Study of Clusters and Hypernuclei production within PHSD+SACA model

V. Kireyeu¹, A. Le Fèvre², E. Bratkovskaya³, J. Aichelin⁴, Y. Lefeils²

¹ JINR, Dubna, Russia
² GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany
³ FIAS, Frankfurt University, Germany
⁴ SUBATECH, UMR 6457, Ecole des Mines de Nantes - IN2P3/CNRS - Université de Nantes, France
Outline

- Motivation
- Searching clusters with PHSD+SACA model
- Current state
- Summary
Motivation

At 3 A GeV, even in central collisions **20% of the baryons are in clusters.**

... and baryons in clusters have quite different properties.
Motivation

If we do not describe the dynamical formation of fragments
- we cannot describe the nucleon observables \((v_1, v_2, \text{dn/dp}_T)\)
- we cannot explore the new physics opportunities like
  hyper-nucleus formation
  1\textsuperscript{st} order phase transition
  fragment formation at midrapidity (RHIC, LHC)

Present microscopic approaches fail to describe fragments at NICA/FAIR (and higher) energies.
- VUU(1983), BUU(1983), (P)HSD(96), SMASH(2016) solve the time evolution of the one-body phase space density -> no fragments
- UrQMD is a n-body theory but has no potential -> nucleons cannot be bound to fragments
- (I)QMD is a n-body theory but is limited to energies < 1.5 AGeV -> describes nicely fragments at SIS energies, but conceptually not adapted for NICA/FAIR
PHSD — basic concepts


Initial A+A collisions – HSD: string formation and decay to pre-hadrons

Fragmentation of pre-hadrons into quarks: using the quark spectral functions from the Dynamical QuasiParticle Model (DQPM) approximation to QCD


Partonic phase: quarks and gluons (= „dynamical quasiparticles“)
with off-shell spectral functions (width, mass) defined by DQPM

- elastic and inelastic parton-parton interactions:
  - \( q + \overline{q} \) (flavor neutral) \( \leftrightarrow \) gluon (colored)
  - gluon + gluon \( \leftrightarrow \) gluon (possible due to large spectral width)
  - \( q + \overline{q} \) (color neutral) \( \leftrightarrow \) hadron resonances

Hadronization: based on DQPM - massive, off-shell quarks and gluons with broad spectral functions hadronize to off-shell mesons and baryons:
- gluons \( \rightarrow q + \overline{q} \);
- \( q + \overline{q} \rightarrow \) meson (or string);
- \( q + q + \overline{q} \rightarrow \) baryon (or string) (strings act as ‘doorway states’ for hadrons)

Hadronic phase: hadron-string interactions - off-shell HSD
Simulated Annealing Clusterisation Algorithm


1) Pre-select good «candidates» for fragments according to proximity criteria: real space coalescence = Minimum Spanning Tree (MST) procedure.

2) Take randomly 1 nucleon out of one fragment

3) Add it randomly to another fragment

\[ E = E_{\text{kin}}^1 + E_{\text{kin}}^2 + V^1 + V^2 \]

\[ E' = E'_{\text{kin}}^1 + E'_{\text{kin}}^2 + V'^1 + V'^2 \]

If \( E' < E \) take the new configuration

If \( E' > E \) take the old with a probability depending on \( E' - E \)

Repeat this procedure very many times...

It leads automatically to the most bound configuration.
Searching clusters with PHSD+SACA model

(GSI & NANTES & JINR & FIAS collaboration)

It is very important to choose a good starting time for clusterisation algorithm.

Particles multiplicity per step of PHSD evolution time.

Charge distribution for different SACA starting times. (Red line here – passing time without interaction, for reference only.)

Au+Au, $E_{lab} = 11.450$ GeV, $b = 6$ fm.
Searching clusters with PHSD+SACA model

Multiplicity of different kind of particles and fragments

\[ \langle Z_{\max} \rangle \text{ versus formation time} \]

Hypernuclei multiplicity

\[ t = 15 \text{ fm/c has been chosen to start SACA simulations at 11.45 GeV} \]
SACA comparison with E-802 experimental data 11.45 GeV

«Proton and deuteron production in Au+Au reactions at 11.6A GeV/c» Phys. Rev. C, 60 064901

Model reproduce experimental data dN/dy distributions for protons and deuterons
SACA hypernuclei production

One of the tasks of the Multi-Purpose Detector is to study the strangeness production. This task demands a good identification and reconstruction of heavy strange objects like hypernuclei and hyperons.

This plot shows the yields of hypernuclei and hyperons predicted by the PHSD+SACA approach in Au+Au collisions at 11.45A GeV.
MPD hypertriton feasibility study

Event topology of two-particle decay of the particle:

- PV – primary vertex
- \( V_M \) – vertex of ³ΛH decay
- dca – distance of the closest approach
- path – decay length

Dataset:
500,000 events, Au+Au, \( b = 0 \ldots 3 \) fm, 5 A GeV (11.45 GeV in lab frame)

\[ ^3\Lambda H \rightarrow ^3He + \pi^- \]
Current state

SACA → FRIGA (Fragment Recognition In General Application)

PHSD → PHQMD (Parton-Hadron Quantum Molecular Dynamics*)

PHQMD = (QMD & PHSD) & SACA (FRIGA)

A non-equilibrium microscopic transport model which describes n-body dynamics based on QMD propagation with collision integrals from PHSD and cluster formation by the SACA model or by the Minimum Spanning Tree model (MST).

Produced particles are well reproduced at SIS/NICA/FAIR energies, as well as at SPS energies.
First Results of PHQMD

5.10.2017

The 3rd International Conference on Particle Physics and Astrophysics
For very peripheral reactions we expect that only the remnant is bound and no intermediate mass clusters appear, and at very central collisions we expect that a fireball is created which contains essentially protons and neutrons, so \( Z_{\text{bound}} \) is small as well as \( M_{\text{IMF}} \). In mid-central reactions we observe multifragmentation, meaning several intermediate fragments are produced together with a lot of protons. The understanding of this is a big challenge in present day heavy ion physics.
There are all kinds of fragments at midrapidity and they are stable (MST finds at 60fm/c the same fragments as at 90fm/c)
PHQMD: fragments and hypernuclei formation

BM@N energy

Still activity in spectator matter after 30 fm/c

- Fragments are stable from 30 fm/c -> 90 fm/c
- Hyper-nuclei are produced in number
Central collisions: light clusters;
Semi-peripheral collisions: existence of heavy clusters – remnants from spectators

Upper estimates for the hypernuclei production: visible contribution → opens perspectives for the new physics as hypernucleus spectroscopy, experimental determination of L-N potential etc.
Summary

- PHSD+SACA can produce clusters and hypernuclei;
- These predictions have been used for MPD performance studies;
- PHSD+SACA model reproduce experimental data for 11.45 GeV;
- Model is actively developing, soon there will be some new results.
Simulation/reconstruction chain

PHSD  SACA  MpdGenerators  MpdRoot  MC Sim  GEANT3  Geant4  ...  Reco