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Sub-threshold strangeness and charm production in UrQMD

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Abstract. We present recent results on the sub-threshold production of strange and charmed hadrons in nuclear collisions. In particular we highlight how the excitation and decay of heavy baryonic resonances can be used to describe the production yield of ϕ mesons at the SIS18 accelerator and show how this production mechanism also consistently describes the ϕ nuclear transparency ratio. Including even more massive baryonic resonances in the model we are able to extend our approach and make, for the first time, realistic predictions on the sub-threshold production of J/Ψ and Λ_c in nuclear collisions at the SIS100 accelerator at FAIR. We find that even at a beam energy of $E_{\rm lab} = 6$ A GeV, charm physics is feasible at the CBM experiment, which opens up new opportunities to study charmed hadron properties at large baryon densities.

1. Introduction

As heavy flavors in nuclear collisions have to be newly produced (as $s + \overline{s}$ or $c + \overline{c}$ pair), it is possible to study near and sub-threshold production of strange and chamed hadrons in nuclear collisions at energies where systems of large net baryon density are created [1]. The properties of such hot and dense systems are in the focus of current and planned experimental programs at the GSI/FAIR [2], NICA and RHIC facilities. For the energies considered, microscopic transport models are usually employed and have a history of succesfully describing experimental observables. Several previous works found that the production rates and properties of Kaons, for example are a promising probe to extract their medium interactions in low energy nuclear collisions [3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15].

In particular strange particles, which are produced below their elementary production threshold have proven to show interesting properties. Here one tries to understand the large production probability for multi strange hadrons, the ϕ and the Ξ^-, as measured by experiments at the SIS18 accelerator [16, 17, 18, 19, 20]. Furthermore, charmed hadron production is considered to be also an excellent probe of the properties of hot and dense nuclear matter. Early works have argued that charmonium suppression in central nuclear collisions may serve as signal for the formation of a deconfined medium, the so called quark gluon plasma (QGP) [21]. In essence, it serves as a messenger of the properties of the deconfined stage. A focus of recent investigations was on charm production at ultrarelativistic energies, i.e. in experiments at the LHC and RHIC accelerators (see e.g. [22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32]).

In the physics program of the CBM experiment at FAIR the study of open charm and

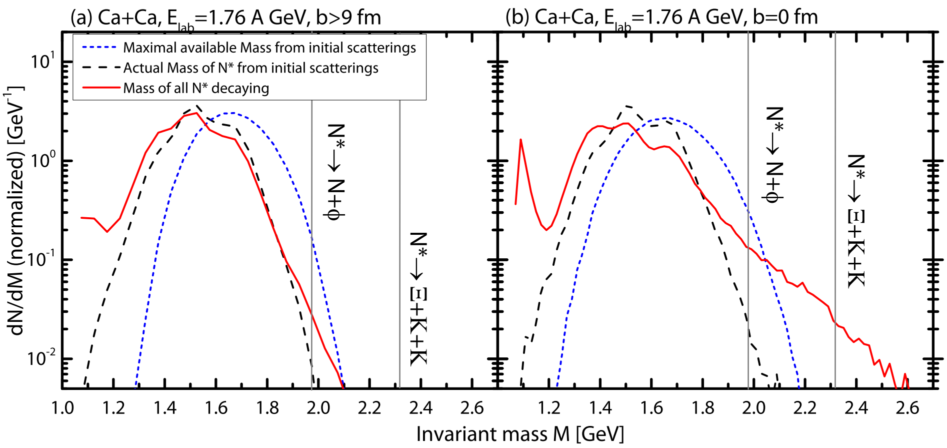

Figure 1. Shown (as blue short dashed line) is the distribution of the maximally available invariant mass for resonance creation from initial scatterings of target and projectile nucleons. Note that the peak of the distribution corresponds to the energy available in proton+proton collisions, at the same beam energy, while the Fermi momenta in the nucleus smear out the distribution. The black dashed line shows the actual invariant mass distribution of N* resonances from these initial nucleon+nucleon scatterings, which is shifted because the outgoing particles have finite momenta. The red solid line depicts the invariant mass distribution of all N* resonances which decay during the systems whole evolution. The left sub-figure presents results of very peripheral collisions of Ca+Ca at $E_{\rm lab} = 1.76$ A GeV, while he right sub-figure depicts results for head on collisions.

