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Conference Report

Strangeness Production in Nucleus-Nucleus Collisions at SIS Energies

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Received: 30 November 2017; Accepted: 15 January 2018; Published: 13 February 2018

Abstract: Simulating Many Accelerated Strongly-interacting Hadrons (SMASH) is a new hadronic transport approach designed to describe the non-equilibrium evolution of heavy-ion collisions. The production of strange particles in such systems is enhanced compared to elementary reactions (Blume and Markert 2011), providing an interesting signal to study. Two different strangeness production mechanisms are discussed: one based on resonances and another using forced canonical thermalization. Comparisons to experimental data from elementary collisions are shown.

Keywords: relativistic heavy-ion collisions; monte carlo simulations; transport theory; strangeness

1. Introduction

Relativistic heavy-ion collisions provide a unique opportunity to study matter under extreme conditions. These experiments allow the creation of high temperatures similar to the universe during the first few microseconds after the Big Bang, yielding insights into the equation of state of nuclear matter, which is crucial for understanding the high-density physics of neutron stars.

Nuclear matter exclusively consists of up and down quarks, therefore, the newly produced strange quarks during heavy-ion collisions are a particularly interesting probe for studying the evolution of the reaction, see [1] for a recent overview. Strangeness enhancement in heavy-ion reactions compared to elementary proton-proton collisions has been observed some time ago [2]. The High-Acceptance Di-Electron Spectrometer (HADES) collaboration measured surprisingly high multiplicities of ϕ and Ξ hadrons in heavy-ion collisions below the production threshold [3,4]. In the intermediate energy range between the threshold and $\sqrt{s} = 10A\,\mathrm{GeV}$, the multiplicities of multi-strange particles are still unknown and of high interest to understand this effect.

Overall, there are still a lot of open questions about how strangeness is produced: what role do kaon-nucleon potentials play; how strongly are cross sections affected by the medium; and what are the production mechanisms in and out of equilibrium?

In the following, we focus on heavy-ion reactions at Schwerionen-Synchrotron (SIS) energies ($E_{\mathrm{kin}} = 0.5 - 3.5\,\mathrm{GeV}$) and explore how the hadronic transport approach, Simulating Many Accelerated Strongly-interacting Hadrons (SMASH) [5], models strangeness production out of equilibrium via resonances and in equilibrium via forced thermalization. The aim is to provide a baseline founded on vacuum properties and low-energy physics that can be extended to higher energies and larger systems. Comparisons to elementary cross sections and dilepton measured in experiments are shown, verifying that the resonance approach successfully describes such vacuum properties and providing the foundations for studying the questions raised above within this approach.

2. Model Description

The results presented here are obtained from simulations using SMASH, a microscopic transport approach that solves the relativistic Boltzmann equation

$$p^\mu \partial_\mu f_i(x,p) = C_{\text{coll}}(f_i) \tag{1}$$

using the test particle ansatz and the geometric collision criterion

$$d_{\text{trans}} < d_{\text{int}} = \sqrt{\frac{\sigma_{\text{tot}}}{\pi}}\,, \tag{2}$$

where d_{trans} is the distance of closest approach between two particles and d_{int} is the interaction distance given by the total cross section σ_{tot}. SMASH has been tested against exact solutions of the Boltzmann equation within an Friedmann-Lemaître-Robertson-Walker expanding metric to verify the numerical implementation of the collision criterion [6]. The $2 \leftrightarrow 2$ and $2 \leftrightarrow 1$ reactions are included, implementing all 106 hadrons species made of up, down and strange quarks that are considered experimentally established by the Particle Data Group (PDG) [7]. This results in tens of thousands of possible reaction pairs, for most of which the cross sections are not measured. In SMASH, these interactions are mostly modeled via resonances. This approach has the advantage that the cross sections can be calculated from the resonance properties, for which the available experimental data has been compiled by the PDG . It can be extended to $m \to n$ reactions by approximating them with a cascade of $1 \leftrightarrow 2$ reactions, maintaining a detailed balance. However, this approach is limited in energy (by the highest mass of the known resonances) and some cross sections are not resonant and have to be parametrized. Furthermore, many resonance properties are only sparsely constrained by experimental data.

SMASH can be used to simulate nuclear collisions (as in this work) or infinite matter and as an afterburner for hydrodynamic simulations of the quark-gluon plasma. It is also able to generate dileptons [8,9] and photons in heavy-ion collisions. The current goal is to test physics at SIS energies, establishing a baseline that can be extended for predictions at Nuclotron-based Ion Collider Facility (NICA) and Facility for Antiproton and Ion Research (FAIR) energies. See [5] for a detailed description of the model and results on pion and proton production in heavy-ion collisions compared to experimental data.

