of probabilities above excitation energies of 2 GeV. Therefore, most of the Ω's are produced from rather low mass strings. This is in contrast to the expectations that early (high energetic) collisions lead to high mass excitations and give the major contribution to the multi-strange hyperon yield.

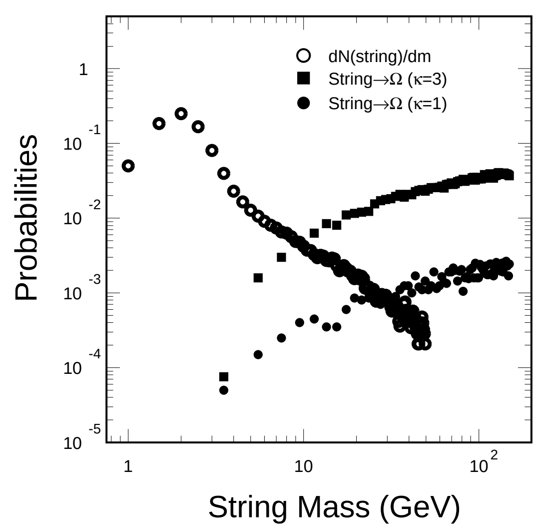

FIG. 3. Probability distributions of strings (open circles). Filled circles and squares represent the probabilities of strings to decay into Ωs with $\kappa = 1$ and 3 GeV/fm, respectively.

In conclusion, the UrQMD model has been applied to Au+Au reactions at RHIC energies. This model treats the dynamics of the hot and dense system by constituent (di-)quark and hadronic degrees of freedom. (Anti-)Hyperon yields in central Au+Au collisions at the full RHIC energy ($\sqrt{s} = 200$ AGeV) strongly enhanced in comparison to inelastic pp interactions at $\sqrt{s} = 200$ GeV

[1] The number of participating nucleons in this paper is defined as:
$A_{\rm part} = A_1 + A_2 - \Sigma\,$(Nucleons with $p_T \leq 270$ MeV). This prescription yields a reasonable parametrization of the experimental data on $A_{\rm part}$.

or peripheral Au+Au collisions. This enhancement grows dramatically with the strangeness content of the hyperon. The present model predicts that strangeness enhancement occurs as a threshold effect already at rather small number of participants (≈ 25) due to rescattering. Increasing the string tension, similar to SPS energies (or reducing the effective masses of the constituent quarks to the current quark mass values yields large additional enhancement, which grows with the strangeness content even stronger: Λ's are enhancement by a factor of 7, while Ω's are enhanced by a factor of 60 compared to pp.

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