

# Recent results from strangeness in transport models

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**Abstract.** In these proceedings we discuss recent developments in the microscopic description of strange particle production in nuclear collisions. We put a special emphasis on the production of hypernuclei at the upcoming FAIR and NICA facilities as well as the deep sub threshold,  $\phi$  and  $\Xi^-$  production yields measured with the HADES experiment. Employing new resonance decay channels we obtain a satisfactory description of  $\phi$  and  $\Xi^-$  production in deep sub threshold Ar+KCl reactions. Our results implicate that no new medium effects are required to describe the rare strange particle production data from low energy nuclear collisions.

## 1. Introduction

Strange hadrons have long since been considered to be a good probe for the properties of dense hadronic matter [1, 2] created in nuclear collisions. The properties of such hot and dense systems are subject of investigation of running and planned experimental programs at the GSI/FAIR [3], NICA [4] and RHIC facilities. To understand the dynamics in such collisions one usually employs microscopic transport models.

For example, by modifying the medium properties of strange hadrons in a transport study, it was found that the production rates and properties of Kaons are a promising probe to extract their medium interactions in low energy nuclear collisions [2, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16].

Furthermore recent progress has been made in the understanding of strange hadron dynamics at the LHC [17] and RHIC [18] with special attention payed to the role of strange particle dynamics in the hadronic, non-equilibrium, phase of ultra relativistic nuclear collisions [19, 20, 21, 22, 23].

Similarly, the investigation of hypernuclei is a rapidly progressing field of nuclear physics, since these nuclei provide methods to study nuclear interactions in particle physics and nuclear astrophysics (see, e.g., [24, 25, 26, 27, 28] and references therein). Presently, hypernuclear physics is still focused on spectroscopic information and is dominated by a set of reactions induced by high-energy hadrons and leptons leading to the production of only few particles. Many experimental collaborations have started or plan to investigate hypernuclei and their properties in hadron and heavy ion induced reactions.

In the following we will highlight recent results on the formation of hypernuclei in nuclear collisions and explore new mechanisms for the production of the  $\phi$  meson and  $\Xi$  baryons at sub-



threshold energies, in the microscopic transport model UrQMD. These proceedings are based on [47, 34]

## 2. Particle production in UrQMD

Strange hadron production in the UrQMD transport model [29, 30] proceeds through different channels: the excitation and de-excitation (decay) of hadronic resonances, the excitation and de-excitation of a string and the annihilation of a particle with its anti-particle. The probabilities of the different processes are governed by their reaction cross sections. These cross sections serve as input for the model and are, whenever possible, taken from experimental measurements of elementary (binary) collisions. For example the total and inelastic resonance cross sections of binary proton+proton collisions has been measured in many experiments over a wide range of beam energies [31].

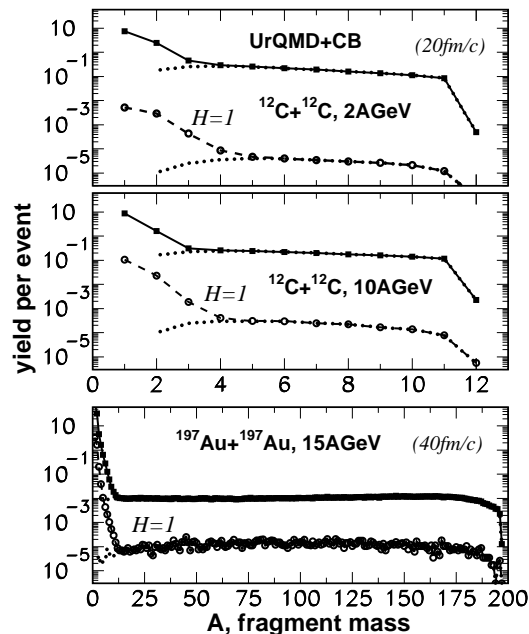
Another important channel for the description of strange particle production in nuclear collisions is the strangeness exchange reaction which can change the flavor content of a hadron. This includes reactions of the type  $N + \bar{K} \leftrightarrow Y + \pi$  as well as  $Y + \bar{K} \leftrightarrow \Xi + \pi$ . Such reactions are included in the UrQMD transport approach however it was shown that they are not sufficient to explain the large  $\Xi/\Lambda$  ratio in Ar+KCl and p+Nb reactions measured with the HADES experiment (see [32] for a detailed discussion).