The implemented strange particle species are kaons, 11 kaonic resonances, Λ, Σ, Ξ, Ω baryons and 28 baryonic resonances, plus antiparticles. In nucleus-nucleus collisions, hyperons ($Y \in \{\Lambda, \Sigma\}$) and kaons are primarily produced by nucleon resonances

$$NN \to NN^*/\Delta^* \to NYK\,, \tag{3}$$

while antikaons are produced from strangeness exchange and ϕ decays:

$$NN \to NN^*/\Delta^* \to NYK \quad \pi Y \to Y^* \to \bar{K}N \quad N^* \to \phi N \tag{4}$$

The non-resonant contribution to the strangeness exchange $\pi Y \leftrightarrow \bar{K}N$ is parametrized similar to ref. [10].

3. Results

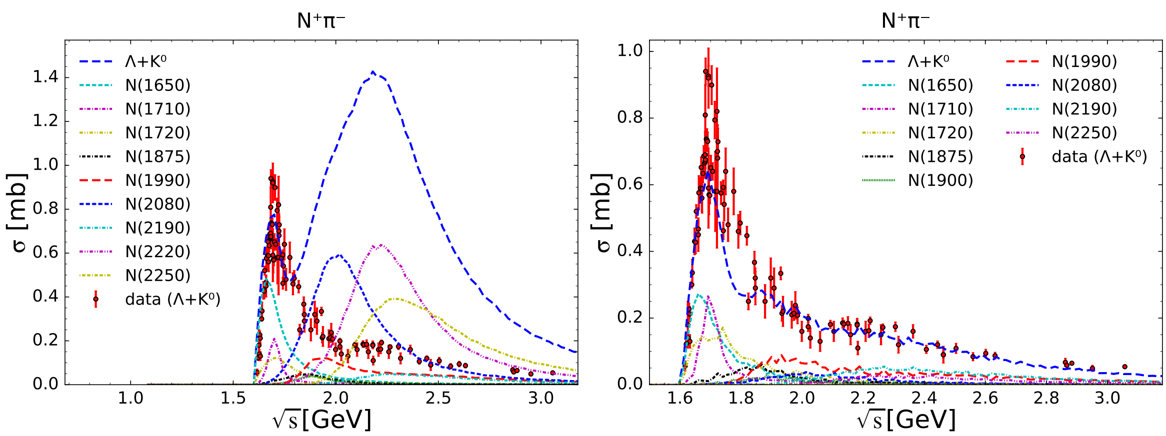
Let us first concentrate on strangeness production out of equilibrium by resonance excitation. The production of hyperons and ϕ mesons are discussed separately because they are constrained very differently by the available experimental data. Finally, strangeness production via a different approach forcing local thermal equilibrium in hadronic transport is briefly presented and compared to a more traditional hybrid approach of modeling heavy-ion collisions.

3.1. Hyperon Production via Resonances

While the masses and decay widths of the resonances are well-established, their branching ratios are only sparsely known. This can be alleviated by studying elementary cross sections. For example, the reaction $p\pi^- \to \Lambda K^0$ is dominated by the $N^* \to \Lambda K$ branching ratios. Taking the middle of the range given by the PDG results in a cross section as shown in Figure 1a: The cross section reconstructed from SMASH output (lines) overestimates the experimental data (circles) at the threshold and at $\sqrt{s} > 1.8\,\mathrm{GeV}$. Looking at the contributions of the individual resonances reveals that $N(1650)$, $N(2080)$, $N(2190)$, $N(2220)$ and $N(2250)$ overshoot the data and that their branching ratios should be decreased, while the $N(1710)$ and $N(1720)$ branching ratios can be increased to compensate. Adapting the branching ratios in the range given by the PDG data results in Figure 1b: now the cross section is reproduced rather well, especially at the threshold and at high energies. There might be a slight underestimation at $\sqrt{s} = 1.7\,\mathrm{GeV}$ and $\sqrt{s} = 1.8\,\mathrm{GeV}$, but it is hard to tell, due to large uncertainties in the experimental data.

Another constraint on the $N^* \to \Lambda K$ branching ratio is given by the $pp \to \Lambda p K^+$ cross section. Potential conflicts with the constraints posed by the $p\pi^- \to \Lambda K^0$ cross section can usually be resolved by adapting the $N^* \to \pi N$ branching ratios. This has to be done under careful consideration of the effect on pion production. Similarly, the $N^*, \Delta^* \to \Sigma K, \pi N$ branching ratios are constrained by the $N\pi \to \Sigma K$ and $NN \to \Sigma N K$ cross sections. Due to the different possible charge combinations, there are more constraints given by the measured cross sections than for the Λ.