charmonium plays an essential role [2]. However, the FAIR project is planned to start with the SIS100 accelerator, which will be able to accelerate a beam of heavy ions only to an energy of $E_{\rm lab} \approx 11$ A GeV, an energy which is below the charm production threshold in elementary collisions. In order to verify if the planned CBM experiment at the FAIR facility is fit to do studies on open charm and charmonium production, it is of great importance to have reliable estimates on the production cross sections of these states.

To this aim we will show how the transport model UrQMD is extended to investigate near and sub-threshold strangeness and charm production.

2. The UrQMD model

In this work we employ the newest version of the UrQMD transport model [33, 34]. The UrQMD model is based on the propagation and scattering of hadrons and hadronic resonances. All the hadron properties, i.e. their masses, quantum numbers, widths as well as scattering cross sections are, where known, taken from the particle data book [35]. In recent publications we have presented new features that were implemented and which turned out to be essential for the description of strange particle production below their elementary energy threshold [36, 37]. These processes are the strangeness exchange reactions $Y + \pi \leftrightarrow N + \overline{K}$ as well as new decay channels for the most massive baryonic resonances included in UrQMD.

The direct resonance production cross section, in elementary p+p collisions, implemented in UrQMD follows from a phenomenological parametrization of measured experimental cross sections and phase space considerations. Here the cross section has the general form:

$$\sigma_{1,2\rightarrow 3,4}(\sqrt{s}) \propto (2S_3+1)(2S_4+1)\frac{\langle p_{3,4}\rangle}{\langle p_{1,2}\rangle}\frac{1}{s}\left|M(m_3,m_4)\right|^2 \quad , \tag{1}$$

where S_3 and S_4 are the spin of the outgoing particles, and $\langle p_{i,j}\rangle$ the average momentum of

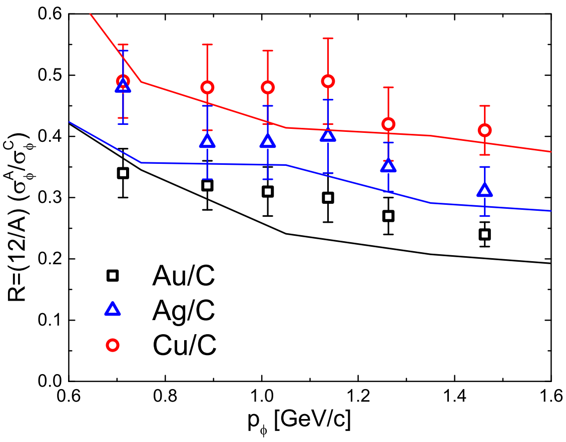

Figure 2. The transparency ratio R calculated within our approach (lines) compared to ANKE data from [38] (symbols).

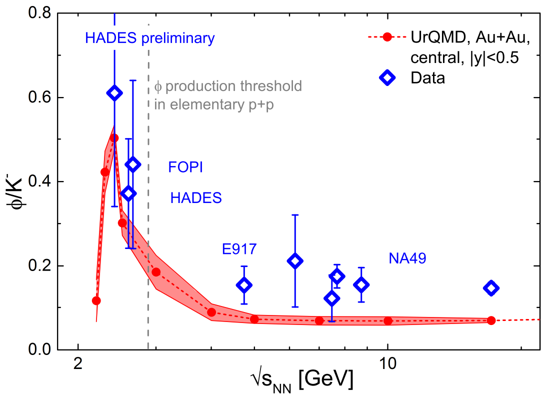

Figure 3. Excitation function of the ϕ/K ratio for central ($b < 5$ fm) Au+Au collisions, calculated with the UrQMD model. Experimental results are shown as symbols [17, 39, 20, 40, 41, 42].