## 3. Hypernuclei

To study hyperon production in nuclear collisions we apply the Ultra-relativistic Quantum Molecular Dynamics model (UrQMD), described above, and a recently developed, alternative, formulation of the coalescence model, the coalescence of baryons (CB), which is suitable for event by event simulations [33]. Baryons (nucleons and hyperons) can produce a cluster with mass number  $A$  if their velocities relative to the center-of-mass velocity of the cluster is less than  $v_c$ . Accordingly we require  $|\vec{v}_i - \vec{v}_{cm}| < v_c$  for all  $i = 1, \dots, A$ , where  $\vec{v}_{cm} = \frac{1}{E_A} \sum_{i=1}^A \vec{p}_i$  ( $\vec{p}_i$  are momenta and  $E_A$  is the sum energy of the baryons in the cluster). This is performed by sequential comparison of the velocities of all baryons.

The results on the total mass yields of the normal fragments and hyper-fragments (with one bound  $\Lambda$ ) are shown in Fig. 1. The coalescence of baryons (the CB model) was applied on output from UrQMD, for the reactions presented in Fig. 1. The yields are normalized per one inelastic event (More detailed information on the model can be found in [34]). However, one should take into account that only events with at least one hyperon produced are analysed in this case. For this reason there is no characteristic increase of the yield of normal fragments with masses around the projectile/target mass, which are caused by very peripheral collisions. The explanation of this behaviour was already suggested in Ref. [35]; production of hyperons usually requires many particle collisions leading to a considerable emission of fast nucleons from the residues.

One can see that the production of fragments of all sizes is possible. As expected the yield of conventional fragments is by few orders of magnitude higher than the yield of hyper-fragments. Nevertheless, the production of hyper-fragments is sufficient to be experimentally measured (see also [36, 37]). It is a natural result of the coalescence that the yield of the lightest hyper-fragments is dominating. However, the capture of hyperons by residues saturates the yield for large masses and leads to abundant production of heavy hyper-fragments. Within this approach one can clearly see nearly all the normal fragments and hyper-fragments with  $A > 3 - 4$  in the carbon collisions and with  $A > 10$  in the gold collisions originate from the capture of  $\Lambda$  hyperons by spectator residues (dotted lines). As was mentioned, we believe that these hyper-fragments represent excited pieces of hyper-matter whose evolution can be calculated with statistical models [38, 28]. The excitation energy of such primary fragments can also be evaluated from the analysis of experimental data [39, 40, 41, 42]. This demonstrates that big



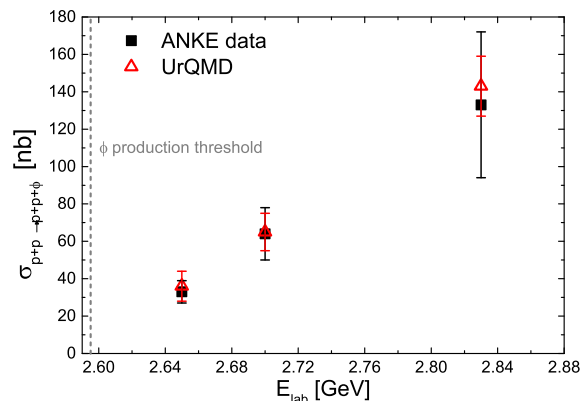
**Figure 1.** Yields (per one inelastic event) of normal fragments (solid lines with squares) and hyper-fragments with one captured  $\Lambda$  (notation  $H=1$ , dashed lines with circles) versus their mass number ( $A$ ) in reactions induced by carbon and gold collisions. The dotted lines present the corresponding fragments originated from the spectator residues. The calculations are performed within the hybrid UrQMD plus CB model, with the coalescence parameter  $v_c = 0.22c$ , and integration over all impact parameters. The projectile lab energies and the transition times from UrQMD to CB are shown in panels.

hyper-fragments are mostly produced from the spectator residues, while the light ones can be formed at all rapidities. We expect that some large species of hypermatter will be excited and decay as in usual fragmentation and multifragmentation reactions. Such a mechanism should allow the investigation of possible phase transitions in hypermatter with statistical models describing the secondary disintegration. The significant production yields at beam energies higher than 5–10 GeV per nucleon open up the possibility to study hypernuclei at GSI/FAIR (Darmstadt), Nuclotron/NICA (Dubna), RHIC (Brookhaven), HIAF (Lanzhou) and other heavy-ion accelerators of moderate relativistic energies.