Having constrained the branching ratios using only elementary data, it is now possible to compare strangeness production in SMASH to heavy-ion experiments in the future. Discrepancies in large systems might hint at in-medium effects.



(a) **(b)**

Figure 1. $p\pi^- \to \Lambda K^0$ cross section reconstructed from SMASH output (lines) compared to experimental data [11] (circles). (**a**) Using N^* branching ratios by choosing the middle of the range given by the PDG [7]. (**b**) After tuning the branching ratios to fit the experimental cross section.

3.2. ϕ Production via Resonances

The HADES collaboration concluded that at low energies a significant fraction of the K^- are produced by ϕ decays [3]. However, none of the baryonic resonances given by the PDG decay into any ϕ [7]. To be still able to produce ϕ in a resonance approach, it was proposed to use the experimental uncertainty of the N^* beyond $2\,\mathrm{GeV}$ to introduce a small ϕN branching ratio [12]. Independent experimental data constraining this arbitrary branching ratio is required.

A potential candidate is the $pp \to pp\phi$ cross section shown in Figure 2a. Unfortunately, it has only been measured close to the threshold, so it does not constrain the ϕ production very well. In our resonance approach, the largest contribution stems from higher energies where no data is available. Other observables are the invariant mass spectra of dileptons measured by the HADES collaboration at $E_{\mathrm{kin}} = 3.5\,\mathrm{GeV}$ in pNb collisions. As shown in Figure 2b, the experimental data resolves the ϕ peak well enough, constraining the $N^* \to \phi N$ branching ratios. By choosing a branching ratio of 0.5%, SMASH is able to reproduce the dilepton spectra and the cross section shown in Figure 2. It remains to be seen how this approach compares to experimental data from larger systems, where so the far neglected in-medium effects on the ϕ may be important.

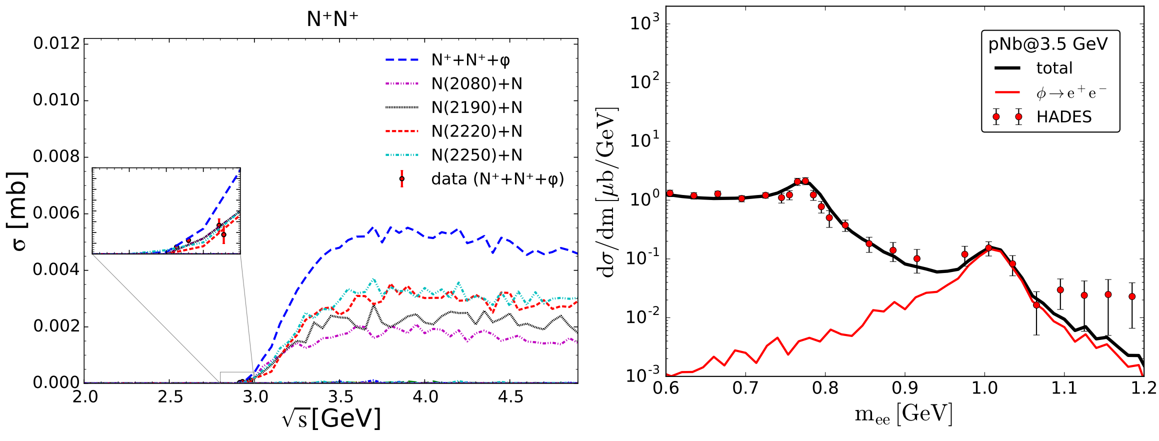


Figure 2. (**a**) $pp \to pp\phi$ cross section reconstructed from SMASH output (lines) compared to experimental data [13,14] (circles). (**b**) Dielectron mass spectrum in proton-niobium collisions at $E_{\mathrm{kin}} = 3.5\,\mathrm{GeV}$ in SMASH (lines) compared to HADES data (circles). Unlike the elementary cross section, the pNb dilepton spectrum constrains the ϕ production.

3.3. Strangeness Production via Thermalization

Traditionally, hybrid models have been successfully used to simulate high-energy heavy-ion collisions: a hydrodynamical model for the partonic phase and a microscopic model (like SMASH) for the hadronic phase. However, it is not clear how to extend them to intermediate energies relevant for the beam energy scan program at the Relativistic Heavy-Ion Collider (RHIC) and future measurements at NICA and FAIR. In [15] it was proposed to use a different approach based on hadronic transport: if there is a region beyond some critical energy density ϵ_{th}, force thermalization in that region by resampling all particles according to a canonical thermal distribution while conserving all relevant quantum numbers. This has similarities to a thermal model but it assumes local instead of global equilibrium. Effectively, it mimics many-particle scattering and interpolates dynamically between two limits of kinetic theory: the dilute gas and the ideal fluid.

