New developments in heavy ion theory:

Subthreshold charm and strangeness production at GSI/FAIR energies

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What is sub-threshold particle production?

And why is it interesting for us?
Production of hadrons below threshold

• In elementary reactions, e.g. $pp$, it is not possible to produce a particle with mass $m_{\text{new}}$, if $m_P + m_P + m_{\text{new}} > E_{\text{CM,pp}}$ (energy conservation)

• However, in $p+A$ and $A+A$ reaction this is possible

• The question is, what mechanism allows for the production and are they realized
Mechanisms

• Generally three different mechanisms are available:
  
  1) Fermi motion
     (more energy available than we thought)
  
  2) mass reduction/potentials
     (lowers the threshold for production)
  
  3) multi-step/multi-particle processes
     (collect energy to reach the threshold)
This talk...

• Explores multi-strange particle production
  i.e. $\phi$ and $\Xi$ production
  $\rightarrow$ solves a long standing puzzle at GSI energies

• Explores charm production
  i.e. $J/\Psi$, Lc and D-mesons
  $\rightarrow$ new road for a charm program at FAIR
Motivation: \( \phi \)

Recent measurements on near and below threshold production. HADES and FOPI reported unexpected large contribution to the \( K^- \) yield.

\[ \phi \text{ production} \]

HADES and FOPI reported unexpected large \( \phi \) contribution to the \( K^- \) yield.

Motivation: $\Xi$

$\phi$ production

HADES and FOPI reported unexpected large $\phi$ contribution to the $K^-$ yield.

$\Xi^-$ production

$\Xi^-$ yield, measured in Ar+KCl much larger than thermal model.
Confirmed in p+Nb $\rightarrow$ No Y+Y exchange!!

Both particles are not well described in microscopic transport models and thermal fits are also not convincing.

Threshold for $p+p \rightarrow p+p+\phi \approx 2.895$ GeV
Threshold for $p+p \rightarrow N+\Xi+K+K \approx 3.24$ GeV
Probabilities

Sub-threshold production baseline

- Fermi momenta lift the collision energy above the threshold.
- Secondary interactions accumulate energy.

Why not introduce these decays for the less known resonances?
New resonances

Important: New resonances replace the strings, no additional pp cross section is introduced
We use ANKE data on the $\phi$ production cross section to fix the $N^* \rightarrow N + \phi$ branching fraction.

Cross sections

Detailed balance → absorption cross section

\[
\frac{d\sigma_{b\rightarrow a}}{d\Omega} = \frac{\langle p_a^2 \rangle (2S_1 + 1)(2S_2 + 1)}{\langle p_b^2 \rangle (2S_3 + 1)(2S_4 + 1)} \sum_{J=J_-}^{J_+} \frac{\langle j_1 m_1 j_2 m_2 | J M \rangle^2}{\langle j_3 m_3 j_4 m_4 | J M \rangle^2} \frac{d\sigma_{a\rightarrow b}}{d\Omega}
\]

- \( \phi + p \) cross section from detailed balance is very small.
Detailed balance → absorption cross section

\[
\frac{d\sigma_{b\rightarrow a}}{d\Omega} = \frac{\langle p_a^2 \rangle (2S_1 + 1)(2S_2 + 1)}{\langle p_b^2 \rangle (2S_3 + 1)(2S_4 + 1)} \sum_{J=J_-}^{J_+} \frac{\langle j_1 m_1 j_2 m_2 \mid J M \rangle^2}{\langle j_3 m_3 j_4 m_4 \mid J M \rangle^2} \frac{d\sigma_{a\rightarrow b}}{d\Omega}
\]

- $\phi + p$ cross section from detailed balance is very small.
- Still the transparency ratio is well reproduced. Remember: this is what lead to the 20 mb cross section from ANKE.
- Cross section from transparency ratio is model dependent!
When applied to nuclear collisions:

- Qualitative behavior nicely reproduced
- Predicted maximum at 1.25 A GeV
- High energies: too low due to string production
- HADES preliminary results for 1.23 A GeV, see HADES talks by R. Holzmann and T. Scheib.

Even centrality dependence is very well reproduced: Signal for multi step processes.
Centrality

Even centrality dependence works well:

- Centrality dependence nicely reproduced.
- Good indicator for multi step production.

Data from: K. Piasecki et al., arXiv:1602.04378 [nucl-ex].
Plain Kaon yields

Good description of the Kaon data
Comparison to other model studies

The $K^-/K^+$ ratio is used to determine the Kaon nuclear potentials.
Quantitative result relies on the baseline of non-potential case.
$\phi$ contribution to the $K^-$ found to be important.