#### 4. Deep sub threshold $\phi$ and $\Xi$ production

When discussing sub-threshold production of  $\phi$ 's and  $\Xi$ 's in nuclear collisions, one should note that, apart from in-medium modifications of hadron properties (see e.g. recent results in [43] and references therein), there are two distinct mechanisms, which allow for the production of hadrons with masses higher than what would be energetically forbidden in elementary reactions:

- (i) One is the fact, that in a nucleus, the nucleons acquire a Fermi momentum due to their bound state. This allows for collisions of nucleons at energies higher than the actual beam energy.
- (ii) Furthermore, energy can be accumulated due to secondary interactions of already excited



**Figure 2.** Total production cross section of the  $\phi$  meson in p+p reactions near the  $\phi$  production threshold. We compare experimental data from [46] with UrQMD results including the  $\phi$  decay of the  $N^*$  resonances.

states, produced earlier in the collision [44, 45].

From this one can conclude that a moderate amount of excited states with sufficiently high mass are available that may produce  $\phi$  mesons as well as  $\Xi$  baryons. In the following, we will show how decays of the most massive  $N^*$  resonances implemented in UrQMD, namely the  $N^* \rightarrow N + \phi$  and  $N^* \rightarrow \Xi + K + K$  channels, can be used to describe the production of  $\phi$  and  $\Xi$  particles near and below their elementary threshold energies (more details on the method and results is given in [47]).

To determine the probability that a heavy baryonic resonance state decays into the specific final states introduced above, one can use recently published ANKE data on the cross section of single  $\phi$  production in near threshold p+p collisions [46]. These cross sections are shown in figure 2 as black squares. Using these, we find that a (constant) branching fraction of  $\frac{\Gamma_{N+\phi}}{\Gamma_{\text{tot}}} = 0.2\%$ , for all the above mentioned  $N^*$  resonances, provides a very good description (red triangles) of the measured  $\phi$  production cross section.

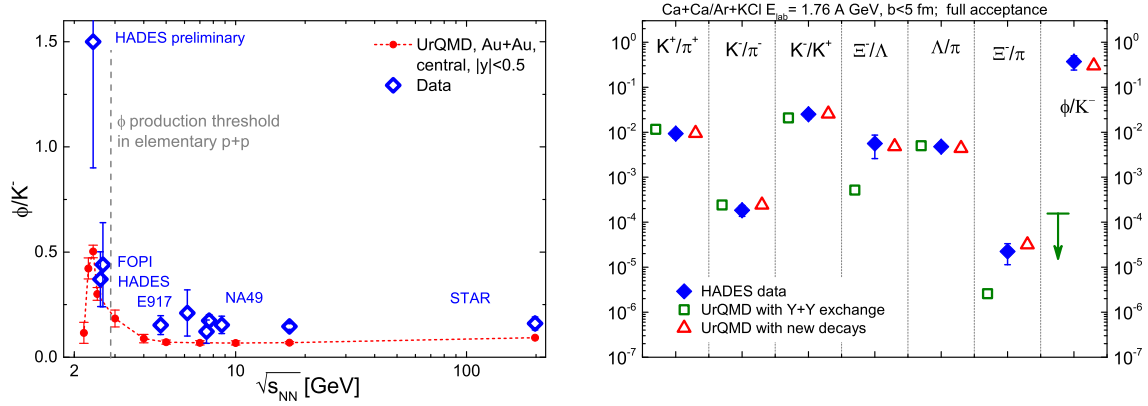
Determining a similar branching fraction of  $N^* \rightarrow \Xi + K + K$  is not as straight forward as it is with the  $\phi$  decay. There exists no experimental data on  $\Xi$  production in elementary collisions near its production threshold. Using the new HADES data on  $\Xi$  production in p+Nb reactions as a proxy for the unavailable elementary collision data to fix the  $N^* \rightarrow \Xi + K + K$  branching fraction, one obtains a branching  $\frac{\Gamma_{\Xi+K+K}}{\Gamma_{\text{tot}}} = 10\%$  for all  $N^*$  states mentioned above that have a sufficiently high mass for this decay. A branching fraction of 10% appears to be large; however, one should keep in mind that this branching fraction applies only in the high mass tails of the resonances and the integrated fraction is less than one percent. Table 1 summarizes the results for  $\Xi^-$  production in p+Nb at  $E_{\text{lab}} = 3.5$  GeV, measured with the HADES experiment, as well as results from the simulations.