As shown in Figure 3, the forced thermalization does barely affect the pion multiplicity but enhances strangeness similar to a hybrid approach. Note that no mean-field potentials were applied because the collision energy is high enough that they are not so important ($\sqrt{s} = 3A\,\mathrm{GeV}$). The amount of produced strangeness in the forced thermalization approach is regulated by the parameter ϵ_{th} (the threshold energy density above which thermalization is performed). For low ϵ_{th}, as for instance twice the nuclear ground-state energy density as in Figure 3, strangeness is strongly enhanced and might be too high compared to experiment. High ϵ_{th} leads to a transport simulation without forced thermalization where strangeness is usually underestimated. It remains for future studies to fix ϵ_{th} versus collision energy and test if different strange particles can be described simultaneously.

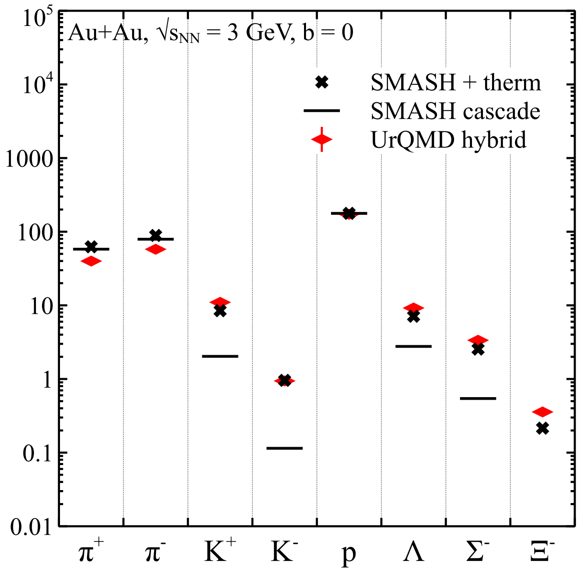


Figure 3. SMASH with and without forced canonical thermalization compared to a UrQMD hybrid model [15]. The energy density threshold for thermalization in SMASH (ϵ_{th}) and particlization in the hybrid approach was set to twice the nuclear ground-state energy density. The strangeness enhancement due to the forced thermalization is comparable to the hybrid approach.

4. Conclusions and Outlook

In this work, it was shown how elementary K, $\bar{K}$, Λ, Σ and ϕ production at low energies can be modeled by via resonances. The PDG data on branching ratios was complemented with constraints from elementary, exclusive cross sections. The ϕ production was modeled by introducing small ϕN branching ratios to heavy N^* resonances, which were successfully constrained by dilepton spectra in pNb collisions. This non-equilibrium strangeness production at low energies via resonances provides a baseline that can be extended to higher energies by including production from strings. Future comparisons to experimental results for larger systems might hint at in-medium effects required to describe the data, such as kaon-nucleon potentials, in-medium cross sections and kaon self-energies [16]. As a mechanism for strangeness production in equilibrium, effective many-particle interactions by forced thermalization were discussed. Promising results of how such an approach enhances strangeness production in heavy-ion collisions similar to a more traditional hybrid approach were shown. It remains to be seen how well this approach can describe the experimental data.

Acknowledgments: The authors thank J. Steinheimer for fruitful discussions. Computational resources have been provided by the Center for Scientific Computing (CSC) at the Goethe-University of Frankfurt and by the Green IT Cube at Gesellschaft für Schwerionenforschung (GSI). The authors acknowledge funding of a Helmholtz Young Investigator Group VH-NG-822 from the Helmholtz Association and GSI. This work was supported by the Helmholtz International Center for the Facility for Antiproton and Ion Research (HIC for FAIR) within the framework of the Landes-Offensive zur Entwicklung Wissenschaftlich-Ökonomischer Exzellenz (LOEWE) program launched by the State of Hesse. D. O. acknowledges support by the Deutsche Telekom Stiftung. D. O. and V. S. acknowledge support by the Helmholtz Graduate School for Hadron and Ion Research (HGS-HIRe). J. S. acknowledges funding by the Deutsche Forschungsgemeinschaft (DFG) grant CRC-TR-2111.

