Fragments formation within PHQMD and do we really we need it?

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Introduction

At 3 A.GeV even in central collisions almost 20% of the baryons are bound in the clusters (it’s a lot!)

Without dynamical fragments formation we cannot properly describe observables like $v_1$, $v_2$, $p_T$ spectra,

Many present transport models fail to describe fragments at NICA/FAIR (and higher) energies. We made a new one.
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:
using the effective cross sections from the DQPM
✓ q + qbar (flavor neutral) <=> gluon (colored)
✓ gluon + gluon <=> gluon (possible due to large spectral width)
✓ q + qbar (color neutral) <=> hadron resonances

Hadronization: based on DQPM - massive, off-shell quarks and gluons with broad spectral functions hadronize to off-shell mesons and baryons:

- gluons → q + qbar;
- q + qbar → meson (or string);
- q + q +q → baryon(or string)(strings act as 'doorway states’ for hadrons)

Hadronic phase: hadron-string interactions – off-shell HSD
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

\[ E = E_{1\text{kin}} + E_{2\text{kin}} + V_1 + V_2 \]

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

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.
Parton-Hadron Quantum Molecular Dynamics

= PHSD + QMD* + FRIGA

Clusterization time

Maybe here..?

Too early

Oops...

Too late
Clusterization time

\[ \text{Au+Au, } E_{\text{lab}} = 1.23 \text{ GeV, } b = 12 \text{ fm, } n \cdot t_{\text{pass}} = 16.86 \text{ fm/c} \]

\[ \text{Au+Au, } E_{\text{lab}} = 1.23 \text{ GeV, } b = 12 \text{ fm, } 2 \cdot t_{\text{pass}} = 33.72 \text{ fm/c} \]

\[ \text{Au+Au, } E_{\text{lab}} = 1.23 \text{ GeV, } b = 12 \text{ fm, } 3 \cdot t_{\text{pass}} = 50.58 \text{ fm/c} \]

\[ \text{Au+Au, } E_{\text{lab}} = 1.23 \text{ GeV, } b = 12 \text{ fm, } 4 \cdot t_{\text{pass}} = 67.43 \text{ fm/c} \]
Model predictions

Single particle spectra still the same as in PHSD

Produced particles are well reproduced at NICA/FAIR energies
Model predictions

*(preliminary results at NICA energies)*

Central collisions: light clusters;
Semi-peripheral collisions: existence of heavy clusters – remnants from spectators
$M_{\text{IMF}}$ vs $Z_{\text{bound}}$ @ 1.23 GeV

Courtesy of the ALADIN Collaboration for the new S254 data

Au+Au, $E_{\text{lab}} = 1.23$ A.GeV, $t_{\text{pass}} = 16.86$ fm/c

$\langle M_{\text{IMF}} \rangle$ – average number of medium mass fragments ($2 < Z < 30$)

$Z_{\text{bound}}$ – number of charges bounded in clusters ($Z > 1$)
$M_{\text{imf}}$ vs $Z_{\text{bound}}$ @ 2 GeV

Courtesy of the ALADIN Collaboration for the new S254 data

$\langle M_{\text{imf}} \rangle$ – average number of medium mass fragments ($2 < Z < 30$)

$Z_{\text{bound}}$ – number of charges bounded in clusters ($Z > 1$)
$M_{\text{imf}} \text{ vs } Z_{\text{bound}} \ @ \ 4 \ A.\text{GeV}$

Courtesy of the ALADIN Collaboration for the new S254 data

$\langle M_{\text{IMF}} \rangle$ – average number of medium mass fragments (2<Z<30)

$Z_{\text{bound}}$ – number of charges bounded in clusters (Z>1)
$M_{\text{imf}}$ vs $Z_{\text{bound}}$ @ 6 A.GeV

 Courtesy of the ALADIN Collaboration for the new S254 data

$\langle M_{\text{imf}} \rangle$ – average number of medium mass fragments (2<Z<30)

$Z_{\text{bound}}$ – number of charges bounded in clusters (Z>1)
$M_{\text{imf}}$ vs $Z_{\text{bound}}$ @ 8 A.GeV

Courtesy of the ALADIN Collaboration for the new S254 data

Au+Au, $E_{\text{lab}} = 8.00$ A.GeV, $t_{\text{pass}} = 6.61$ fm/c

$\langle M_{\text{IMF}} \rangle$ – average number of medium mass fragments (2<Z<30)

$Z_{\text{bound}}$ – number of charges bounded in clusters (Z>1)
$M_{\text{imf}}$ vs $Z_{\text{bound}}$ @ 11 A.GeV

Courtesy of the ALADIN Collaboration for the new S254 data

\[ \sqrt{S_{\text{NN}}} \approx 5 \text{ GeV} \]

NICA!

Au+Au, $E_{\text{lab}} = 11.00$ A.GeV, $t_{\text{pass}} = 5.64$ fm/c

\[ <M_{\text{IMF}} > \] – average number of medium mass fragments (2<Z<30)

$Z_{\text{bound}}$ – number of charges bounded in clusters (Z>1)
Why not to use just coalescence?

It fails to describe spectators
Some yields

Old
Au+Au, $\sqrt{s} = 5$ GeV, b = 0.3 fm

New
Au+Au, $\sqrt{s} = 5$ GeV, b = 0.3 fm
PHQMD+FRIGA may be also used for engineering stuff

We can estimate damage caused to detector
Z vs $\Theta$ @ 1.23 A.GeV

Au+Au, $E_{\text{lab}} = 1.23$ A.GeV
$Z$ vs $\Theta$ @ 2 A.GeV

$\text{Au+Au, } E_{\text{lab}} = 2.00 \text{ A.GeV}$
$Z \text{ vs } \Theta @ 4 \text{ A.GeV}$

$Au+Au, E_{\text{lab}} = 4.00 \text{ A.GeV}$
\( Z \) vs \( \Theta \) @ 4 A.GeV

\( \text{Au+Au, } E_{\text{lab}} = 4.00 \text{ A.GeV} \)
PHQMD can produce clusters and hypernuclei;
Model reproduce experimental data;
Model`s predictions can be used for analysis, feasibility and engineering studies;
Model is actively developing.
Au+Au, $E_{\text{lab}} = 11000\text{ MeV}$

DCM-QGSM
Some yields

Fragments $Z \geq 2$

Hypernuclei

\[ \text{Au+Au, } E_{\text{lab}} = 11.00 \text{ GeV, } t_{\text{pass}} = 5.64 \text{ fm/c} \]