D J B U U:  
A new transport model for RAON experiments

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Content

• Introduction
• Transport theory / DJBUU model
• Results comparison with TMEP
• For RAON experiments
Heavy-ion collisions: why study?

- explore phase diagram of strongly interacting matter in the hadronic sector
- nuclear matter above saturation: EOS & hadronic properties in dense medium
- importance for astrophysics: SN and NS
Levels of descriptions in HICs

1. Transport models
2. Hydrodynamical model in expanding system (EES)
3. Statistical multifragmentation models (SMM)
4. Statistical emission in expanding system (EES)

Local thermal equilibrium

Non-equilibrium aspects of the temporal evolution of a collision
Collisions and microscopic interactions

- simple and first model focusing only $NN$ collisions (no interactions)
- collision criterion: point of closest approach (Bertsch prescription)
- scattering can be elastic or inelastic
- giving great insight of heavy-ion physics

- free Lagrangian for Dirac field + interaction

Lagrangian for meson field

\[
\left[ i \gamma_\mu \partial^\mu - (m_N + g_\sigma \sigma) - g_\omega \gamma^0 \omega^0 - g_\rho \gamma^0 \tau^3 \rho^0 - \frac{e}{2} \gamma^0 (1 + \tau^3) A^0 \right] \psi = 0
\]

\[
m_\sigma^2 \sigma + a \sigma^2 + b \sigma^3 = - g_\sigma \rho_S
\]

\[
m_\omega^2 \omega^0 = g_\omega \rho_B
\]

\[
m_\rho^2 \rho^0_3 = g_\rho \rho_{B,I3}
\]

B. Liu et al. PRC 65, 045201
Relativistic transport equation (BUU eq.)

**Aim:** microscopic description of nucleus-nucleus collisions

\[
(p^*0)^{-1}\left[p^\mu \partial_\mu - (p^\mu \mathcal{F}_\mu^i - m^i m^*(x)) \frac{\partial}{\partial p^*i}\right] f(\vec{x}, \vec{p}^*) = C(\vec{x}, \vec{p}^*)
\]

- possible collisions up to two-body collisions
- uncorrelated momenta of two incoming \( (p_1, p_2) \) as well as outgoing \( (p_1', p_2') \)
- local collisions in time & space \( (x_i = x_i') \)
- Pauli exclusion principle in collision term by \( 1-f(x,p) \)

\[
C^{(2)}(\vec{x}', \vec{p}_1') = \frac{1}{2} \int \frac{d^3p_2}{(2\pi)^3 2p_2^0} \int \frac{d^3p_2'}{(2\pi)^3 2p_2'^0} M_{12 \to 1'2'}^2 \delta(p_1 + p_2 - p_1' - p_2')
\]

\[
\int f_1(\vec{x}', \vec{p}_1') f_2(\vec{x}', \vec{p}_2') \tilde{f}_1(\vec{x}, \vec{p}_1') \tilde{f}_2(\vec{x}, \vec{p}_2') - f_1(\vec{x}, \vec{p}_1) f_2(\vec{x}, \vec{p}_2) \tilde{f}_1(\vec{x}', \vec{p}_1') \tilde{f}_2(\vec{x}', \vec{p}_2')
\]

- cross sections
- propagation of \( f(x,p) \)
- up to 2-body coll.
- energy cons.
- Pauli blocking

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Transport model and families

Boltzmann-Uehling-Uhlenbeck (BUU)

- nucleons divided by \(N_{TP}\) (infinite \(N_{TP}\) = exact solution of BUU eq.)
- 1-body phase-space function under MF potential
- Point or finite size of particles

Quantum Molecular Dynamics (QMD)

- Gaussian wave packets (\(N_{TP} = 1\))
- n-body Hamiltonian
- Correlation & fluctuations
What DJBUU is

Philosophy: EASY HANDLING & OPTIMIZING to RAON experiments

- DaeJeon Boltzmann-Uehling-Uhlenbeck project
- Jan. 2016 - Primary version of DJBUU (c/c++)
- 2016 ~ 2017 - innumerable test runs by M. Kim (short article in New Physics: Sae Mulli) supporting parallel calculation by openMP
- 2018 - advertising and joining Transport Model Evaluation Project (TMEP)
- 2019 ~ 2020 - application of parity doublet model in HIC (dynamical properties)
- 2021 ~ - study of pion production and symmetry energy
• Transport2014 (2014): Mainly 100A MeV, also 400A MeV Au+Au collisions. Stability, stopping, and flow of NN scatterings

• Transport2017 (2017): Box calculation of NN scatterings, mean-field evolutions, and pion-like particle production

Average density in time steps of Au+Au @ 100A MeV

\[ \rho \sim \rho_{\text{max}} \]

Sideward flow, form, & break neck, spectator fragmentation

Lower \( \rho \) init., fat & stretch out necks for BUU

Higher \( \rho \) init.
Transverse flow and slop parameter

- Theoretical uncertainties of flow parameter:
  - about 30% at 100A MeV and 13% at 400A MeV

- What is the origin of the uncertainties?
  - from collisions or interactions (MF)
Box calculations with periodic boundary conditions

- Details of periodic boundary conditions
  - a box of volume $V = L_1*L_2*L_3$, where the system is confined
  - the position of the center of box is $(L_1/2, L_2/2, L_3/2)$
  - a particle leaving the box, entering the opposite side with same momentum (number of particle is conserved)

- Initialization
  - uniform density with $\rho_0 = 0.16$ fm$^{-3}$, with isospin asymmetry = 0
    (1280 nucleons, 640 protons and 640 neutrons)
**Box-Cascade calculation**

without Pauli blocking

averaged over $t=60-140$ fm/c

- comparable DJBUU with rel. kinetic theory
  - well under control
  - not essentially affect to results of HIC simulation

- Pauli blocking - evolution of phase space occupations
- numerical fluctuations
  - BUU - shape & TP, QMD - width

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Box-Vlasov calculation

M. Colonna, et al., PRC (2021)

Damping sources:

- Landau damping: mixing modes
- Numerical damping: fluctuations

1. Decreases with increasing TP numbers
2. Decreases with increasing particle size

\[ \rho_k(t) = \int dz \sin(kz) \rho(z,t) \]

![Graph showing damping sources and characteristics](image-url)
RAON / LAMPS

LAMPS
(Large Acceptance Multi-Purpose Spectrometer)

- Possible experiment
  - Using 18.5 ~ 250 MeV/u Rl beam through IF separtor, perform N/Z controlled heavy-ion collision experiment for studying density dependent symmetry energy of nuclear matter possible Day-1 experiment: Ca + Ca to measure proton, neutron spectrum
  - Then, series of experiment for Ca + Ca, Ni + Ni, 58Ni + 112Sn, 106,112,124,130,132Sn + 112,118,124Sn to measure particle spectrum, yield, ratio, collective flow etc. at the same time

Present Constraints on the Symmetry Energy (shown as $E_{sym}(p/p_0)$)

- Experimental data are measured with stable beams
- Data of pion ratio and data of n/p flow are from different experiments
- Models in the market show different results even within same observable
Symmetry energy and pion productions

- Pion production and comparison with SπRIT @ RIKEN and FOPI @ GSI experiments
- Pion production w/ our NL model set in DJBUU (on going)
- Expansion to HICs with rare isotope: $\pi^-$ from neutron-rich
- rare isotope HICs @ RAON can be a key for symmetry energy since more $\pi^-$ from neutron rich

PRC 91, 014901 (2015)
Thank you.

Hulk vs Iron man, Marvel comics