Hypernuclei production with a modified coalescence model

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Outline

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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 Δ 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 $\rightarrow$ 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 descripton of 2-body reactions (impact parameter description)
  - Causality violations are minimized (time ordering)

The off-shell BUU transport approach - Collisional criteria

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

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

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

$$\left[dt = \frac{1}{2}\left(\frac{e_1}{m_1}\tau_1 + \frac{e_2}{m_2}\tau_2\right)\right]$$

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, rapdities, ...)
- But: Different free parameters, different physics, only small clusters, ... coalescence is still not 'well' understood (even though good fits are possible)

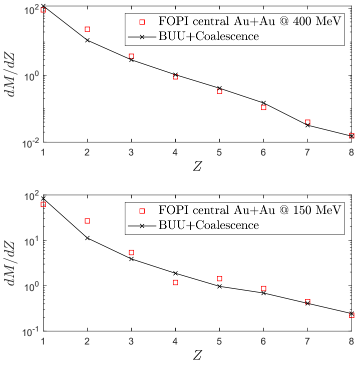
Modified coalescence model - Our approach

- Cluster recognition by the MST algorithm
- The interaction distances are given by the total cross sections of the participants:
  $\rightarrow$ energy and interaction type dependence
  $\rightarrow$ 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)
  $\rightarrow$ penalty factor if the cluster broke up ($p_i = n_i/M$)
  $\rightarrow$ gives small fluctuations in the final yields
- Free parameter: coalescence time Δ_C (parameter in the Kodama criterion - now the reacton is not 'instantenous')

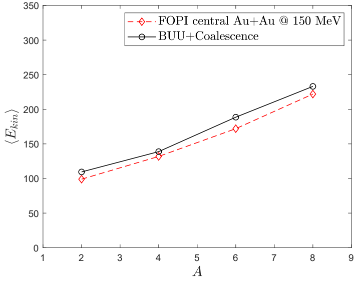
Modified coalescence model - Validation

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

Charged fragment multiplicities



Average kinetic energies of the fragments



Modified coalescence model - Hypernuclei production

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

$$\sigma_{\Lambda\Lambda}(\sqrt{s}) = \mathcal{S} \cdot \sigma_{N\Lambda}(\sqrt{s} - \Delta M)$$

Modified coalescence model - Hypernuclei production

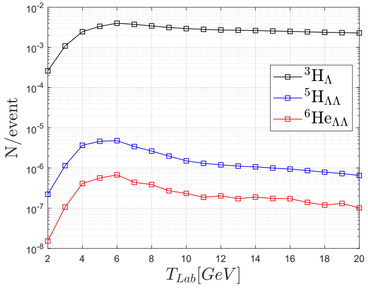


Fig. 2. Hypernuclei production yields in Au+Au collisions at $0-10\%$ centrality, using the assumption of equal $N\Lambda$ and $\Lambda\Lambda$ interaction strengths.

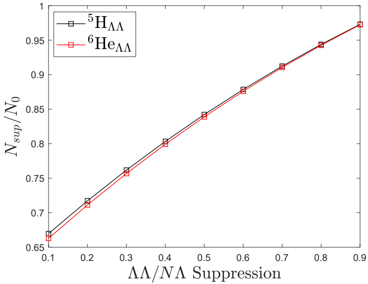


Fig. 3. Dependence of the $^5H_{\Lambda\Lambda}$, and $^6He_{\Lambda\Lambda}$ hypernuclei yields on the $\Lambda\Lambda$ interaction strength at $T_{Lab} = 6$ GeV.

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