Author Contributions: V.S. implemented strangeness production in SMASH; J.S. implemented dileptons and provided the corresponding plot; D.O. and H.P developed forced thermalization; D.O. implemented it and provided the corresponding plot; H.P. supervised the work; V.S. wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Blume, C. Open Questions in the Understanding of Strangeness Production in HIC -Experiment Perspective. In Proceedings of the 17th International Conference on Strangeness in Quark Matter (SQM 2017), Utrecht, The Netherlands, 10–15 July 2017.
2. Blume, C.; Markert, C. Strange hadron production in heavy ion collisions from SPS to RHIC. *Prog. Part. Nucl. Phys.* **2011**, *66*, 834–879.
3. Adamczewski-Musch, J.; Arnold, O.; Behnke, C.; Belounnas, A.; Belyaev, A.; Berger-Chen, J.C.; Biernat, J.; Blanco, A.; Blume, C.; Böhmer, M.; et al. Deep sub-threshold ϕ production and implications for the K^+/K^- freeze-out in Au+Au collisions. *arXiv* **2017**, arXiv:1703.08418.
4. Agakishiev, G.; Balanda, A.; Bassini, R.; Belver, D.; Belyaev, A.V.; Blanco, A.; Böhmer, M.; Boyard, J.L.; Braun-Munzinger, P.; Cabanelas, P.; et al. Deep sub-threshold Ξ^- production in Ar+KCl reactions at 1.76A-GeV. *Phys. Rev. Lett.* **2009**, *103*, 132301.
5. Weil, J.; Steinberg, V.; Staudenmaier, J.; Pang, L.G.; Oliinychenko, D.; Mohs, J.; Kretz, M.; Kehrenberg, T.; Goldschmidt, A.; Bäuchle, B.; et al. Particle production and equilibrium properties within a new hadron transport approach for heavy-ion collisions. *Phys. Rev. C* **2016**, *94*, 054905.
6. Tindall, J.; Torres-Rincon, J.M.; Rose, J.B.; Petersen, H. Equilibration and freeze-out of an expanding gas in a transport approach in a Friedmann-Robertson-Walker metric. *Phys. Lett. B* **2017**, *770*, 532–538.
7. Patrignani, C.; Particle Data Group. Review of Particle Physics. *Chin. Phys. C* **2016**, *40*, 100001.
8. Staudenmaier, J.; Weil, J.; Petersen, H. Non-equilibrium dilepton production in hadronic transport approaches. *J. Phys. Conf. Ser.* **2017**, *832*, 012037.
9. Weil, J.; Staudenmaier, J.; Petersen, H. Dilepton production with the SMASH model. *J. Phys. Conf. Ser.* **2016**, *742*, 012034.
10. Graef, G.; Steinheimer, J.; Li, F.; Bleicher, M. Deep sub-threshold Ξ and Λ production in nuclear collisions with the UrQMD transport model. *Phys. Rev. C* **2014**, *90*, 064909.
11. Baldini, A. Numerical Data and Functional Relationships In Science and Technology. Grp. 1: Nuclear and Particle Physics. Vol. 12: Total cross-sections for reactions of high-energy particles (including elastic, topological, inclusive and exclusive reactions). Subvol. In *Landolt-Börnstein, New Series, 1/12B*; Springer: Berlin, Germany, 1988.
12. Steinheimer, J.; Bleicher, M. Sub-threshold ϕ and Ξ^- production by high mass resonances with UrQMD. *J. Phys. G Nucl. Part. Phys.* **2016**, *43*, 015104.
13. Maeda, Y.; Hartmann, M.; Keshelashvili, I.; Barsov, S.; Büscher, M.; Drochner, M.; Dzyuba, A.; Hejny, V.; Kacharava, A.; Kleber, V.; et al. Kaon Pair Production in Proton-Proton Collisions. *Phys. Rev. C* **2008**, *77*, 015204.
14. Balestra, F.; Bedfer, Y.; Bertini, R.; Bland, L.C.; Brenschede, A.; Brochard, F.; Bussa, M.P.; Choi, S.; Debowski, M.; Dressler, R.; et al. ϕ and ω meson production in pp reactions at $p_{\text{lab}} = 3.67\,\text{GeV}/c$. *Phys. Rev. C* **2001**, *63*, 024004.
15. Oliinychenko, D.; Petersen, H. Forced canonical thermalization in a hadronic transport approach at high density. *J. Phys. G Nucl. Part. Phys.* **2017**, *44*, 034001.
16. Hartnack, C.; Oeschler, H.; Leifels, Y.; Bratkovskaya, E.L.; Aichelin, J. Strangeness Production close to Threshold in Proton-Nucleus and Heavy-Ion Collisions. *Phys. Rep.* **2012**, *510*, 119–200.