UrQMD Simulation Model: User Guide & Manual

Hadronic Transport Theory & Hands-on Simulation Workshop

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Session Agenda & 4 Core Modules

1. Physics Background

- Why simulate heavy-ion collisions?
- Hadronic Transport Theory (UrQMD)
- Relativistic Boltzmann Transport (RBTE)
- QCD Phase Diagram
- Resonances vs String Excitation

2. Reaction Mechanisms

- Resonance Formation / Decay ($\Delta(1232)$)
- Lund String Fragmentation
- Equation of State (EoS)
- Chemical & Kinetic Freeze-out

3. UrQMD Installation & Usage

- Prerequisites and Code Compilation
- Writing Main `inputfile`
- Run Control Scripts & Environment Variables
- Impact Parameter b from Centrality

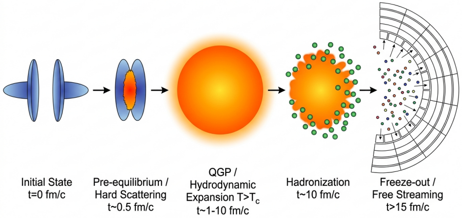
4. Output Files & Data Analysis

- Structure of `.f13` Output (23 Columns)
- ITYP Particle ID Tables (Baryons, Mesons, Nuclei)
- File `.f14` & Process IDs
- Python Data Analysis (p_T Spectra)

1. Hadronic Transport Theory: Why Simulate Heavy-Ion Collisions?

Physics Goal & Experimental Limitations

- **Primary Goal:** Create and study Quark-Gluon Plasma (QGP) under extreme conditions.
- **Subatomic Scale Limits:** Collision volume is tiny ($\sim 10^{-15}$ m) and lifetime is short ($\sim 10^{-23}$ s). Detectors cannot be placed inside the collision zone.
- **Experimental Measurement:** Detectors record only **Final State Particles**.
- Microscopic Monte Carlo transport "rewinds time" to track every particle from initial contact to detector freeze-out!



1. Relativistic Boltzmann Transport Equation (RBTE)

Governing Kinetic Equation in Phase Space

For particle species i of mass m_i, phase-space distribution function $f_i(x, p)$ obeys:

$$p^\mu \frac{\partial f_i(x,p)}{\partial x^\mu} + m_i F^\nu \frac{\partial f_i(x,p)}{\partial p^\nu} = C_i(x,p)$$

1. Free Streaming

$$p^\mu \frac{\partial f_i}{\partial x^\mu}$$

Free spatial propagation of particles in phase space.

2. Mean Field

$$m_i F^\nu \frac{\partial f_i}{\partial p^\nu}$$

Forces from nuclear mean field ($U(\rho)$) altering momenta.

3. Collision Term

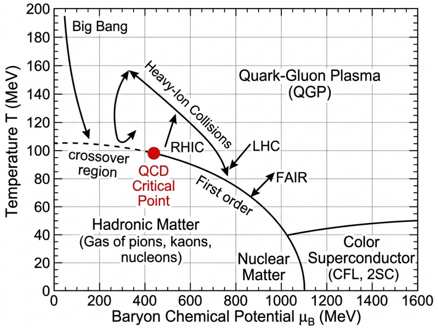
$$C_i = C_i^{\text{gain}} - C_i^{\text{loss}}$$

Describes 2-body scatterings, resonance formation, and decays.

1. QCD Phase Diagram & Global Research Objectives

Key Research Questions

- **Phase Transition:** Transition from Hadron Gas to Quark-Gluon Plasma (QGP).
- **QCD Critical Point:** Locate critical point on the (T, μ_B) plane.
- **Global Facilities:** RHIC Beam Energy Scan (BES), LHC, FAIR (GSI), NICA (JINR).
- **UrQMD Role:** Standard theoretical baseline model for experimental comparisons.



1. Reaction Regimes: Resonances vs String Excitation

Low Energy ($\sqrt{s_{NN}} < 5$ GeV)

- Dominated by **Resonance Formation**.
- Excitation of $\Delta, N^*, \Lambda^*, \Sigma^*$ and decays.
- Supports over 50 resonance species.