A word on the K potential

Kaon Potentials

- To constrain the Kaon potentials from kaon spectra one needs to understand the baseline.
- For example the $\phi$ contribution to the $K^-$. But also the general shape of the spectra may depend on the model.

UrQMD results

- $K^-/K^+$ ratio as function of Kaon energy.
- With and without the $\phi$ the ratio is much closer to the data already as in a comparable study with $K^-$ potential.
- Can we make robust quantitative statements?
Now for the $\Xi$.

No elementary measurements near threshold.
We use $p+\text{Nb}$ at $E_{\text{lab}} = 3.5$ GeV data \( \rightarrow \Gamma_{N^*\rightarrow \Xi+K+K}/\Gamma_{\text{tot}} = 3.0\% \)

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<thead>
<tr>
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<th>HADES data</th>
<th>UrQMD</th>
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<tbody>
<tr>
<td>$\langle \Xi^- \rangle$</td>
<td>$(2.0 \pm 0.3 \pm 0.4) \times 10^{-4}$</td>
<td>$(1.44 \pm 0.05) \times 10^{-4}$</td>
</tr>
<tr>
<td>$\Xi^-/\Lambda$</td>
<td>$(1.2 \pm 0.3 \pm 0.4) \times 10^{-2}$</td>
<td>$(0.71 \pm 0.03) \times 10^{-2}$</td>
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Table: $\Xi^-$ production yield and $\Xi^-/\Lambda$ ratio for minimum bias $p + \text{Nb}$ collision at a beam energy of $E_{\text{lab}} = 3.5$ GeV, compared with recent HADES results

Comparison to data for $\Xi$

- $\Xi^-$ yield in Ar+KCl collisions is nicely reproduced.
- Consistent with the p+Nb data.
- Indication for $\Xi$ production from non-thermal 'tails' of particle production.
- All other strange particle ratios are also in line with experiment.
Can we also use this for charm?

... Bold..., but possible...

Fixing the branching ratio

We use data from p+p at $\sqrt{s} = 6.7$ GeV to fix the $N^* \rightarrow N + J/\Psi$ branching fraction.

**Assumptions**

- We assume the associated production of $N^* \rightarrow \Lambda_c + \bar{D}$ to be a factor 15 larger at that beam energy and to contribute about half of the total charm production.
- We neglect $D + \bar{D}$ pair production as it has a significantly higher threshold.
- We neglect string production.
- All the contributions should even increase the expected yield.

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**Only 1 parameter**

$$\frac{\Gamma_{N^* \rightarrow N J/\Psi}}{\Gamma_{tot}} = 2.5 \cdot 10^{-5}$$
**J/Ψ cross section**

**Detailed balance → absorption cross section**

- $J/Ψ + p$ cross section from detailed balance is very small.
- Not 'absorption' of the $J/Ψ$, but of the mother resonance.
- Reactions of the type:
  \[ N^* + N \rightarrow N'^* + N'^* \]
  \[ N^* + N \rightarrow N'^* + N'^* \]
  where the mass of $N'^* < N^*$ so no $J/Ψ$ can be produced.

Predictions for SIS-100

When applied to central nuclear collisions (min. bias: divide by 5):

- $E_{lab} = 11 \text{ A GeV}$
- $1.5 \cdot 10^{-6} \ J/\psi \text{ per event}$
- $2 \cdot 10^{-5} \ \Lambda_c \text{ per event}$
- $\approx 3 - 4 \cdot 10^{-5} \ \bar{D} \text{ per event}$
Comparison to others I

Parametrized cross section for $J/\Psi$

\[
\sigma_{NN}^{1N}(s) = f_i a \left(1 - \frac{m_i}{\sqrt{s}}\right)^\alpha \left(\frac{\sqrt{s}}{m_i}\right)^\beta \theta(\sqrt{s} - \sqrt{s_{0i}})
\]

HSD results taken from:
Comparison to others II

Cross section for $p + p \rightarrow p + \bar{D}^0 + \Lambda_c$

Hadronic Lagrangian

Taken from:
Summary

• A new mechanism for the production of Ξ and φ is introduced and validated in elementary collisions

• This new branching ratio of high mass resonances is fitted to available data and extrapolated to AA

• It allows for the first time to describe the sub-threshold multi-strange particle production

• If this mechanism is also be applicable to charm production it may open a new road for charm studies at FAIR-SIS 100