PHQMD: Flow and Clustering

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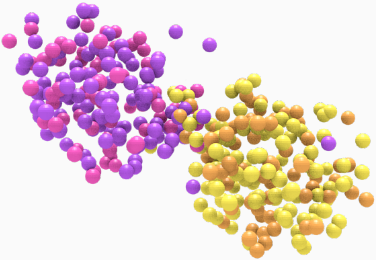

PHQMD

PHQMD(Parton Hadron Quantum Molecular Dynamics)[1]is a simulation code that is based on PHSD(Parton Hadron String Dynamics)[2](quasi particle description of QGP of PHSD)but uses N-body dynamics for propagation

Quantum Molecular Dynamics

Using n-body theory to track nucleon by nucleon the collision, and calculate the mutual interactions between all of the nucleons.

- IQMD[3](Limited to lower energies 1.5 GeV/A)
- UrQMD[4](Relativistic, used for coalescence, no potential)

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[1] J. Aichelin and, E. Bratkovskaya et al.*Phys. Rev. C 101, 044905*
[2] W. Cassing and E. Bratkovskaya*Phys.Rev.C 78,034919*
[3] C. Hartnack et al.*Eur.Phys.J.A1:151-169,1998*
[4] S. A. Bass et al.*Nucl.Phys.41:225-370*

Why is it needed ?

Current models are not well adapted to address cluster formation, and current QMD models are not usable at relativistic energies

Challenges

Production of clusters with binding energy of $B_E \approx 8[MeV]$ in environment of the fireball at $E \approx 100[MeV]$

Hyper clusters production[5][6]is an area of renewed interest, and which is not currently addressed

Transition form low energy hadron dominated interactions and high energy quark and gluon dominate reactions

Transition regime is characterised by a finite chemical potential thus a finite baryonic density

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[5]C. Rappold et al.*P.L.B. Volume 747 Pages 129-134*

[6]J. Adam et al*Phys. Rev. C 93, 024917*

Future experimental data

New energy range from 2 GeV/A - 100 GeV/A, used to investigate the first order phase transition from hadronic to QGP matter, and degrees of freedom of hadronic matter (strangeness) .

- FAIR
- NICA

Experimental results so far

- 0.6 [GeV/A] ALADIN [7]
- 1.23 [GeV/A] HADES [8]
- 1.5 [GeV/A] FOPI [9]

[7] A. Schüttauf et al *N.P.A Volume 607 Pages 457-486*
[8] J. Adamczewski-Musch et al *Nucl.Phys. A982*
[9] W. Reisdorf et al. *Nuclear Experiment 1112.3180*

Brief PHQMD model overview

Generalised Ritz variational principle

$$\delta \int_{t_1}^{t_2} \mathrm{dt} \left\langle \Psi(t) \right| i \frac{\mathrm{d}}{\mathrm{d}t} - H \left| \Psi(t) \right\rangle = 0 \tag{1}$$

Gaussian test wave function which yields the Wigner density:

$$f(\vec{r}_i, \vec{p}_i, \vec{r}_{i0}, \vec{p}_{i0}, t) = \\ \frac{1}{\pi^3 \hbar^3} \exp\left[-\frac{2}{L}(\vec{r}_i - \vec{r}_{i0})^2\right] \exp\left[-\frac{2}{L}(\vec{p}_i - \vec{p}_{i0})^2\right] \tag{2}$$

Classical type equations of motion for expectation value of the Hamiltonian

$$\dot{r} = \frac{\partial \langle H \rangle}{\partial p} \qquad \dot{p} = -\frac{\partial \langle H \rangle}{\partial r} \tag{3}$$

Brief PHQMD model overview

Hamiltonian composed of Kinetic term and Two body potentials

$$\langle H \rangle = \sum_{i}^{N} \langle H_i \rangle = \sum_{i}^{N} \left(\langle T_i \rangle + \sum_{i \neq j}^{N} \langle V_{i,j} \rangle \right) \tag{4}$$

Potentials

$$\langle V_{i,j} \rangle = \langle V_c \rangle (\vec{r}) + \langle V_s \rangle (\rho) + (\langle V_{SM} \rangle (\Delta \vec{p}^2)) \tag{5}$$

Interaction density

$$\rho_{int}(i,t) = C \sum_{j,j \neq i}^{N} \exp \left[\frac{1}{L} (\vec{r_i} - \vec{r_j})^2 \right] \tag{6}$$