High Energy ($\sqrt{s_{NN}} > 5$ GeV)

- Resonance mechanism is insufficient.
- Transitions to **Lund String Model**.
- Color strings stretch and fragment into multiple hadrons.

Mechanism Transition Energy

UrQMD transitions between Resonance and String excitation at $\sqrt{s} \approx 3$ GeV (configurable via `CTP(60)`).

2. Resonance Formation & Decay Dynamics

Example: $\Delta(1232)$ Dynamics

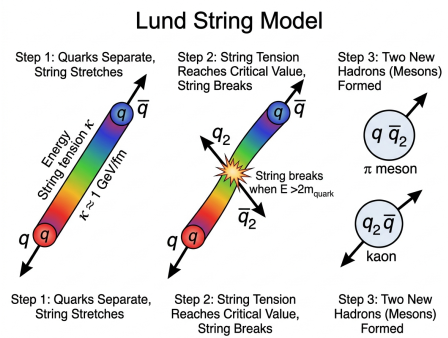
$$p + p \to p + \Delta^+(1232) \quad \text{(Formation)}$$
$$\Delta^+(1232) \to p + \pi^0 \quad \text{(Main Decay)}$$
$$\Delta^+(1232) \to n + \pi^+ \quad \text{(Alternative Channel)}$$

Resonance Lifetime (τ_Δ)

Mass $m_\Delta = 1232$ MeV, Width $\Gamma_\Delta \approx 120$ MeV:

$$\tau_\Delta = \frac{\hbar}{\Gamma_\Delta} = \frac{197.3 \text{ MeV} \cdot \text{fm}/c}{120 \text{ MeV}} \approx 1.6 \text{ fm}/c$$

$$\tau_\Delta \approx 5.5 \times 10^{-24} \text{ seconds}$$



4 Steps of String Fragmentation ($\sqrt{s} > 5$ GeV)

1. Quarks q and diquarks qq are pulled apart.
2. Color string stretches with constant tension $\kappa \approx 1$ GeV/fm.
3. When field energy is sufficient, string breaks producing $q\bar{q}$ pairs from vacuum.
4. Fragmented string bits hadronize into new mesons and baryons.

2. Equation of State (EoS) Options

eos	EoS Mode Name	Physical Meaning & Application	K (MeV)
0	Cascade Mode	No mean fields; straight line propagation between collisions	—
1	Hard Skyrme EoS	Hard Skyrme potential $U(\rho)$; stiff nuclear matter	380
2	Soft Skyrme EoS	Soft Skyrme potential $U(\rho)$; compressible nuclear matter	200

Skyrme Potential Formula

$$U(\rho) = \alpha \left(\frac{\rho}{\rho_0} \right) + \beta \left(\frac{\rho}{\rho_0} \right)^{\gamma}$$

where $\rho_0 = 0.16\ \mathrm{fm}^{-3}$ is normal nuclear density, and α, β, γ are incompressibility parameters.

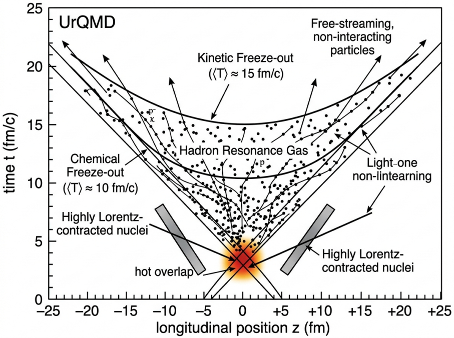
2. Two Freeze-out Stages: Chemical vs Kinetic Freeze-out

1. Chemical Freeze-out ($T_{ch} \approx 160$ MeV)

- **Inelastic collisions cease.**
- Abundances and ratios of particle species (π, K, p, Λ) are fixed.