A ratio which has shown an interesting beam energy dependence, especially below the  $\phi$  production threshold, is the  $\phi/K^-$  ratio, which is depicted in figure 3 for nuclear collisions at different beam energies, measured by several experiments [49, 50, 51, 52, 53, 54]. Results from simulations, including the new branching fractions, 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 behavior of the data, a rapid increase of the  $\phi/K^-$  ratio for sub-threshold energies, is nicely reproduced by the new process. Also the value of the ratio is in agreement for beam energies at and above 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

| HADES data                             |  |
|--|--|
| $\langle \Xi^- \rangle$                | $\Xi^-/\Lambda$                        |
| $(2.0 \pm 0.3 \pm 0.4) \times 10^{-4}$ | $(1.2 \pm 0.3 \pm 0.4) \times 10^{-2}$ |
| UrQMD                                  |  |
| $\langle \Xi^- \rangle$                | $\Xi^-/\Lambda$                        |
| $(1.44 \pm 0.05) \times 10^{-4}$       | $(0.71 \pm 0.03) \times 10^{-2}$       |

**Table 1.**  $\Xi^-$  production yield and  $\Xi^-/\Lambda$  ratio for minimum bias  $p + Nb$  collision at a beam energy of  $E_{\text{lab}} = 3.5$  GeV, compared with recent HADES results [48]



**Figure 3.** Left: Excitation function of the  $\phi/K$  ratio for central ( $b < 5$  fm) Au+Au collisions, calculated with the UrQMD model including the new  $N^*$  decays (red line). Experimental results from different beam energies and systems are shown as symbols [49, 50, 51, 52, 53, 54]. Right: Different strange particle ratios from the UrQMD model in its default settings (green squares), compared to our results including the new  $N^*$  decays (red triangles). We compare the simulations for Ca+Ca at  $E_{\text{lab}} = 1.76$  A GeV and  $b < 5$  fm with published HADES data [55, 56, 49, 57] for Ar+KCl collisions at the same beam energy (blue diamonds).

A GeV. However, one also observes that above the low SPS energy regime the present model underpredicts the  $\phi/K^-$  ratio. This can be understood as a result of the high threshold for  $\phi$  production in the string break-up. Because string excitation dominate the particle production at beam energies above  $\sqrt{s_{NN}} > 5$  GeV, the  $\phi$  must always be produced together with a Kaon-Antikaon pair, which strongly suppresses the  $\phi$  production.

Finally, one can compare the multitude of strange particles produced in UrQMD, including the new  $N^*$  decays, with sub-threshold nuclear collision data. Figure 3 shows results on strange particle ratios, in Ca+Ca collisions at  $E_{\text{lab}} = 1.76$  A GeV from the UrQMD model. The default calculation with the previously released UrQMD version (v3.4) is shown as green squares. Compared to the default calculation the new results, including the  $\phi$  and  $\Xi$  decay channels of the  $N^*$  are depicted as red triangles. A considerable increase in the  $\phi$  and  $\Xi^-$  production is visible. More importantly, when compared to data from the HADES experiment (blue diamonds), one observes a very good description of all measured ratios, including the  $\phi$  and  $\Xi$ . Such a good description of the full set of data has not been achieved in any previous study. Hence, we conclude that strange particle production in Ar+KCl collisions at the HADES experiment can be explained, and is in fully consistent, with production cross sections obtained in elementary reactions.

## 5. Nuclear absorption of the $\phi$

An important aspect of  $\phi$  production in nuclear collisions is the possibility of medium modifications of the  $\phi$  meson. An interesting observable in this context is the so-called nuclear transparency, which measures the suppression (absorption) of  $\phi$  meson production on nuclear targets of increasing mass number. It is thought to be sensitive on the  $\phi + N$  absorption cross section in a nuclear medium and should give constraints on in-medium models of hadronic interactions. First experiments measured the  $\phi$  absorption in photo-production reactions at the CLAS and LEPS-SPring8 experiments [58, 59] to be of the order of 35 mb. A rather large  $\phi + N$  absorption cross section of 14-21 mb was also inferred from hadronic production at the ANKE experiment [60]. These numbers were extracted using certain assumptions. For example the LEPS-SPring8 results used a Glauber model analysis and assumed that the  $\phi$  is essentially produced instantaneously, while the ANKE analysis relied on comparisons to different models which may or may not be valid descriptions.