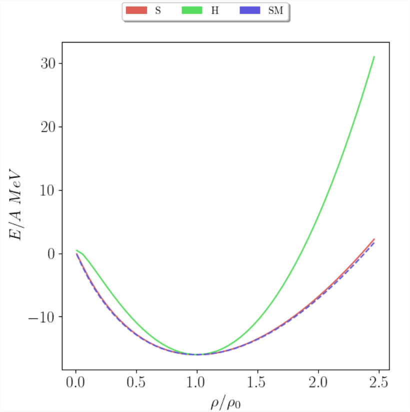
E.o.S parametrisation

Static Skyrme parametrisation

$$\langle V_{skyrme} \rangle (\vec{r}) \propto \alpha\rho + \beta\rho^{\gamma} \quad (7)$$

Constraints for the potentials

$$\begin{cases} \rho_0 = 0.1695\,[fm^{-3}] \\ E_0 = -16\,[MeV] \\ K_0 = 200 \text{ or } 380\,[MeV] \\ \text{(Soft/Hard)} \end{cases}$$



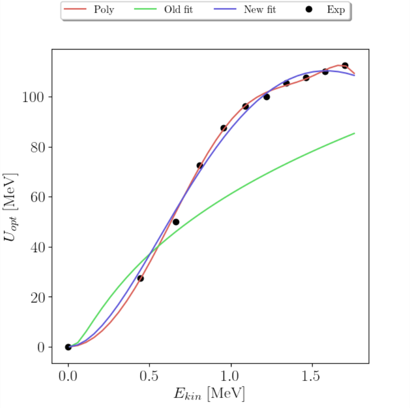
Equations of state parametrised for soft and hard nuclear matter compressibility

E.o.S parametrisation

Momentum dependent Skyrme parametrisation

$$\langle V_{mom} \rangle = \langle V_{skyrme} \rangle (\vec{r}) + \langle U_{opt} \rangle (\Delta p^2) \quad (8)$$

$$U_{opt}(\Delta p^2) = \exp\left[-c\sqrt{\Delta p}\right] \left(a\Delta p + b\Delta p^2\right)\rho(t) \quad (9)$$



Optical potential fit to expermimental data[10]

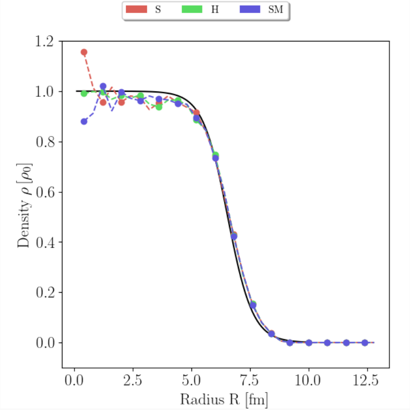
[1]Nuclear Physics A640

Nucleon distribution

Wood-Saxon distribution in position space of nucleons

$$\rho^{WS}(r) = \frac{\rho_0}{1 + \exp\left[\frac{r - R_A}{a}\right]} \qquad (10)$$

$$\begin{cases} R_A = r_0 A^{1/3} \\ r_0 = 1.125[fm] \\ a = 0.535[fm] \end{cases}$$



Initial Wood-Saxon position distribution for the three E.o.S.

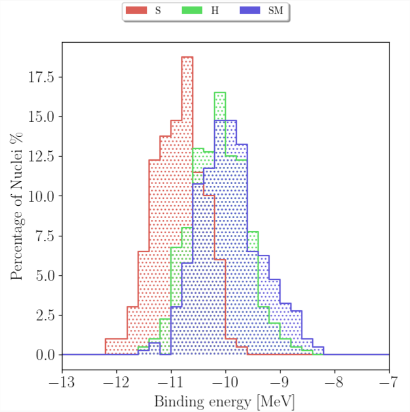
Binding energy

Total binding energy of our nucleus ($< B_E >= -10[MeV]$)

$$B_E = E_k(\vec{p}) + E_c(\vec{r}) + E_s(\vec{r}) + (E_{sm}(\vec{r}, \Delta p)) \quad (11)$$