2. Kinetic Freeze-out ($T_{kin} \approx 100$–120 MeV)

- **Elastic collisions cease.**
- Particle momenta and trajectories are fixed (Free Streaming).
- **Recorded in `.f13` Columns 16–23!**



3. Installation & Code Compilation (5 Core Steps)

```
# 0. Install required build prerequisites (Ubuntu/Debian)
sudo apt update && sudo apt install -y build-essential gfortran tar gzip bash

# 1. Extract source archive urqmd-4.0.tar.gz
tar -xzvf urqmd-4.0.tar.gz

# 2. Set directory access permissions
chmod -R 700 urqmd-4.0

# 3. Compile source code via make (use FFLAGS for gfortran 10+)
cd urqmd-4.0
make
```

Compilation Output

Executable binary file `urqmd.x86_64` is generated in the working directory!

3. Writing the Main Input File (`inputfile`)

Actual inputfile ($p+p$ @ 5.02 TeV)

```
pro 1 1 ! Proton projectile
tar 1 1 ! Proton target

nev 5 ! 5 Events (or 1000)
imp 0.0 ! p+p collision

ecm 5020 ! sqrt(s) = 5.02 TeV
tim 200 200 ! Run 200 fm/c

#f13 ! Enable freeze-out .f13
f14 ! Disable .f14
f15 ! Disable .f15
f16 ! Disable .f16
f19 ! Disable .f19
f20 ! Disable .f20

xxx ! End of input
```

Main Flags Explanation

- `nev`: Number of events to simulate
- `tim`: Maximum simulation time (fm/c)
- `eos`: Equation of State mode ($0 =$ Cascade)
- `pro/tar`: Colliding nuclei (A, Z)
- `ene`: Center-of-mass energy $\sqrt{s_{NN}}$ (GeV)
- `imp`: Impact parameter b (fm)
- `cto 64 1`: Enable light nuclei output (d, t)
- `eee`: End of input file

3. Program Execution & Environment Variables

```
# Run via standard control script
./runqmd.bash

# Or run directly via executable binary
./urqmd.x86_64 < inputfile
```

Variable	Default File	Role and Description
`ftn09`	`inputfile`	Main input control file
`ftn13`	`test.f13`	Final state particle output (Kinetic Freeze-out)
`ftn14`	`test.f14`	Time snapshot output file
`ftn15`	`test.f15`	Full collision history log file

3. Impact Parameter b Calculation from Centrality Class ($n\%$)

Glauber Model Formula

$$b_{n\%} = \sqrt{\frac{n\%}{100}} \times 2 \times r_0 \times A^{1/3} \quad (r_0 = 1.25 \text{ fm})$$

1. Gold-Gold Collision (^{197}Au + ^{197}Au)

$$b_{5\%} = \sqrt{0.05} \times 2.5 \times (197)^{1/3} \approx \mathbf{3.25} \text{ fm}$$

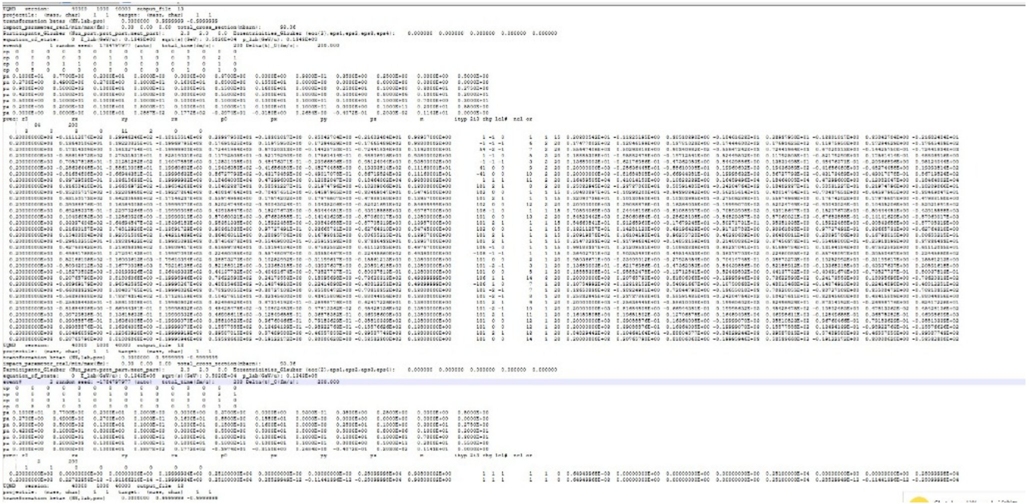
Input setting for 0–5% Central: `imp -3.25`

