QCD matter under extreme conditions: The role of hadronic interactions

Hannah Elfner

December 5\textsuperscript{th} 2019, Colloquium Eötvös University, Budapest
Quantum Chromodynamics (QCD)
What Matter is Made of...

Quarks are basic constituents

Molecule  Atom  Nucleus  Proton/Neutron  Quark
Standard Model of Particle Physics

- 12 elementary building blocks
- Only 3 are needed for known matter (u, d, e)

Picture: DESY and Teilchenzoo
Standard Model of Particle Physics

- 12 elementary building blocks
- Only 3 are needed for known matter (u, d, e)

$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{D} \gamma_{\mu} X + h.c. + \chi_{i} X_{ij} X_{3i} \phi + h.c. + 12 \phi - V(\phi)$

Picture: DESY and Teilchenzoo
The Strong Force

- Gluons act like a string and prevent quarks from roaming around freely

production of quark-antiquark pairs out of vacuum
Constituents of Matter

- Chroma (Χρώμα) = 'Color' (Greek)
- Analogy to electric color, possible states are 'white'

**Mesons** \((q\bar{q})\)
e.g. pions \((u\bar{u},d\bar{d},d\bar{u},u\bar{d})\)

**Baryons** \((qqq)\)
e.g. proton \((uud)\)  
neutron \((udd)\)

Quantum Chromodynamics

- Coupling is strong in the regime of interest
- Perturbation theory is not valid
- Hadronization is one of the unsolved big questions

- With expensive lattice calculations thermodynamic properties can be calculated
- Many-body non-equilibrium dynamics is not solvable from first principles

Reference: PRC 78, 2016
The Origin of Mass

- Higgs is only responsible for a small part, the bare mass (~2% of the proton mass)
- $3 + 3 + 5 << 1000$

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- The strong interaction generates the same amount of mass for all quark species

C. Fischer

Nobel prize 2013
Big Bang in the Laboratory
A New State of Matter

High densities and temperatures change the properties of nuclear matter.

- Major goals of heavy ion research:
  - Exploring the phase diagram of strongly interacting matter
  - Understanding the properties of the quark gluon plasma
The Big Bang in the Laboratory

- Microseconds after the Big Bang the whole universe was in the quark gluon plasma phase

Heavy ion collisions provide hot and dense nuclear matter, the quark gluon plasma in the laboratory
• 'White' nuclei produce colored plasma
Creating the QGP in the Lab

• ALICE at **Large Hadron Collider**, CERN

• How to find relics of the QGP in the traces of thousands of hadrons?

Reference to PRC 78, 2016
Theoretical models are essential to gain insights about the properties of the quark gluon plasma.

Fundamental field theory of strong interactions (QCD)

\[ \mathcal{L}_{\text{QCD}} = \bar{\psi}_i (i\gamma^\mu (D_\mu)_{ij} - m \delta_{ij}) \psi_j - \frac{1}{4} G^{\alpha}_{\mu\nu} G^{\alpha}_{\mu\nu} \]

Dynamical description of heavy ion reactions

Measurements in the detector (CBM@FAIR)
Dynamic description of heavy ion collisions has to capture all the stages of the reaction:

- Due to the short time scale of $10^{-22}$ seconds and the tiny volume $(10 \times 10^{-15} m)^3$ the quark gluon plasma escapes direct detection.
Hybrid Approaches

Transport

Microscopic description of the whole phase-space distribution
Non-equilibrium evolution based on the Boltzmann equation
\( \left( p^\mu \partial_\mu \right) f = I_{\text{coll}} \)
Partonic or hadronic degrees of freedom
Cross-sections are calculable using different techniques
Phase transition?

Hydrodynamics

Macroscopic description
Local equilibrium is assumed
\( \partial_\mu T^{\mu\nu} = 0 \quad \partial_\mu (nu^\mu) = 0 \)
Propagation according to conservation laws
Equation of state is an explicit input
Boundary conditions: Breakdown of equilibrium assumptions?

