Summary on transport code descriptions

Remarks on the nature of discrepancies between transport codes

physical input
(EOS, $\sigma_{inmed}$, $
\pi\Delta$ physics, ..)

→ transport code

→ observables

→ unique?, e.g. like 2N transfer
→ very complex, simulation of an equation rather than a solution
→ depends on the question you ask
Transport theory based on a chain of approximations

Martin-Schwinger hierarchy in many body densities:
    truncation, introduction of self energies (1-body quantities)

Quantum transport theory: Irreversibility, Kadanoff Baym theory

semiclassical approximation:
    Wigner transform, not necc. Phase space probabilities
    Gradient approximation (sep.of short and long scales)

Quasiparticle approximation
    Spectral function $\rightarrow$ delta function with effective quantities

$\rightarrow$ BUU equation

$$
\frac{\partial f}{\partial t} + \frac{\vec{p}}{m} \nabla^{(r)} f - \nabla^{(p)} U(r) f(r, p; t) = \int d\vec{v}_2 \, d\vec{v}_1' \, d\vec{v}_2' \, \nu_2, \sigma_{12}(\Omega) (2\pi)^3 \delta(p_1 + p_2 - p_1' - p_2') \delta(f_1 f_2' (1 - f_1)(1 - f_2') - f_1 f_2 (1 - f_1')(1 - f_2)) + \delta f(r, p, t)
$$

6-dim integro-differential equation, non-linear
$\rightarrow$ simulate solutions
    introduces many technical details

fluctuations variance of 2b collisions
neglect of higher orders
methods of solutions:

\[
\frac{\partial f}{\partial t} + \frac{\mathbf{p}}{m} \mathbf{\nabla}^{(r)} f - \mathbf{\nabla} U(r) \mathbf{\nabla}^{(p)} f = \int d\mathbf{v}_2 \, d\mathbf{\nu}_1 \cdot d\mathbf{\nu}_2 \cdot \mathbf{v}_{21} \sigma_{12}(\Omega) (2\pi)^3 \delta(p_1 + p_2 - p_1 - p_2') \left[f_1 f_2 (1 - f_2)(1 - f_2) - f_1 f_2 (1 - f_2')(1 - f_2') \right]
\]

Boltzmann-Vlasov-like (BUU) solve as exactly as possible:
- test particle method
- exact in the limit of \(N_{TP} \to \infty\)
- deterministic, no fluctuations
- include fluctuations explicitely
- connection between \(U\) and \(\sigma\)
  by approx of self energy,
  e.g. Brueckner theory

Molecular dynamic-like (QMD)
- inject classical fluctuations
- and correlations (nuclenton wave packet)
- damped (finite Gaussians,
  averaging width \(\Delta x\), parameter
+ Pauli correlations (AMD)
- relation between \(U\) and \(\sigma\) not so clear,

biggest difference:
role of fluctuations
fragmentation, correlation functions
but also affects Pauli blocking and collective excitations
Fluctuations: almost a „fight“ between MD and Boltzmann models:

\[
\frac{df}{dt} = I_{\text{coll}} + I_{\text{fluc}}
\]

now discussed beyond ideological barriers
"... in full bloom..." – a good sign for the expanding activity, but try to make relation and changes transparent,
„...lots of individuals...“
Steps in solving transport simulation
- initialization
- propagation of (test) particles (Vlasov)
- Collision partners and probabilities, elastic (Boltzmann)
- Pauli blocking (Ühling-Uhlenbeck)
- inelastic collisions (new particles), often perturbative, dep. on energy

Code comparison:
- differences of results of codes, e.g. isospin diffusion, pion ratios
- 1. phase: comparison of HIC with controlled input
  - differences seen (talk of Betty)
  - indications of reasons (initialization, Pauli blocking)
  - but difficult to pin point
  - general systematic theoretical error (30% (100 MeV), 13% (400 MeV)
    how to improve?
- 2. phase: box calculations
  - better controlled conditions
  - exact limits often available
  - resolve differences because of strategies and of errors
    from intrinsic differences (like BUU vs. QMD)
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**Initialization:** solvable,
- initialize consistent with density functional used in transport
  so that initial nucleus is a good approximation to the ground state
- more important than having identical density distributions

**Propagation:** hamiltonian eom, easy
but
fluctuation dampen critically collective motions
momentum dependence, energy conservation
Second formulation of Homework #2:

*Longer final time and results given each 0.5-1 fm/c*

\[ \rho_k(t) = \int dz \, \sin(kz) \rho(z,t) \quad k = n \frac{2\pi}{L} \]

**Time evolution of Fourier transform** \( \rho_k \)

**Different oscillation frequency in BUU-like**

**Larger damping and structureless fluctuations in QMD-like**
Collision probabilities:

**Bertsch prescription**: particles collide,
- if their distance is below the interaction length and
- if they reach the distance of closest approach in this time step
- improve: the same nucleons should not collide again in the next time step

Lesson: exact results come from kinetic theory, which makes assumptions in complete independence of collisions and equilibrium

→ not so easy to follow in simulations (not always good)

**Mean free path description**: assure mean free path from kinetic theory
assure agreement limits put perhaps oversimplified in collisions (no equilibrium)
Theoretical results for CT0

Effect in $dN_{\text{coll}}/dt$ for CT0: $124^1$ (nonrelativistic) $\rightarrow$ 119 (relativistic)

Ideal value for Boltzmann: 116.8 (nonrelativistic) $\rightarrow$ 112.6 (relativistic, by J. Xu)
Pauli blocking:

occupation probability \( f(r,p,t) \)

- local
- but realistically averaged over a volume
- often very large, non-localities
- fluctuations!

consequence: evolution to a MB distribution, \( f(p) > 1 \)
prescription: \( f \leq 1 \)

how much this affects a transport simulation not clear, very likely in the initial stages, e.g. pre-eq emission
**Fluctuations**: biggest differences between families of codes and implementation of codes

important: yes!
indirect: blocking, mf propagation
direct: fragments formation

test also fluctuations and fragmentation

how treated:
- BV-like $\rightarrow$ Boltzmann-Langevin eq.
  - realizations: BOB, SMF, BLOB
- MD-like: damped classical fluctuations
  - parameter $D_x$ of wave packets

light clusters: another problem, $\rightarrow$ tomorrow afternoon.
freeze out:
assumption of a completely equilibrated primary fragment is probably too naive.
there is still collective motion: expansion

perhaps a differential freeze-out, surface layer of an expanding source
→ see e.g. Natowitz experiments
check with transport models

short range correlations:

proposed treatments:
1. initialize momentum distribution
   - but has to active at every moment
2. calculate correlation energy in nuclear matter
   and use this as a part of the potential energy
   - does not generate high energy particles
3. three body collisions, to conserve energy
   - difficult