Sub-threshold $\phi$ and $\Xi^-$ production by high mass resonances with UrQMD

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We present a possible explanation for the deep sub-threshold, $\phi$ and $\Xi^-$ production yields measured with the HADES experiment in $\text{Ar}+\text{KCl}$ reactions at $E_{\text{lab}} = 1.76$ A GeV and present predictions for $\text{Au}+\text{Au}$ reactions at $E_{\text{lab}} = 1.23$ A GeV. To explain the surprisingly high yields of $\phi$ and $\Xi^-$ hadrons we propose new decay channels for high mass baryon resonances. These new decay channels are constrained by elementary $p+p\rightarrow p+p+\phi$ cross sections, and $\Xi^-$ production in $p+\text{Nb}$. Based on the fits to the elementary reactions one obtains a satisfactorily description of $\phi$ and $\Xi^-$ production in deep sub-threshold $\text{Ar}+\text{KCl}$ reactions. The results implicate that no new medium effects are required to describe the rare strange particle production data in low energy nuclear collisions.

I. INTRODUCTION

The study of strange hadrons in nuclear collisions has since long been considered to be a good probe for the properties of dense hadronic matter. However, when strange hadrons are to be studied in nuclear collisions in particular at low beam energies, i.e. $\sqrt{s_{NN}} < 5$ GeV, it is necessary to study strange hadrons in inelastic exclusive channels. Strange hadrons are of great interest since they are a good probe of the medium effects in low energy nuclear collisions. In nuclear collisions, strange hadrons are produced via strangeness violation processes, which are possible mechanisms of particle production in UrQMD. The probabilities for these decays can be used to describe elementary production cross sections of strange hadrons.

Hadron production in the UrQMD transport model 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. Strange hadrons exchange processes, which can change the flavor content of a hadron are also included. 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 cross section of binary proton-proton collisions has been measured in many ex-
periments over a wide range of beam energies \cite{33} (see green circles and black squares in figure [1]). The corresponding green and black lines in fig. [1] serve as input for model. The difference between the total and elastic cross section therefore should correspond to the inelastic cross section. Here again, many different reactions are possible. In UrQMD the inelastic part of the nucleon-nucleon cross section (up to a certain energy) is described by resonance production channels. The possible channels of resonance excitations are divided into several classes:

1. $NN \rightarrow N\Delta_{1232}$
2. $NN \rightarrow NN^*$
3. $NN \rightarrow N\Delta^*$
4. $NN \rightarrow \Delta_{1232}\Delta_{1232}$
5. $NN \rightarrow \Delta_{1232}N^*$
6. $NN \rightarrow \Delta_{1232}\Delta^*$
7. $NN \rightarrow R^+R^*$

Here $R^*$ could be any excited $N^*$ or $\Delta$ state. Since a large part of the channels are not known, or only measured within a limited energy interval one uses an effective parametrization of the different cross sections:

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

where $\langle p_{i,j} \rangle$ is the average momentum of the in- and outgoing particles and $S_i$ are the spins of the outgoing particles. The matrix element $|M(m_3, m_4)|^2$ is usually not known for all reactions but can be parametrized to fit experimental measurements, if available. A detailed description on how the elementary cross sections of processes 1 to 6 can be parametrized as well as comparisons with data is shown in detail in \cite{30, 31}. The process $NN \rightarrow R^+R^*$ has just recently been introduced into the model with:

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

The parameter $A = 0.05$ was chosen such that the double resonance excitation is consistent with the total and inelastic (total-elastic) part of the p+p cross section. The contribution of double resonance excitation to the p+p cross section is depicted as the blue short-dashed line in figure [1].

However, at some center-of-mass energy resonance excitation becomes unable to describe the inelastic cross section measured in experiment. This increasing difference between the resonance channels and the inelastic cross section is filled with the string excitation channel, which is also shown in figure [1] as dashed grey line. One can see that the string channel starts to dominate particle production at beam energies above 7 to 10 GeV. Since we are interested in near and sub-threshold particle production the string channel is not relevant for most of the following results, whereas the resonance channels are essential for an understanding of the beam energies we will consider.

III. ON THE POSSIBILITY OF $\phi$ AND $\Xi$ PRODUCTION

When discussing sub-threshold production of $\phi$'s and $\Xi$'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 would be energetically forbidden in elementary reactions:

1. One is the fact that in a nucleus, the nucleons acquire a Fermi momentum due to their bound state. Because of the Fermi momenta, the actual energy of two colliding nucleons will not be exactly the beam energy but a smeared out energy distribution. This allows for collisions of nucleons at energies higher than the actual beam energy.

2. Furthermore energy can be accumulated due to secondary interactions of already excited states, produced earlier in the collision \cite{34, 35}.