• Combine the advantages of both approaches
• Successful description from initial to final state
One Event at RHIC Energies

Time: 0.08

MADAI.us
Why Hybrid Approaches?
The Ideal Fluid

- Press release of Brookhaven National Lab (2005):
  - At RHIC a new state of matter has been formed that acts like an ideal fluid

**A New Area of Physics**

RHIC has created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted. Instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions is more like a liquid.

### A "Perfect" Liquid

RHIC scientists had expected collisions between two beams of gold nuclei to mimic conditions of the early universe and produce a gaseous plasma of the smallest components of matter — the quarks.

### Quark-Gluon Plasma

RHIC's perfect liquid also turns out to be the hottest matter ever created in a laboratory, measuring some 4 trillion degrees Celsius, or 250,000 times hotter than the center of the Sun.

Google image search for ‘perfect liquid’

Here is the heavy-ion reaction
Elliptic Flow

- Second coefficient of the Fourier expansion of the azimuthal particle distribution:

\[
\langle \left( \frac{p_x^2 - p_y^2}{p_T^2} \right) \rangle
\]

Coordinate space asymmetry \rightarrow \text{momentum space anisotropy}

- Relativistic fluid dynamics with very low viscosity describes elliptic flow at RHIC (and LHC)
Collective Behaviour

- Response of the system to initial spatial anisotropy

No secondary interactions
mean free path $\lambda \rightarrow \infty$

Spatial anisotropy
$$\epsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

Interactions between particles

Momentum anisotropy
$$v_2 = \frac{\langle p_x^2 - p_y^2 \rangle}{\langle p_x^2 + p_y^2 \rangle}$$

Hydrodynamic behaviour
mean free path $\lambda \rightarrow 0$
Shear Viscosity

- Transport coefficient of the quark-gluon plasma
  - Measures momentum transfer orthogonal to direction of motion

- Small viscosity → strongly coupled system
- Large viscosity → few interactions
Hottest and coldest matter on earth exhibits similar features associated with strongly coupled systems.


- Lithium atoms at release from an optical trap:
  - Initial almond shape is similar to interaction region in heavy ion collisions
  - One can actually observe the build up of elliptic flow through differences in pressure gradients

Hottest and coldest matter on earth exhibits similar features associated with strongly coupled systems.
Comparison to Experimental Data

- Fluctuations from nucleon positions and energy deposition in binary collisions included
- Without tuning anything $v_3$ at RHIC and flow at LHC in agreement with experimental data


Zimanyi Colloquium

Hannah Elfner

25/05/19

Reference to PRC 78, 2016
HP (now Elfner), PRC84 (2011) 034912
Event-by-event Fluctuations
Origin of Fluctuations

Underlying question:
Why do collisions of undistinguishable nuclei in the ground state exhibit different properties?

• Controllable differences:
  • Change of beam energy
  • Selection of centrality
  • Different system sizes (ion species)

• But: Quantum fluctuations are unavoidable

The challenge:
Fluctuations affect the observables of the quark-gluon plasma

And opportunity:
Initial state fluctuations constrain transport coefficients
Event-by-event measurements in heavy-ion reactions contribute to the understanding of initial state of highly excited nuclei
Sources of Fluctuations

- **Granularity** is influenced by
  - Nucleon positions
  - Distribution of collisions
  - Type of interaction
  - Degree of thermalisation

- Differences in form and fluctuations are quantified:
  - Fourier expansion in coordinate space

\[ \varepsilon_2 + \varepsilon_3 + \varepsilon_4 + \varepsilon_5 + \cdots \]
Anisotropic Flow - Higher Coefficients

Simplified picture:
Coordinate space anisotropy $\rightarrow$ Momentum space anisotropy
Status 2010

A multitude of new observables has been defined and requires event-by-event calculations

