Production of Hypernuclei at FAIR

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Introduction

The hybrid GiBUU+SMM approach
Giessen-BUU (GiBUU), SMM, combined GiBUU+SMM

HypHI project: Li(C)+C@2AGeV
Reaction dynamics, spectator fragmentation, results on single-Λ hypernuclei

PANDA subproject: pbar+X@(3-5)GeV
Reaction dynamics & strangeness yields, decay of residual source, predictions on single-Λ and double-Λ hypernuclei

Final remarks
Introduction...

HypHI: Heavy-Ion collisions

$\Lambda, \Sigma, \pi, K, \ldots$

Hyperon-baryon

Antiproton-nucleus reactions

Exploration

$\Lambda, \Sigma, \pi, K, \ldots$

Hyperon-hyperon

Crucial to understand the strangeness sector of the hadronic EoS

Direct implications for nuclear astrophysics (max. mass of neutron stars)
Production of hypernuclei in relativistic HIC / $\bar{p}+X$

hyperon production: $pp\rightarrow p\Lambda K$ / $pp\rightarrow \Lambda\Lambda,\Xi\Xi$, (+) $\pi,\rho,\omega,\ldots$ ($\sigma_{\text{abs}} \sim 20\text{mb}$)

+ Secondary rescattering (A.B. Larionov's talk for details)
Multiple coalescence of hyperons with fragments

Theoretical framework

Phase-Space evolution
Transport approaches (INC, BUU, RBUU, CBUU, (Ur)QMD, HSD, ...)

Description of fragment formation
Statistical picture (SMM, Botvina & Mishustin)

Description of hypernuclei formation?
Phase-Space coalescence in coordinate and in momentum space
Initial non-equilibrium stage

\[
(p_\mu \frac{\partial \mu}{x} + (p_\nu F^{\mu \nu} + m^*(\partial^\mu_m m^*)) \frac{\partial p^*_\mu}{f(x, p^*)} = I_{coll}[f(x, p^*), \sigma_{NN}] \\
F^{\mu \nu} = \frac{g_v^2}{m_v^2} (\partial^\mu j^\nu - \partial^\nu j^\mu) \text{ (repulsive "Lorentz" contribution)} \\
m^* = M - g_\sigma \sigma \text{ (attractive part)}
\]

Relativistic mean-field

- Non-linear Walecka model (soft EoS) \(\rightarrow\) Lalazissis parametrization
- Antibaryon-meson couplings: \(g_\omega = -\xi g_\omega\), \(g_\sigma = \xi g_\sigma\)
- Isovector \(g_\rho\) (anti)baryon-meson interaction (no \(m^*\) isospin splitting), coulomb

Collision term: as usual \(\ldots +\)

- primary: \(\bar{p}p \rightarrow\) mesons
- Primary: \(\bar{p}p \rightarrow \Lambda\Lambda, \Xi\Xi\) (data)
- Secondary: \(\Lambda\Lambda(\Sigma) \leftrightarrow \Xi B\) (data+Nijmegen-calc.), \(\bar{K}B \rightarrow \Xi K\) (data), \(\Lambda B \leftrightarrow \Sigma B\) (data)
Numerical realization (Test-Particle Ansatz):

- Initialization → Propagation (Vlasov, collisions)

Initialization: "test particles" initialized according to empirical density distributions

Problem: density profiles not consistent with mean-field used in propagation

Solution: Use the same energy density functional $\varepsilon[\rho_p, \rho_n]$ for initialization & propagation

→ Relativistic Thomas Fermi (RTF) for spherical nuclei

PR C81, (2010), 054316
GiBUU+SMM...

Asymptotic equilibrated stage

- Statistical Multifragmentation Model (SMM)
- Fission/spallation, evaporation, multifragmentation... (with increasing excitation)
- Statistical determination of partial decay widths → Monte-Carlo method

\[ \Gamma_j = \int_V P_j(\epsilon) d\epsilon \]

SMM code: Botvina & Mishustin, PR257(’95) 133

Hybrid GiBUU+SMM...

* Non-Equilibrium dynamics within BUU until source(s) approaches stable configuration and local equilibration at \( t=t_f \)
* Determination of mass (\( A \)), charge (\( Z \)) and excitation energy \( E_{\text{exc}} \) of a source at time \( t=t_f \), then apply SMM
HypHI-project: C+C@2AGeV...

Def. of Spectators
\[ \rho^{(0)} > 0.75 + \rho / \rho_{\text{sat}} / 100 \]

Spectators
Well defined conditions after onset of instability...