2. Lead-Lead Collision (^{208}Pb + ^{208}Pb)

$$b_{5\%} = \sqrt{0.05} \times 2.5 \times (208)^{1/3} \approx \mathbf{3.31} \text{ fm}$$

Input setting for 0–5% Central: `imp -3.31`

4. Raw Output Screenshot of File .f13



Components of File .f13

4. 23-Column Line Structure in Output File `.f13`

Column	Variable & Meaning	Column	Variable & Meaning
1	Current time t (fm/c)	13	Parent Coll. (Parent particle ID)
2–4	Position r_x, r_y, r_z (fm)	14	N_{coll} (Collision count)
5	Total energy E (GeV)	15	Parent Proc. (Parent Process ID)
6–8	Momentum p_x, p_y, p_z (GeV/c)	**16**	**Freeze-out time t^{fr} (fm/c)**
9	Rest mass m (GeV/c^2)	**17–19**	**Freeze-out position $r_x^{\text{fr}}, r_y^{\text{fr}}, r_z^{\text{fr}}$ (fm)**
10	**Particle ID (`ityp`)**	**20**	**Freeze-out energy E^{fr} (GeV)**
11	Isospin Projection (`iso3`)	**21–23**	**Freeze-out momentum $p_x^{\text{fr}}, p_y^{\text{fr}}, p_z^{\text{fr}}$ (GeV/c)**
12	Electric charge (`chg`)		

4. Standard Particle ID Tables (`ityp`)

Baryons (`ityp`)

- Nucleon (p, n): 1
- $\Delta(1232)$: 24
- $\Lambda(1116)$: 41
- $\Sigma(1192)$: 54
- $\Xi(1317)$: 63
- $\Omega(1672)$: 69

Mesons (`ityp`)

- Pion (π): 101
- Kaon (K): 106
- Eta (η): 102
- Rho (ρ): 104
- Omega (ω): 103
- Phi (ϕ): 109

Nuclei (`ityp`)

- Deuteron (d): 200
- Triton (t): 201
- Helium-3 (^{3}He): 202
- Helium-4 (^{4}He): 203
- Hypertriton ($^3_\Lambda$H): 211

Particle and Antiparticle Convention

Particles have **positive** `ityp` values, while antiparticles have **negative** `ityp` values (e.g., $-1 = \bar{p}$, $-101 = \pi^-$, $-200 = \bar{d}$).

4. File `.f14` & Reaction Process IDs

File `.f14` (Collision History)

- Log of every collision in each event.
- Records time, position, and particle species before/after collision.
- Very large file size (several GB); use when studying collision history.

Process ID	Reaction Type
1	$NN \to N\Delta$ (Δ production)
13	BB elastic scattering
15	$BB \to 2$ strings (String excitation)
20	Resonance Decay
23	$B\bar{B}$ annihilation

Spectrum Formula & Statistical Error (Poisson Uncertainty)

$$\text{Yield} = \frac{1}{N_{\text{ev}}} \times \frac{N_j}{\Delta p_T \times \Delta y}, \quad \delta(\text{Yield}) = \frac{\sqrt{N_j}}{N_{\text{ev}} \times \Delta p_T \times \Delta y}$$

Single Comprehensive Exercise Steps

1. Parse `test.f13` using **21-header line rule** (read N_{part} from line 20).
2. Extract freeze-out momentum $p_x^{\text{fr}}, p_y^{\text{fr}}, p_z^{\text{fr}}, E^{\text{fr}}$ from columns 20–23.
3. Compute $p_T = \sqrt{p_x^2 + p_y^2}$ and $y = \frac{1}{2} \ln \frac{E+p_z}{E-p_z}$; apply $|y| < 0.5$ ($\Delta y = 1.0$).
4. Bin in p_T, count particles N_j, compute Yield and Poisson error $\sqrt{N_j}$.
5. Plot 3 panels ($\pi^+ + \pi^-$, $K^+ + K^-$, $p + \bar{p}$) comparing UrQMD with ALICE Data.

Questions & Comments? (Q&A)

Thank you for your active participation!

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