the in- and out-going particles respectively. The matrix element $|M(m_3, m_4)|$ is assumed to not explicitly depend on the spins but only on the masses of the outgoing particles. It is given as:

$$|M(m_3, m_4)|^2 = A\frac{1}{(m_4 - m_3)^2(m_4 + m_3)^2} . \tag{2}$$

The parameter A is determined by a fit to available data and is the same for any specific process, i.e. $N + N \to N + N^*$, for all N^*. The mass dependence of the production cross section is then essentially determined by phase space which has been shown to lead to a good description of measured resonance production cross sections.

It is important to note that in the current version the model does not include any additional medium effects which would change the hadron properties in nuclear collisions and we have not included any hadronic potentials. Thus, we only investigate basic effects like secondary scatterings as well as Fermi momenta on particle production.

3. Strange results

When discussing sub-threshold production of ϕ's in nuclear collisions one should note that there are two distinct mechanisms which allow for the production of hadrons with masses, higher than what is energetically forbidden in elementary reactions: One reason is that in a nucleus, the nucleons acquire Fermi momenta due to their bound state. Because of the Fermi momenta, the actual energy of two colliding nucleons will not be exactly the initial center of mass energy but a smeared out energy distribution. This allows for collisions of nucleons at energies higher than the initial center of mass energy. Furthermore energy can be accumulated due to secondary interactions of already excited states, produced earlier in the collision [43, 44].

To understand the deep sub-threshold production of multi-strange hadrons we will first investigate the production probability of resonance states with sufficiently high mass to decay into a ϕ in collisions of Ca+Ca. Figure 1 shows the calculated invariant mass distributions of N^* baryons produced in Ca+Ca collisions at a fixed target beam energy of $E_{lab} = 1.76$ A GeV [45]. It is clear from this figure that a substantial number of N^* resonances with masses larger than the apparent threshold energy is produced in the nuclear collision. We can utilize the decays of the most massive N^* resonances implemented in UrQMD, namely the $N^* \to N + \phi$

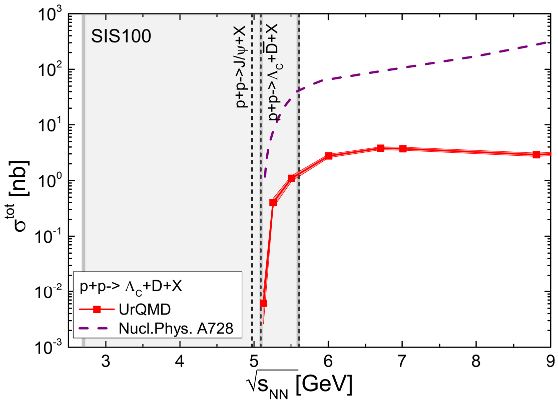

Figure 4. Comparison of the Λ_c cross section in p+p collsions from the UrQMD approach with previous theoretical estimates [46].

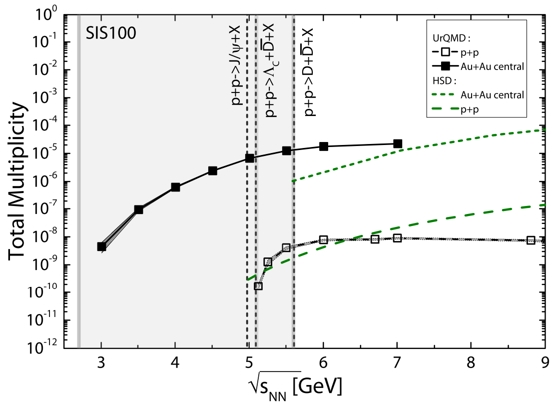

Figure 5. Comparison of the J/Ψ production yield in p+p and central A+A collisions from the UrQMD approach (symbols) with previous theoretical estimates (green short dashed) [47].

channel, in order to describe the production of ϕ mesons near and below their elementary threshold energies [37]. In particular we will use the N^* states with masses larger than 2 GeV, included in the UrQMD model, as their decay channels are experimentally not well constrained and they have a sufficiently large mass. One should note that, by introducing these new decay channels we also naturally, through detailed balance relations, introduce reactions of the kind $M + N \leftrightarrow N^* \leftrightarrow N + \phi$, where M could be any meson that couples to the N^* (e.g. η, ω, ρ or π). We are also able to describe ϕ absorption in cold nuclear matter, within our approach, as shown in figure 2, without the inclusion of an addition in-medium broadening of the ϕ.