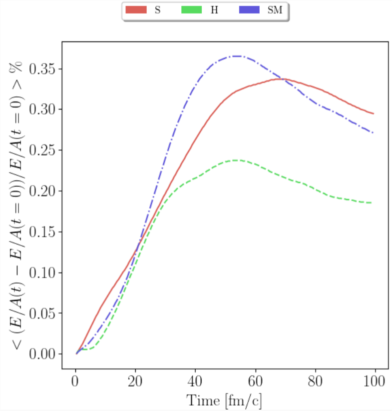
Constraint on momentum distribution

$$0 \leq \sqrt{m^2 + \vec{p}_i^2} - m \leq -V_i(\vec{r}) \quad (12)$$

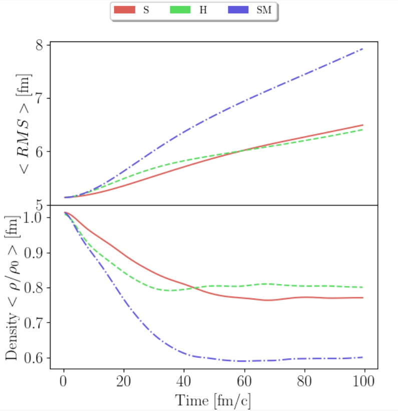


Initial binding energy of the nucleii

Propagation

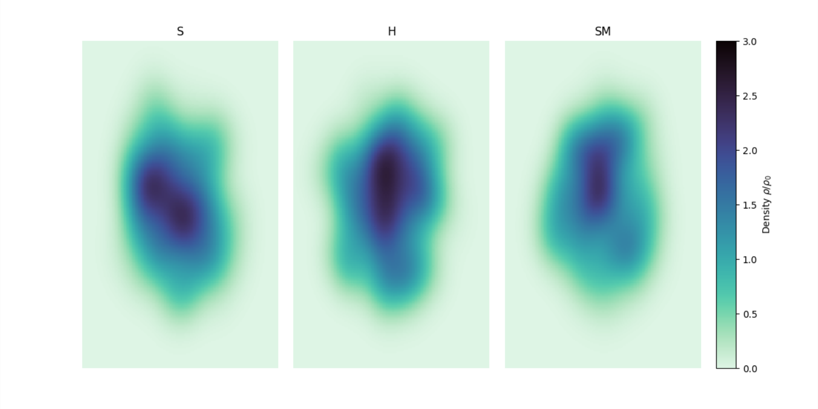


Conservation of the total system energy



Evolution of the average radial nuclei distance, and the average density of the nuclei

Density profile mid-collision



Density profile of the three equations of state for a collision at E = 0.6 [AGeV] for semi-peripheral impact b = 7 [fm] at T = 10 [fm/c]

Cluster formation

SACA[11] and MST[12]

To form the cluster we use two methods

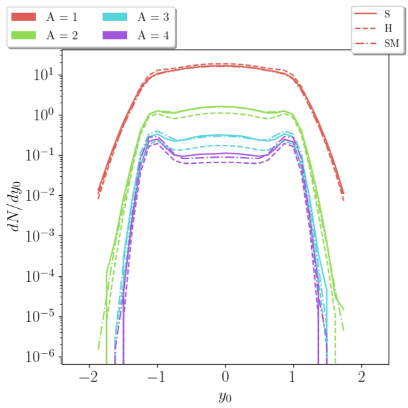
- MST : simple form of spanning tree to create clusters based on distance from other nucleons
- SACA : complex simulated annealing of all possible cluster patterns of the nucleons to find the lowest sum of binding energies of all clusters

All the following results are for the SACA method

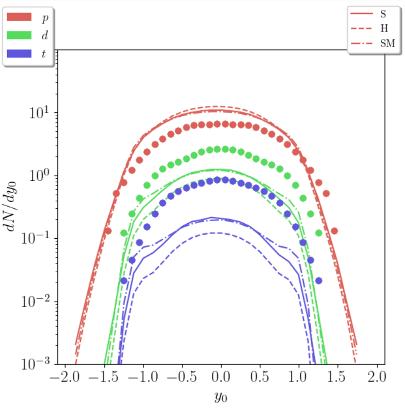
[10] R. K. Puri, C. Hartnack and J. Aichelin *Phys. Rev. C 54, R28(R)*