Using the same parameters for the  $\phi$  production by resonance as used in the previous section one can calculate the momentum dependent  $\phi$  production cross section in different  $p+A$  collisions at a beam energy of  $E_{\text{lab}} = 2.83$  GeV and within the ANKE acceptance. The transparency ratio  $R$ ,

$$R = \frac{12 \sigma_{\phi}^A}{A \sigma_{\phi}^C}, \quad (1)$$

obtained with UrQMD, which is essentially the scaled ratio of the  $\phi$  production cross section on different size nuclear targets, is compared to ANKE data in figure 4. Again the ratio  $R$  is well described by the model, which does not include any explicit medium modification of the  $\phi$ . The explanation of the strong suppression of the  $\phi$  meson production in the resonance approach cannot be a large inelastic  $\phi + N$  cross section (which is of the order of  $< 1$  mb while the elastic cross section is set to 5 mb). Because the  $\phi$  is hardly absorbed (in our model) in the nuclear medium, it is in fact the heavy mother resonance of the  $\phi$  which rescatters with another nucleon before it can decay into  $N + \phi$ . During this inelastic rescattering, the resonance is likely to create one or two other resonances, however with smaller masses, which then are unable to decay into a  $\phi$ , effectively suppressing the  $\phi$  production probability in a nuclear environment. The same processes can also be responsible for the apparently large  $\phi$  cross section measured in the LEPS-SPring8 experiment.

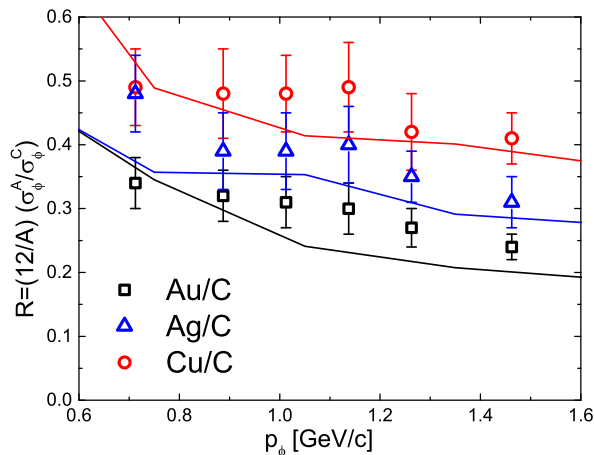
## 6. Summary

Important progress has been made in the description of strange hadron dynamics in nuclear collisions. It was found that relativistic heavy-ion reactions are a very promising source of hyper-matter and hyper-fragments. A large amount of hypernuclei of all masses can be produced. Their properties can be investigated taking into account the advantages of relativistic velocities, e.g., for the life-time and correlation measurements.

Furthermore, a new mechanism for  $\phi$  and  $\Xi$  production in elementary and nuclear collisions, namely the decay of heavy resonances, has been proposed. For the  $\phi$  production, the unknown branching ratios of the baryon resonances were extracted from  $p + p \rightarrow p + p + \phi$  data measured by ANKE. The branching fraction necessary to describe the data is of the order of 0.2%.

The same approach to  $\phi$  production is able to describe the nuclear transparency ratio measured in proton induced reactions at the ANKE experiment, without the inclusion of any additional in-medium effects and only a very small inelastic  $\phi + p$  cross section. The large  $\phi + p$  cross sections, extracted from the LEPS-SPring8 and ANKE experiments, might therefore just be an artifact of not taking into account the  $\phi$  production processes.

For the  $\Xi^-$  production the branching ratios of the heavy baryon resonances were extracted



**Figure 4.** The transparency ratio  $R$  calculated within our approach (lines) compared to ANKE data from [60] (symbols).

from p+Nb data of the HADES collaboration. Here, a larger branching fraction of 10% for  $R^* \rightarrow \Xi + K + K$  is required. With this input from elementary reactions, a good description of the HADES Ar+KCl data is achieved.

Consequently, these results highlight the importance of resonance physics and dynamics in elementary and nuclear collisions in the energy regime of the GSI/FAIR, NICA and BESII accelerator programmes. Rare probes, like the multi-strange hadrons and hypernuclei, discussed in this paper can be very sensitive to unknown resonance states and their properties. Therefore, if any conclusions on new physics are to be drawn from measuring such rare probes, it is necessary to have a detailed understanding of the hadronic resonances and their dynamics in nuclear collisions.

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