Analogy to Cosmology

Temperature fluctuations in early universe

Energy density fluctuations in nuclear collisions

Analysis of multipol moments

Analysis of anisotropic flow

→ Matter content of the universe

→ Transport properties of QCD matter
Triangular flow is **very sensitive** to amount of initial state fluctuations

- Demonstrated in event-by-event calculation with different granularities
Interplay of viscosity and fluctuations in the initial state:
- Large structures and ideal fluid dynamics = small structures and viscous hydrodynamics
- Event-by-event calculations with many parameters required
Transport Coefficients

- Shear viscosity has been constrained over many years

- Bayesian multi-parameter analysis yields confidence interval for temperature dependence of shear viscosity to entropy ratio


RHIC White paper, 2012
Towards Finite $\mu_B$
Lattice QCD cannot be employed at finite densities due to the sign problem — many interesting questions:

- What are the relevant degrees of freedom at high densities?
- Phase transition, critical endpoint?
- Properties of neutron star mergers?

The QCD Phase Diagram

STAR experiment at RHIC

Relevant for neutron star mergers as detected by gravitational waves (GW170817)

Dana Berry, SkyWorks Digital, Inc
• Creation of densest matter world-wide
• High collision rates
• Starting ~2025

Facility for Anti-Proton and Ion Research in Darmstadt-Wixhausen

GSI webpage, August 2019
Exploring the Phase Diagram

Au+Au @ 25 GeV/u

MADAI.us  
Time: 3.67
The Phase Diagram

- Two regimes with well-established approaches
- Goals:
  - Constraints on the equation of state of nuclear matter
  - Determine limit of applicability of hadronic transport approach
  - Qualitative signatures of first order phase transition
SMASH
A Hadron Transport Approach
### Simulating Many Accelerated Strongly-Interacting Hadrons

- **Hadronic transport approach:**
  - Includes > 150 mesons and baryons
  - Based on relativistic Boltzmann equation

\[
p^\mu \partial_\mu f_i(x, p) + m_i F^\alpha_\alpha \partial_\alpha f_i(x, p) = C^{\text{coll}}_i
\]

- Open source code: C++, Git, Python Analysis Suite
- Already used by HADES, CBM, JETSCAPE, BEST and individuals

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Energy density [GeV/fm\(^3\)]

Landau frame velocity (arrows)

- Au+Au at \(E_{\text{Kin}} = 0.8\ \text{AGeV}, b=3\ \text{fm}\)
The SMASH Team

- In Frankfurt:
  - Oscar Garcia-Montero
  - Vinzent Steinberg
  - Jean-Bernard Rose
  - Jan Staudenmaier
  - Anna Schäfer
  - Justin Mohs
  - Natey Kübler
  - Jan Hammelmann
  - Damjan Mitrovic
  - Philip Karan
  - Martha Ege

- In US/Serbia/China:
  - Dmytro Oliinychenko
  - LongGang Pang
  - Jussi Auvinen
  - Sangwook Ryu

Subset of the group in July 2019
## Degrees of Freedom

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- Mesons and baryons according to particle data group
- Isospin multiplets and anti-particles are included

As of SMASH-1.7

- + corresponding antiparticles
- Perturbative treatment of photons and dileptons
- Isospin symmetry
Elementary Cross Sections

- Total cross section for pp/pπ collisions
- Parametrized elastic cross section
- Many resonance contributions to inelastic cross section
- Reasonable description of experimental data
- Transition from resonances to strings at intermediate energies

J. Weil et al, PRC 94 (2016), updated SMASH-1.7
• Comparison to analytic solution of Boltzmann equation within expanding metric

• Perfect agreement proves correct numerical implementation of collision algorithm

D. Bazow et al., PRL 116 (2016) and PRD 94 (2016)  
J. Tindall et al., PLB 770 (2017)
Pion Production in Au+Au

- Potentials decrease pion production, while Fermi motion increases yield
- Nice agreement with SIS experimental data

Note: consecutive addition of features

J. Weil et al, PRC 94 (2016)
Dileptons do not interact strongly and escape the interaction region.

Coarse-grained transport evolution allows for full medium-modified spectral function.