Using ANKE data on near threshold ϕ production in $p + p$ collisions [48] we find, that a branching fraction of $\frac{\Gamma_{N+\phi}}{\Gamma_{\text{tot}}} = 0.2\%$, for all the above mentioned N^* resonances, provides a very good description of the measured ϕ production cross section.

A ratio which has shown an interesting beam energy dependence, especially below the ϕ production threshold is the ϕ/K^- ratio, which is shown in figure 3 for nuclear collisions at different beam energies, measured by several experiments [17, 39, 20, 40, 41, 42]. Results from our simulations for most central ($b < 3.4$ fm) Au+Au collisions are shown as the red line.

From the comparison in figure 3, it is clearly visible that the qualitative and quantitative behavior of the data, a rapid increase of the ϕ/K^- ratio for sub-threshold energies, is nicely reproduced in our simulations. Also the value of the ratio is in nice agreement with the HADES Ar+KCl data with $E_{\text{lab}} = 1.76$ A GeV as well as the FOPI results for Ni+Ni collisions at 1.91 A GeV. An interesting feature of the calculations is the peak in the ratio at a beam energy of approximately 1.2 A GeV. The experimental confirmation of this peak, by ϕ measurements at even lower than the current beam energies, would further support our approach for ϕ production in nuclear collisions.
However, we also observe that above the low SPS energy regime the present model underpredicts the ϕ/K^- ratio. This can be understood as a result of the above mentioned high threshold for ϕ production in the string break-up. Because string excitation dominate the particle production at beam energies above $\sqrt{s_{NN}} > 5$ GeV, the ϕ must always be produced together with a Kaon-Antikaon pair, which strongly suppresses the ϕ production.

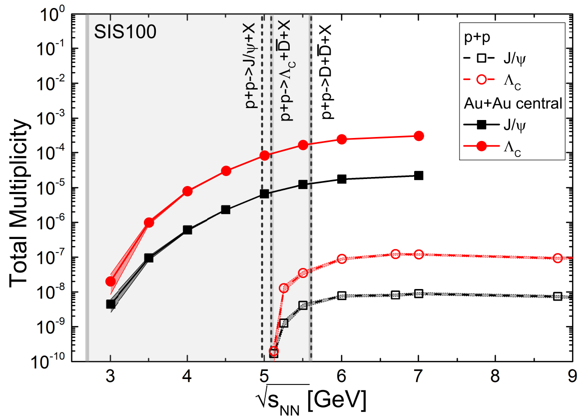

Figure 6. Production yields of J/Ψ and Λ_C in p+p and central Au+Au reactions as a function of the collision energy. The threshold energies of the corresponding channels in p+p reactions are again indicated as vertical lines. The grey area corresponds to the beam energy range expected for heavy ion collisions at the SIS100 accelerator.

4. Charming results

In the previous section we have shown that the near and sub-threshold production of strange hadrons can be well descibed by the use of heavy baryonic resonance decays. The resonances essentially serve as energy reservior and likely decay according to phase space dominance. In the following we will estimate also charm sub-threshold productio rates based on the same basic assumptions. Therefore we need to determine the branching fraction of the N* into the relevant charm channels, i.e. we need to determine the probability of N*→ N + J/Ψ and N*→ $\Lambda_c + \overline{D}$.

To fix this crucial input we use the measured J/Ψ cross section in p+p collisions at $\sqrt{s_{pp}} = 6.7$ GeV. The resulting branching fraction, to describe the experimentally measured J/Ψ yield is $\Gamma_{N+J/\Psi}/\Gamma_{tot} = 2.5 \cdot 10^{-5}$. This branching ratio is two orders of magnitude smaller than the corresponding decay into a ϕ meson.