As an example for deep sub-threshold production of multi-strange hadrons we will first investigate the production probability of resonance states with sufficiently high mass to produce a $\phi$ or $\Xi$ in collisions of Ca+Ca (corresponding to the Ar+KCl collisions studied at the
of initial collisions has sufficient energy to produce a Ξ. Even though a small fraction of events with primary momenta alone, about two percent of all primary N + N collisions will have an invariant mass large enough to excitation because in the string picture a K + is created together with a N. In nuclear collisions, we also indicate, as we will use the N*(1990), N*(2080), N*(2190), N*(2220) and N*(2250) states 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 \( M + N \rightarrow N^* \rightarrow N + \rho \), where \( M \) could be any meson that couples to the \( N^* \) (e.g. \( \eta, \omega, \rho \) or \( \pi \)). Such channels have been discussed in [36] as possible source of \( \phi \) mesons in nuclear collisions. In [36], however, the authors determined the relevant cross sections from theoretical models and found that such processes cannot fully account for the measured \( \phi \) yield. Here we take a different approach and extract the cross sections directly from the comparison with experimental data, i.e. the resonance production in p+p reactions. This has the advantage that we do not have to rely on the validity of certain model assumptions, while on the other hand we can not predict the \( \phi \) meson production in elementary reactions from fundamental calculations.

IV. ELEMENTARY REACTIONS

As a next step we need to determine the probability that a heavy baryonic resonance state decays into the specific final states introduced above. Fortunately the ANKE experiment has recently published a set of data on the cross section of single \( \phi \) production in near threshold p + p collisions [37]. These cross sections are shown in figure 3 as black squares. Using these data we find, that a branching fraction of \( \frac{\Gamma_{N^*\phi}}{\Gamma_{tot}} = 0.2\% \), for all the above mentioned \( N^* \) resonances, provides a very good description (red triangles) of the measured \( \phi \) production cross section. Note that we only fit one parameter, the branching fraction, to obtain a description of the data.
TABLE I. Ξ⁻ production yield and Ξ⁻/Λ ratio for minimum bias p + Nb collision at a beam energy of $E_{\text{lab}} = 3.5$ GeV, compared with recent HADES results [25].

|            | Ξ⁻ | Ξ⁻/Λ |
|------------|-----|------|
| HADES      | (2.0 ± 0.3 ± 0.4) × 10⁻⁴ | (1.2 ± 0.3 ± 0.4) × 10⁻² |
| UrQMD      | (1.44 ± 0.05) × 10⁻¹ | (0.71 ± 0.03) × 10⁻² |

for all three measured beam energies.

One should further note that the extracted branching fraction of 0.2% is roughly two orders of magnitude smaller than that of other channels like the $N^* \to N + \omega$ decay and therefore compatible with the OZI supression factor experimentally extracted from the $\phi/\omega$ production ratio in $p + p$ collisions [35].

Determining a similar branching fraction of $N^* \to \Xi + K + K$ is not as straight forward as it is with the $\phi$ decay. First one should note that the pole masses of all $N^*$ resonances in UrQMD are below the threshold for this decay channel (2.3 GeV) and therefore the branching fraction will only be non-zero in the high mass tails of the resonances. Secondly there exists no experimental data on $\Xi$ production in elementary collisions near its production threshold. Therefore we use the new HADES data on $\Xi$ production in p+Nb reactions as a proxy for the unavailable elementary collision data to fix the $N^* \to \Xi + K + K$ branching fraction, as it is the dataset closest to an elementary reaction. To describe the measured production yield of $\Xi^-$'s (see table) we obtain a branching fraction $\frac{\Gamma_{\Xi \to \Xi + K + K}}{\Gamma_{\Xi}} = 10\%$ 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. Furthermore one expects that even higher mass resonances, not implemented in the model, do contribute stronger to the $\Xi$ production and one can think of this large branching fraction as the effective summed-up contribution of these high mass resonances. Table summarizes the results for $\Xi^-$ production in p + Nb at $E_{\text{lab}} = 3.5$ GeV, measured with the HADES experiment as well as the results from our simulations.