Comparison allows for detailed investigation of medium modifications.

S. Endres et al., PRC 92, 2015
Transport Coefficients
Shear Viscosity of the Hadron Gas

Green-Kubo formalism
UrQMD

Discrepancy with hydro-inspired B3D and VISHNU

- KSS bound: $1/4\pi$
- Chiral Pions
- $N_f=3$ pQCD
- Hadron gas w/ $\mu_B=0$, $\mu_\pi=0$

$\eta/\sigma$

100
Temperature (MeV)

$\eta/\sigma$

0.1


Long standing question: Why are the results so different from each other?

N. Demir and S.A. Bass, PRL 102 (2009)
Shear Viscosity over Entropy Density

- Hadron gas in thermodynamic equilibrium realised by box with periodic boundary conditions
- Entropy is calculated via Gibbs formula from thermodynamic properties
- The shear viscosity is extracted following the Green-Kubo formalism:

\[
T^{\mu\nu} = \frac{1}{V} \sum_{i}^{N_{\text{part}}} p_{i}^{\mu} p_{i}^{\nu}
\]

\[
C^{xy}(t) = \frac{1}{N} \sum_{s} T^{xy}(s) T^{xy}(s + t)
\]

\[
C^{xy}(t) \simeq C^{xy}(0) \exp \left( -\frac{t}{\tau} \right)
\]

\[
\eta = \frac{V C^{xy}(0) \tau}{T}
\]
Resonance Dynamics

- Energy-dependence of cross-sections is modeled via resonances
- Point-like in analytic calculation and finite lifetime in transport approach
- Agreement recovered by decreasing ρ meson lifetime
Comparison to Literature

- Closest similarity to Bass/Demir result as expected
• Adding a constant elastic cross section leads to agreement with B3D result

• Approximately linear relationship between relaxation time and mean free time is recovered

• Viscosity constrains the hadronic interactions
Electric Conductivity

- Comparison to linear response kinetic theory to validate our approach

\[ \sigma_{el} = \frac{V}{T} \int_{0}^{\infty} \langle j_{i}(0)j_{i}(t) \rangle dt \]

- Infinite matter with constant \( \sigma = 30 \text{ mb} \)


Influence of Lifetime

- Results for electric conductivity are independent of resonance lifetimes
  
  [Graphs showing electric conductivity as a function of temperature for different models with and without lifetime effects, along with a kinetic approach]

- Electric current relaxes already at formation of resonances and not only at the decay (full momentum exchange)

Summary
How to Use SMASH?

- Visit the webpage to find publications (DOI for the code 10.5281/zenodo.3484711) https://smash-transport.github.io
- Checkout the physics results at http://theory.gsi.de/~smash/analysis_suite/current/
- Find user guide and documentation at https://github.com/smash-transport/smash/releases

Simulating Many Accelerated Strongly-interacting Hadrons

Manage topics

- Branch: master
- New pull request
- 6,590 commits
- 1 branch
- 2 releases
- 13 contributors

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First public version of SMASH

- elfnerhannah released this on 27 Nov 2018 - 6 commits to master since this release

Useful extras:
- Here is an overview of Physics results for elementary cross-sections, basic bulk observables, infinite matter calculations
- User Guide
- HTML Documentation
Summary and Outlook

- Quark-gluon plasma properties are explored in heavy-ion reactions
- At ultra-relativistic energies (LHC/RHIC) similar conditions to early universe
- Shear viscosity and initial state structures constrained by higher order flow coefficients
- Dynamical description essential to draw conclusions from experimental data
- At finite densities a first order phase transition is expected
- SMASH is a new hadronic transport approach that has been employed to study viscosity and conductivity of hot and dense hadron gas
- Importance of resonance lifetimes has been pointed out