First we can compare the obtained Λ_c and J/Ψ production cross sections with previous near threshold estimates [46, 47], as shown in figures 4 and 5. Our estimates are in reasonable agreement (J/Ψ) or even very conservative estimates (Λ_c) as compared to previous work.

Figure 6 summarizes the results of the sub-threshold charm production in nuclear collisions, obtained with our model [49]. Even at a fixed target beam energy of $E_{\rm lab} = 6$ A GeV we expect a yield of 3×10^{-7} J/Ψ and 4×10^{-6} Λ_c and $\overline{D}$ per central Au+Au event. For the highest available beam energy for heavy nuclei at the SIS100, $E_{\rm lab} = 11$ A GeV, we expect that yield to be one order of magnitude larger. Hence we predict that a significant number of charmed hadrons can be measured at the CBM experiment, already with the SIS100 accelerator in place. This is of particular interest as the baryon number densities achieved at these low beam energies are very large, opening up the possibility to study charm production and propagation in a very dense hadronic environment. Of particular interest here is to understand and quantify the interaction of charmed hadrons with the nuclear environment and possible effects of chiral symmetry restoration of charmed hadron properties.

5. Summary

We have presented a method to describe the near and sub-threshold production of strange and charmed hadrons in a microscopic transport approach. By employing baryonic resonances as energy reservoir we are able to explain the measured beam energy dependence of the ϕ/K^- ratio. For the first time predictions for the sub-threshold production of charmed hadrons in nuclear collisions are presented showing that charm studies are feasible at the SIS100 accelerator planned for FAIR.