Spectators
...and onset of equilibration

PL B663, 197 (08) & PLB675 (09) 297

Münster, 23.03.11
HypHI-project: Li+C@2AGeV...

**BUU**: fragmenting sources & strangeness (consistent with FOPI/KaoS)

**SMM**: spectator fragmentation (consistent with ALADIN)

In preparation...
**HypHI-project: Li+C@2AGeV...**

Coal.: momentum coalescence for $\Lambda$ close to spectators

*Predictions*: projectile/target fragmentation: $\sigma(^{3}\Lambda, ^{4,5}\Lambda) \sim (6-10)\mu b$

In preparation...
PANDA-subproject: \( \bar{p} + X \mathbin{(3-5)\text{GeV}} \) ...(Why \( \bar{p} \)-nucleus ?)

- Residual source: minor differences
- Particle yields: huge differences

In preparation...
fragmentation in p+X... (reminder)

F. Rejmund et al., Nucl. Phys. A683 (2001) 540 (Saclay)
S. Leray et al., PRC65,044621

PL B663, 197 (08) & PLB675 (09) 297
In preparation...
\[ E^* = E_p + (M_{\text{targ}} - B_{\text{targ}})A_{\text{targ}} - (M_{\text{res}} - B_{\text{res}})A_{\text{res}} - E_{\text{em}} - E_{\text{rec}} \] (energy balance event-by-event)

**Good description of excitation spectrum**

data: PRC63, 034616  \( \vec{p}A@1.22 \text{ GeV} \)
PANDA-subproject: $\bar{p}+X@$(3-5)GeV... (fragmentation)

data: PRC63, 034616

Overal good description of different fragment multiplicities
PANDA-subproject: $\bar{p}+X@(3-5)\text{GeV}$...(particle production)

In preparation...

Strangeness production...
(consistent with data-> Larionov's talk)

Coalescence with stopped $\Lambda$'s possible
No coalescence with $\Xi$'s (in 2th target)
PANDA-subproject: $\bar{p} + X @(3-5) \text{GeV}$... (particle production)

Coal: momentum coalescence with captured $\Lambda$

Production of single-$\Lambda$ & double-$\Lambda$ hypernuclei possible

Production of double-$\Lambda$ hypernuclei via $\Xi$-capture in 2th target...
Final remarks...

**Theoretical studies: “FAIR” @ Giessen**

- GiBUU+SMM: NE-dynamics + statistical process of fragmentation
- suitable tool for HypHI- & PANDA-reactions

**Benchmark tests (low energy)**

- proper description of fragmentation process in p- & \( \bar{p} \)-reactions and in heavy-ion collisions

**First predictions on single-Λ hypernuclei (HypHI)**

- \( \sigma \sim \mu b \) for \(^{\Lambda}H\) & \(^{\Lambda}He\) in spectator/target fragmentation in HIC
- consistency with HypHI-experiment... (on work together with T. Saito)

**First predictions on double-Λ hypernuclei (PANDA)**

- multiply coalescence of captured Λ's already in first target
- Ξ's escape, might need 2th target...(on work)
Backup slides
Application-I: Fragmentation in p+X@0.8 GeV (energy spectra...)

Final Result: Hybrid GiBUU+SMM

Asymptotic final state (SMM): Statistical decay of excited source

Pre-Equilibrium (GiBUU): high-energy n-emission, QE-peak

data: S. Leray et al., PRC65,044621

Applications-II: Fragmentation in X+X reactions

absolute yields from spectator fragmentation in Au+Au@0.6AGeV (ALADIN-data)

fragment velocity spectra in Xe+Pb@1.0AGeV

data:
Henzlova, PRC78, 044616
Applications-II: Hypernuclei in spectator fragmentation...
(HypHI, $^{12}$C+$^{12}$C@2AGeV)

- First transport theoretical predictions: total yields $\sim \mu$b
- Consistent with previous studies: M.Wakai, NPA547(92)89c

Applications-II: Hypernuclei from high energy proton-induced reactions…
(PANDA/J-PARC, p+^{12}C@50GeV)

Two sources (residual target+moving source)
Most of hyperons created & rescatter inside moving source

Getting started: Spectator fragmentation at Au+Au@0.6 GeV

Prog. Part. Nucl. Phys. (2009), in press
New initialization: Binding energy & rms-radius in BUU...
Mean-field vs cascade - the role of the mean-field...

(PANDA/J-PARC, p+\textsuperscript{12}C@50GeV)
Ground state in BUU-II: Results (application to proton-induced reactions)