Lecture
Introduction:
′Dynamical models for relativistic heavy-ion collisions′

SS2019: ′Dynamical models for relativistic heavy-ion collisions′
Lectures:
Monday, 10:15-11:45
Room: FIAS_0.101

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Manuscript:
http://theory.gsi.de/~ebratkov/LecturesSS2019/Lec_SS2019.html
From Big Bang to Formation of the Universe

Can we go back in time?
... back in time

'Re-create' the Big Bang conditions:
matter at high temperature and pressure
such that nucleons/mesons decouple to quarks and gluons -- Quark-Gluon-Plasma

'Little Bangs' in the Laboratory:
Heavy-ion collisions at ultrarelativistic energies
Heavy-ion collisions

- **Heavy-ion collision experiment**
  - 're-creation' of the Big Bang conditions in laboratory:
    - Matter at high pressure and temperature

- **Heavy-ion accelerators**:
  - Large Hadron Collider - LHC (CERN):
    - Pb+Pb up to 574 A TeV
  - Relativistic-Heavy-Ion-Collider - RHIC (Brookhaven):
    - Au+Au up to 21.3 A TeV
  - Facility for Antiproton and Ion Research – FAIR (Darmstadt)
    - (Under construction)
    - Au+Au up to 10 (30) A GeV
  - Nuclotron-based Ion Collider fAcility – NICA (Dubna)
    - (Under construction)
    - Au+Au up to 60 A GeV
Quantum Chromo Dynamics:

predicts strong increase of the energy density $\varepsilon$ at critical temperature $T_C \sim 160$ MeV

$\Rightarrow$ Possible phase transition from hadronic to partonic matter (quarks, gluons) at critical energy density $\varepsilon_C \sim 0.5$ GeV/fm$^3$

Critical conditions - $\varepsilon_C \sim 0.5$ GeV/fm$^3$, $T_C \sim 160$ MeV - can be reached in heavy-ion experiments at bombarding energies > 5 GeV/A
Dense and hot matter – average quantities

Time evolution of the baryon density and energy density

huge energy and baryon densities are reached ($\varepsilon > \varepsilon_{\text{crit}} = 0.5 \text{ GeV/fm}^3$) at FAIR/NICA energies (> 5 A GeV)
The 'holy grail' of heavy-ion physics:

- Study of the phase transition from hadronic to partonic matter – Quark-Gluon-Plasma
- Search for the critical point
- Study of the in-medium properties of hadrons at high baryon density and temperature

The phase diagram of QCD

- Early universe
- RHIC, LHC
- Far SIS 300
- Color Superconductor?
'Little Bangs' in the Laboratory

Initial State

\[ \text{Au} + \text{Au} \]

Quark-Gluon-Plasma?

Hadronization

How can we prove that an equilibrium QGP has been created in central heavy-ion collisions?!
Signals of the phase transition:
- Multi-strange particle enhancement in A+A
- Charm suppression
- Collective flow ($v_1$, $v_2$)
- Thermal dileptons
- Jet quenching and angular correlations
- High $p_T$ suppression of hadrons
- Nonstatistical event by event fluctuations and correlations
- ...

Experiment: measures final hadrons and leptons

How to learn about physics from data?

Compare with theory!
Basic models for heavy-ion collisions

- **Statistical models:**
  - **basic assumption:** system is described by a (grand) canonical ensemble of non-interacting fermions and bosons in thermal and chemical equilibrium = thermal hadron gas at freeze-out with common $T$ and $\mu_B$
  - [ - : no dynamical information]

- **Hydrodynamical models:**
  - **basic assumption:** conservation laws + equation of state (EoS);
  - assumption of local thermal and chemical equilibrium
  - Interactions are ‘hidden‘ in properties of the fluid described by transport coefficients (shear and bulk viscosity $\eta$, $\zeta$, ..), which is ‘input’ for the hydro models
  - [ - : simplified dynamics]

- **Microscopic transport models:**
  - based on transport theory of relativistic quantum many-body systems
  - Explicitly account for the interactions of all degrees of freedom (hadrons and partons) in terms of cross sections and potentials
  - Provide a unique dynamical description of strongly interaction matter in- and out-off equilibrium:
  - In-equilibrium: transport coefficients are calculated in a box – controled by IQCD
  - Nonequilibrium dynamics – controled by HIC
  - Actual solutions: Monte Carlo simulations
  - [+ : full dynamics | - : very complicated]
Models of heavy-ion collisions

- Initial
- Transport
- Thermal + Expansion
- Hydro
- Thermal model
- Final
Results from statistical models for HIC


Good description of the hadron abundances by the thermal hadron gas model ➔
The hadron abundances are in rough agreement with a thermally equilibrated system !

➔ Partial thermal and chemical equilibration is approximately reached in central heavy-ion collisions at relativistic energies!

! Statistical models do not provide an answer to the origin of thermalization.
HIC dynamics and the approach to thermal equilibrium is driven by the interactions !

➔ dynamical models of HIC
Stages of a collision in VISHNU

From u.osu.edu/vishnu/
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$Au + Au$ at 200 A GeV, $b = 2.2$ fm

$t = 0.1$ fm/c
Au+Au at 200 A GeV, b=2.2 fm

\[ t = 1.63549 \text{ fm/c} \]
Au+Au at 200 A GeV, b=2.2 fm

t = 2.06543 fm/c
Au+Au at 200 A GeV, b=2.2 fm

\[ t = 3.20258 \text{ fm/c} \]
Au+Au at 200 A GeV, b=2.2 fm

t = 5.56921 fm/c
Au+Au at 200 A GeV, b=2.2 fm

t = 8.06922 fm/c
Au+Au at 200 A GeV, b=2.2 fm

\[ t = 10.5692 \text{ fm/c} \]
Au+Au at 200 A GeV, $b=2.2$ fm

$t = 15.5692$ fm/c
Au+Au at 200 A GeV, b=2.2 fm

t = 20.5692 fm/c
Dynamical models for HIC

**Macroscopic**

- **hydro-models:**
  - description of QGP and hadronic phase by hydrodynamic equations for fluid
  - assumption of local equilibrium
  - EoS with phase transition from QGP to HG
  - initial conditions (e-b-e, fluctuating)

  - ideal
    (Jyväskylä, SHASTA, TAMU, ...)
  - viscous
    (Romachkke, (2+1)D VISH2+1, (3+1)D MUSIC, ...)

**Microscopic**

- **Non-equilibrium microscopic transport models – based on many-body theory**

  - **Hadron-string models**
    (UrQMD, IQMD, HSD, QGSM ...)

  - **Partonic cascades**
    pQCD based
    (Duke, BAMPS, ...)

- **Parton-hadron models:**
  - QGP: pQCD based cascade
  - massless q, g
  - hadronization: coalescence
    (AMPT, HIJING)

- **QGP: IQCD EoS**
  - massive quasi-particles (q and g with spectral functions) in self-generated mean-field
  - dynamical hadronization
  - HG: off-shell dynamics (applicable for strongly interacting systems)

**fireball models:**

- no explicit dynamics: parametrized time evolution (TAMU)

**Hybrid**

QGP phase: hydro with QGP EoS
- hadronic freeze-out: after burner - hadron-string transport model
  (hybrid*: UrQMD, EPOS, ...)

*PHSD*
References

Eds: B. L. Friman, C. Höhne, J. E. Knoll, S. K. K. Leupold, J. Randrup, R. Rapp, and P. Senger;
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