V. SUB-THRESHOLD $\phi$ AND $\Xi$ PRODUCTION IN NUCLEAR COLLISIONS

Having constrained the branching fractions in the previous section, we employ this new mechanism to estimate the production probabilities of $\phi$'s and $\Xi$'s in nuclear collisions, particularly at sub-threshold energies. A ratio which has shown an interesting beam energy dependence, especially below the $\phi$ production threshold is the $\phi/K^-$ ratio, which is shown in figure for nuclear collisions at different beam energies, measured by several experiments [26, 33, 12]. Results from our simulations for most central ($b < 3.4$ fm) Au+Au collisions are shown as the red line. Because the $\phi$ is an unstable particle it will never be directly measured in an experiment and therefore it is important to clarify how we define a measurable $\phi$ in our model simulation. We define a measurable $\phi$, for all the following results, as a $\phi$ which has decayed into a Kaon-Antikaon pair and whose decay partners have not rescattered. With rescattering we strictly mean no elastic or inelastic scattering of the decay products, noting that there can be a small fraction of $\phi$'s which can be reconstructed even though their decay daughter had an inelastic scattering. However, we expect this correction to be on the order of a few percent.

From the comparison in figure 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 in our simulations. Also the value of the ratio is in nice agreement for beam energies at and above the HADES Ar+KCl data with $E_{\text{lab}} = 1.76$ A GeV. However, one also observes that above the the low SPS energy regime the present model underpredicts the $\phi/K^-$ ratio. This can be understood as a result of the above mentioned 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.

We also seem to underpredict the measured $\phi/K^-$ ratio for the lowest available beam energy of $E_{\text{lab}} = 1.23$ GeV.
A GeV, which is however still a preliminary result from the HADES collaboration. An interesting feature of the calculations is the peak in the ratio at the aforementioned beam energy. The experimental confirmation of this peak, by \( \phi \) measurements at even lower beam energies, would further support our approach for \( \phi \) production in nuclear collisions.

Finally we compare the multitude of strange particles produced in UrQMD, including the new \( N^* \) decays, with sub-threshold nuclear collision data. In figure 5 we present results on strange particle ratios, in Ca+Ca collisions at \( E_{\text{lab}} = 1.76 \) A GeV. The default calculation with the previously released UrQMD version (v3.4) is shown as green squares. Compared to the default calculation we show the new results, including the \( \phi \) and \( \Xi \) decay channels of the \( N^* \) as red triangles. A considerable increase in the \( \phi \) and \( \Xi^- \) production is visible. More importantly when we compare all the obtained strange particle ratios with Ar+KCl data from the HADES experiment (blue diamonds) we observe 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 previous work. 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.

In figure 5 we present predictions for the same strange particle ratios shown in figure 5 in Au+Au reactions at 1.23 A GeV with the new \( \phi \) and \( \Xi \) production. The red triangles indicate the ratios for Ca+Ca collisions already shown in figure 5 for comparison, while the black triangles are the predictions for Au+Au collisions at an beam energy of \( E_{\text{lab}} = 1.23 \) A GeV and \( b = 9.5 \) fm. Collisions at this energy have been recently investigated at the HADES experiment. Up to now only preliminary data is available for few particle ratios, shown as blue diamonds. Apparently the preliminary \( \phi/K^- \) ratio seems to indicate a small difference between data and our model study. It will be very interesting to see whether this holds for the final data and whether a similar difference will also be seen for the \( \Xi^-/\Lambda \) ratio.

VI. CONCLUSION

In summary we have proposed and investigated a new mechanism for \( \phi \) and \( \Xi \) production in elementary and nuclear collisions, namely the decay of heavy resonances. 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 \( 0.2\% \), in accordance with an OZI suppression of \( \phi \) production.

For the \( \Xi^- \) production the branching ratios of the heavy baryon resonances were extracted from \( p+\text{Nb} \) 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 \( \text{Ar+KCl} \) data is achieved. Such a large branching fraction appears unlikely, however one should keep in mind that the invariant mass required for the decay of \( N^* \rightarrow \Xi + K + K \) is on the order of \( 2.3 \) GeV, larger than the pole mass of any \( N^* \) included in UrQMD. Therefore only resonances from the high mass tails may decay into a \( \Xi \). Including resonances with pole mass...
larger than 2.3 GeV in the model may therefore change the picture quantitatively.

In the future we intend to investigate the role of such higher mass resonances on particle production in elementary and nuclear collisions, with UrQMD. An important input for such a study would be measurements of $\Xi$ production rates in near threshold elementary collisions, giving direct constraints on heavy resonance production and decays. Consequently our study highlights the importance of resonance physics and dynamics in elementary and nuclear collisions in the energy regime of the SIS18 and the future SIS100 accelerator. Rare probes, like the multi-strange hadrons 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.

VII. ACKNOWLEDGMENTS

We would like to thank Manuel Lorenz, Tetyana Galatyuk and Christian Wendisch from the HADES collaboration for their help with the experimental data. This work was supported by GSI and the Hessian initiative for excellence (LOEWE) through the Helmholtz International Center for FAIR (HIC for FAIR). The computational resources were provided by the LOEWE Frankfurt Center for Scientific Computing (LOEWE-CSC).

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