[11] J. Aichelin, Phys. Rept.202, 233

FOPI results for E = 1.5 [GeV/A] Multiplicity



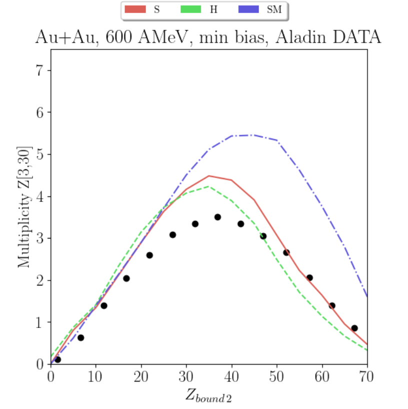
Fragment multiplicity



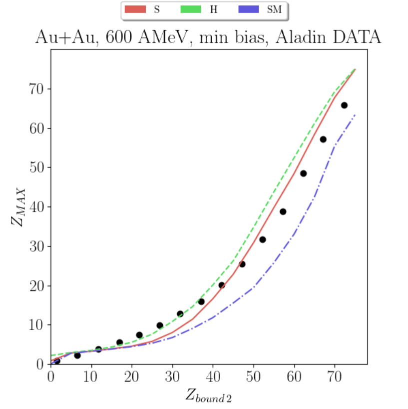
Z=1 isotopes multiplicities for central collisions (b < 2 [fm])

Aladin results for E = 0.6 [GeV/A]

Z_{bound2} the sum of the charges all fragments with $Z \geq 2$, and Z_{MAX} the charge of the largest cluster

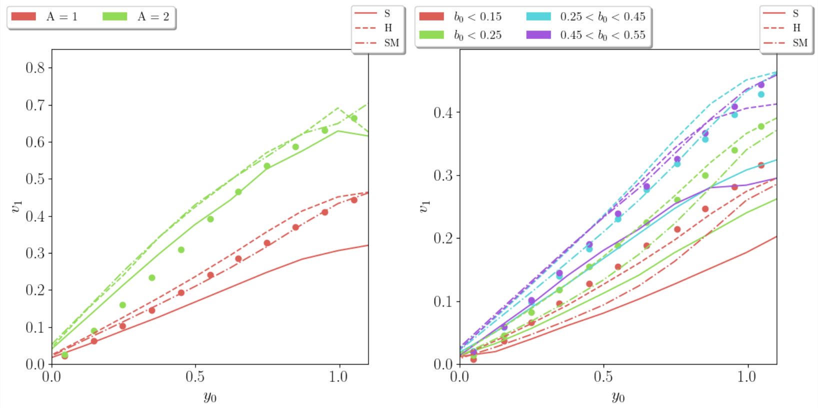


Rise and Fall curve for all three equations of state



Zmax curve for all three equations of state

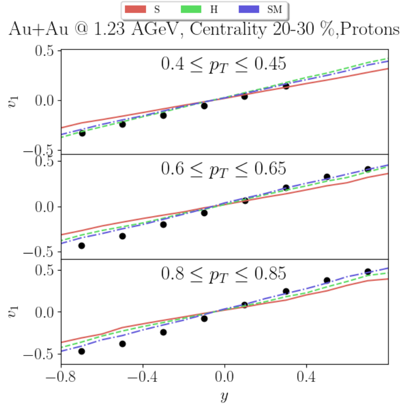
FOPI results for E = 1.5 [GeV/A] Flow



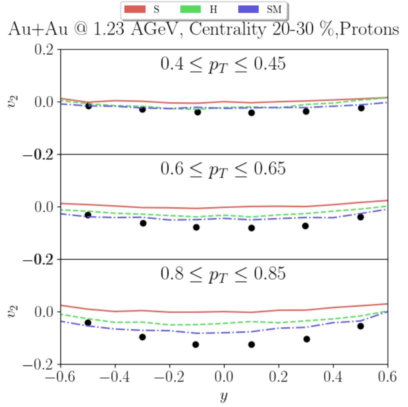
Direct flow for proton and deuteron with a threshold on transverse momentum

Direct proton flow for 4 different impact parameter classes for all protons with a threshold on transverse momentum

HADES results for E = 1.23 [GeV/A] Flow



Direct proton flow as a function of rapidity for three p_T classes compared with the HADES data



Elliptical proton flow as a function of rapidity for three p_T classes compared with the HADES data

Conclusions

- PHQMD quite nicely replicate heavy fragments spectra and reasonable agreement for Z=1 fragments
- Flow reproduction with similar behaviour for Hard E.o.S. and Soft momentum E.o.S. reinforcing the need for momentum dependence
- Some issues that are being fixed for small fragments at Mid Rapidity