6. Acknowledgments

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References

[1] J. Randrup and C. M. Ko, Nucl. Phys. A **343**, 519 (1980) [Erratum-ibid. A **411**, 537 (1983)].
[2] B. Friman *et al.*, Lect. Notes Phys. **814**, 1 (2011).
[3] J. Aichelin and C. M. Ko, Phys. Rev. Lett. **55**, 2661 (1985).
[4] A. Shor *et al.*, Phys. Rev. Lett. **63**, 2192 (1989).
[5] G. Hartnack, L. Sehn, J. Jaenicke, H. Stoecker and J. Aichelin, Nucl. Phys. A **580**, 643 (1994).
[6] X. S. Fang, C. M. Ko, G. Q. Li and Y. M. Zheng, Nucl. Phys. A **575**, 766 (1994)
[7] G. Q. Li, C. M. Ko and X. S. Fang, Phys. Lett. B **329**, 149 (1994).
[8] G. Q. Li and C. M. Ko, Phys. Lett. B **351**, 37 (1995)
[9] U. Mosel, Ann. Rev. Nucl. Part. Sci. **41**, 29 (1991).
[10] D. Miskowiec *et al.*, Phys. Rev. Lett. **72**, 3650 (1994).
[11] W. Cassing, E. L. Bratkovskaya, U. Mosel, S. Teis and A. Sibirtsev, Nucl. Phys. A **614**, 415 (1997)
[12] E. L. Bratkovskaya, W. Cassing and U. Mosel, Nucl. Phys. A **622**, 593 (1997)
[13] C. Hartnack, H. Oeschler and J. Aichelin, Phys. Rev. Lett. **90**, 102302 (2003)
[14] C. Hartnack, H. Oeschler and J. Aichelin, Phys. Rev. Lett. **96**, 012302 (2006)
[15] C. Hartnack, H. Oeschler, Y. Leifels, E. L. Bratkovskaya and J. Aichelin, Phys. Rept. **510**, 119 (2012)
[16] G. Agakishiev *et al.*, Phys. Rev. Lett. **114**, no. 21, 212301 (2015).
[17] G. Agakishiev *et al.* [HADES Collaboration], Phys. Rev. C **80**, 025209 (2009)
[18] G. Agakishiev *et al.* [HADES collaboration], Phys. Rev. Lett. **103**, 132301 (2009)
[19] E. E. Kolomeitsev, B. Tomasik and D. N. Voskresensky, Phys. Rev. C **86**, 054909 (2012)
[20] K. Piasecki *et al.* [FOPI Collaboration], Phys. Rev. C **91**, no. 5, 054904 (2015).
[21] T. Matsui and H. Satz, Phys. Lett. B **178**, 416 (1986).
[22] H. van Hees, M. Mannarelli, V. Greco and R. Rapp, Phys. Rev. Lett. **100**, 192301 (2008)
[23] R. Rapp and H. van Hees, arXiv:0903.1096 [hep-ph].
[24] M. He, R. J. Fries and R. Rapp, arXiv:1204.4442 [nucl-th].
[25] J. Aichelin, P. B. Gossiaux and T. Gousset, Acta Phys. Polon. B **43**, 655 (2012)
[26] J. Uphoff, O. Fochler, Z. Xu and C. Greiner, Phys. Rev. C **84**, 024908 (2011)
[27] J. Uphoff, O. Fochler, Z. Xu and C. Greiner, Phys. Lett. B **717**, 430 (2012)
[28] C. Young, B. Schenke, S. Jeon and C. Gale, Phys. Rev. C **86**, 034905 (2012)
[29] I. Vitev, A. Adil and H. van Hees, J. Phys. **G34**, S769 (2007)
[30] P. B. Gossiaux, J. Aichelin, T. Gousset and V. Guiho, J. Phys. **G37**, 094019 (2010)
[31] P. Gossiaux, J. Aichelin and T. Gousset, Prog. Theor. Phys. Suppl. **193**, 110 (2012)
[32] T. Lang, H. van Hees, J. Steinheimer and M. Bleicher, arXiv:1211.6912 [hep-ph].
[33] S. A. Bass *et al.*, Prog. Part. Nucl. Phys. **41**, 255 (1998) [Prog. Part. Nucl. Phys. **41**, 225 (1998)]
[34] M. Bleicher *et al.*, J. Phys. **G25**, 1859 (1999)
[35] K. A. Olive *et al.* [Particle Data Group Collaboration], Chin. Phys. C **38**, 090001 (2014).
[36] G. Graef, J. Steinheimer, F. Li and M. Bleicher, Phys. Rev. C **90**, 064909 (2014).
[37] J. Steinheimer and M. Bleicher, J. Phys. G **43**, no. 1, 015104 (2016).
[38] M. Hartmann *et al.*, Phys. Rev. C **85**, 035206 (2012)
[39] M. Lorenz [HADES Collaboration], Nucl. Phys. A **931**, 785 (2014).
[40] B. Holzman *et al.* [E917 Collaboration], Nucl. Phys. A **698**, 643 (2002)
[41] S. V. Afanasev *et al.* [NA49 Collaboration], Phys. Lett. B **491**, 59 (2000).
[42] J. Adams *et al.* [STAR Collaboration], Phys. Lett. B **612**, 181 (2005)
[43] C. Spieles, A. Jahns, H. Sorge, H. Stoecker and W. Greiner, Mod. Phys. Lett. A **8**, 2547 (1993).
[44] G. Zeeb, M. Reiter and M. Bleicher, Phys. Lett. B **586**, 297 (2004)
[45] J. Steinheimer, M. Lorenz, F. Becattini, R. Stock and M. Bleicher, Phys. Rev. C **93**, no. 6, 064908 (2016).
[46] W. Liu, C. M. Ko and S. H. Lee, Nucl. Phys. A **728**, 457 (2003)
[47] O. Linnyk, E. L. Bratkovskaya and W. Cassing, Int. J. Mod. Phys. E **17**, 1367 (2008)
[48] Y. Maeda *et al.* [ANKE Collaboration], Phys. Rev. C **77**, 015204 (2008)
[49] J. Steinheimer, A. Botvina and M. Bleicher, arXiv:1605.03439 [nucl-th].