Hypernuclei production with a modified coalescence model

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Outline

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2. The off-shell BUU transport approach
3. Modified coalescence model
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Hypernuclei physics

- Hypernuclei measurements could give us insight into nuclear dynamics, nuclear forces, and general baryonic interactions with strange quarks.
- Bound state studies could be important in neutron stars (dense, low temperature hypermatter).
- Can be studied by low-energy heavy-ion reactions (low temperature, high density).
- The dynamics are currently not well understood even for small systems e.g.
  - Hypertriton lifetime, and binding energy (new STAR results show a significantly larger value than what has been measured before).
  - $nn\Lambda$ bound states?
The off-shell BUU transport approach

- **Aim:** Study hypernuclei production in heavy-ion reactions
- **Model:** Boltzmann-Uehling-Uhlenbeck (BUU) type off-shell transport
- **Hadronic degrees of freedoms** (baryons, mesons, many $N$ and $\Delta$ resonances, dileptons, onium states,...)
- Momentum dependent mean field to baryons
- Coulomb force to charged particles
- Pauli exclusion (Gaussian smearing) included
The off-shell BUU transport approach

- Off-shell propagation (propagate the spectral functions → new EOM’s)
- Proton, neutron, pion, antiproton, and heavy-ion beam possibilities
- $2 \leftrightarrow 2$, $2 \leftrightarrow 3$, and some inclusive reactions
- Kodama collisional criteria:
  - Covariant description of 2-body reactions (impact parameter description)
  - Causality violations are minimized (time ordering)
The off-shell BUU transport approach - Collisional criteria

\[
b = \sqrt{R_{12}^2 - \frac{h_{12}^2}{v_{12}^2}} \quad , \quad R_{12}^2 = -(x_1 - x_2)^2 - \left( \frac{p_1(x_1 - x_2)}{m_1} \right)^2
\]

\[
h_{12} = \frac{p_1(x_1 - x_2)}{m_1} - \frac{p_2(x_1 - x_2)m_1}{p_1 p_2} \quad , \quad v_{12} = 1 - \left( \frac{m_1 m_2}{p_1 p_2} \right)^2
\]

\[
\tau_1 = -\frac{p_1(x_1 - x_2)}{m_1} + \frac{h_{12}}{v_{12}^2} \quad , \quad \tau_2 = \frac{p_2(x_1 - x_2)}{m_2} + \frac{h_{21}}{v_{12}^2}
\]

\[
\left[ dt = \frac{1}{2} \left( \frac{e_1}{m_1} \tau_1 + \frac{e_2}{m_2} \tau_2 \right) \right]
\]
Modified coalescence model - Introduction

- Three main approaches:
  - Static: The coalescence happens after at the kinetic freeze-out (Static coalescence models)
  - Hybrid: The coalescence happens during the evolution (MST, SACA, FRIGA, Multifragmentation)
  - Full dynamic: creation and dissociation of clusters during the evolution of the system

- Not a trivial problem (e.g. deuteron in the heat bath)
- Many different approaches could reproduce some of the data (multiplicities, rapidities, ...)
- But: Different free parameters, different physics, only small clusters, ... coalescence is still not 'well' understood (even though good fits are possible)
Modified coalescence model - Our approach

- Cluster recognition by the MST algorithm
- The interaction distances are given by the total cross sections of the participants:
  - energy and interaction type dependence
  - Kodama criterion is used to calculate the impact parameters
- Cluster formation during $M\Delta t$ near the ’end’ of the heavy-ion reaction (around 40 fm/c for Au+Au @ a few A GeV)
  - penalty factor if the cluster broke up ($p_i = n_i/M$)
  - gives small fluctuations in the final yields
- Free parameter: coalescence time $\Delta_C$ (parameter in the Kodama criterion - now the reaction is not ’instantaneous’)
Modified coalescence model - Validation

- Low energy FOPI data for charged fragment multiplicities
- $\Delta_C = 28$ fm/c

![Graphs showing charged fragment multiplicities and average kinetic energies of fragments.](image.png)
Modified coalescence model - Hypernuclei production

- $^3H_\Lambda$, $^5H_\Lambda\Lambda$, $^6\text{He}_\Lambda\Lambda$ production in Au+Au collisions at 0 – 10% centrality:
- $NN$ interaction strength - Cugnon parametrization
- $N\Lambda$ interaction strength (cross sections) - measurements
- $\Lambda\Lambda$ interaction strength - estimation (suppression factor)

\[ \sigma_{\Lambda\Lambda}(\sqrt{s}) = S \cdot \sigma_{N\Lambda}(\sqrt{s} - \Delta M) \]
Modified coalescence model - Hypernuclei production

Fig. 2. Hypernuclei production yields in Au+Au collisions at 0 – 10% centrality, using the assumption of equal $N\Lambda$ and $\Lambda\Lambda$ interaction strengths.

Fig. 3. Dependence of the $^5H_{\Lambda\Lambda}$ and $^6He_{\Lambda\Lambda}$ hypernuclei yields on the $\Lambda\Lambda$ interaction strength at $T_{Lab} = 6$ GeV.
Summary

- We proposed a modified coalescence model based on the Kodama collisional criteria.
- The only free parameter is the coalescence time $\Delta_C = 28$ fm/c.
- Good results for the low energy FOPI data.
- Comparable results to other calculations for Hypernuclei production.