Heavy-ion physics, lecture 1

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Today

Introduction to heavy-ion collisions (HIC) & the quark-gluon plasma (QGP)

• Some brief QCD reminders
• Thermodynamics of the QCD phase transition
• Space-time evolution of heavy-ion collisions
  – Concept of collision centrality
  – Produced energy density in the Bjorken picture
• Particle production from the QGP
  – Statistical hadro-production
  – Strangeness enhancement

Tomorrow focus on a few types of measurements that probe properties of the quark gluon plasma
HIC: definition

Au: 79 protons & 100 neutrons
Pb: 82 protons & 126 neutrons
Note: Nuclear size of order 10 fm

Interested in colliding nuclei, we strip off the e’s to accelerate them
The proton is also an ion (of hydrogen). proton-ion collisions are also of interest

Currently performed at RHIC and the LHC
Max energy per nucleon pair ($\sqrt{s_{NN}}$) of 5 TeV $\rightarrow$ 1PeV ($\sqrt{s}$) total energy!

So one should expect large energy density from HIC’s (we’ll estimate it later)
What happens to matter in these conditions?
Why collide heavy ions?

In normal matter, parton degrees of freedom confined to hadrons. Does this change at high temperature and/or large density?

Based on the recent discovery of asymptotic freedom (1973), Collins & Perry hypothesized that it would in 1975:

“A neutron has radius of about 0.5 – 1 fm and so has a density of about 8 \times 10^{14} \text{ gm/cm}^3, whereas the central density of a neutron star, can be as much as 10^{16} – 10^{17} \text{ gm / cm}^3. In this case, one must expect the hadrons to overlap, and their individuality to be confused. Therefore we suggest that there is a phase change, and that the nuclear matter at such high densities is a quark soup”
The quark-gluon plasma

10^5 x hotter than core of the sun!

- Critical temperature (T_c ≈ 150 MeV) estimated pre-QCD by Hagedorn based on # of hadrons vs. energy
- Later confirmed with lattice QCD
- Heavy-ion collisions create high temperature, but low density → smooth crossover in this region
- Also phase transition at high density, but lattice calculations difficult there due to “sign problem”

Heavy-ion collisions allow us to probe QCD at high temperature
→ Requires different theoretical tools, e.g., high temperature QFT, thermodynamics, …
→ QCD matter exhibits novel features in these conditions
Far-reaching connections

Cosmology

- The universe was composed of QGP from $10^{-10}$ to $10^{-5}$ sec after the Big Bang

Cold quantum gasses

- Ideal fluid behavior observed in QGP & other strongly coupled systems

Elliptic flow of a strongly interacting Fermi gas
QCD reminder

Structure of QCD driven by SU(3) color gauge symmetry

In principle, all is calculable from the QCD Lagrangian:

$$\mathcal{L}_{QCD} = \sum_{\text{flavours}} \bar{\psi}_a \left( (i \gamma^\mu \partial_\mu - m) \delta_{ab} - g_s \gamma^\mu t^C_{ab} A^C_\mu \right) \psi_b - \frac{1}{4} F^A_{\mu\nu} F^{\mu\nu,A}$$

Quark propagator

Quark-gluon vertex

Field strength tensor

$\frac{N_c^2 - 1}{N_c N_f} = 8$ gluons

$N_c^2 - 1 = 8$ gluons

$N_c^* N_f$ quarks

Quark masses

<table>
<thead>
<tr>
<th>Charge</th>
<th>Mass</th>
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<tbody>
<tr>
<td>+2/3</td>
<td>u (~5 MeV)</td>
</tr>
<tr>
<td>+1/3</td>
<td>c (~1.5 GeV)</td>
</tr>
<tr>
<td>-1/3</td>
<td>t (~175 GeV)</td>
</tr>
<tr>
<td>-2/3</td>
<td>d (~10 MeV)</td>
</tr>
<tr>
<td>-1/3</td>
<td>s (~100 MeV)</td>
</tr>
<tr>
<td>-1/3</td>
<td>b (~5 GeV)</td>
</tr>
</tbody>
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Compare to $T_c \sim 150$ MeV
Asymptotic freedom & confinement

Whereas in QED vacuum fluctuation screen charge,
in QCD they “anti-screen”

- At short distance coupling is small
- Quarks can be probed inside the nucleon with high energy leptons (DIS)
- pQCD works well in this regime

- At “large” distance (1 fm), potential is linear
- Quarks confined inside hadrons
- Perturbation theory breaks at large coupling
QCD thermodynamics

In high T limit $\rightarrow$ QGP an ideal gas of weakly interacting quarks and gluons

Equation of state is given by pressure vs. temperature or equivalently energy density vs. temperature

Can be calculated from the partition function

$$\epsilon = \int \frac{d^3p}{(2\pi)^3} \sum_i \frac{E_i}{e^{EBT} \pm 1}$$

+1, 0, 1 for fermions, classical or bosons

$$\Rightarrow \epsilon(T) \approx \frac{\pi^2}{30} N T^4 \quad N = 3$$

Hadron phase can be approximated as a gas of pions, i.e., 3 states: $\pi^+, \pi^0, \pi^-$

For a QGP on the other hand, we expect

$$\epsilon(T) = \frac{\pi^2}{30} \left( N_B + \frac{7}{8} N_F \right) T^4$$

$$= \frac{\pi^2}{30} (47.5) T^4$$

$N_B = 2 \times 8$, $N_F = 2 \times 2 \times 3 \times 3$

$\rightarrow$ 15x jump in the energy density at $T_c$
E.O.S. from the lattice

Lattice calculations are reliable for zero net baryon density, which is a reasonable approximation for high energy HICs. They indeed show a spike in ratio of $\epsilon / T^4$, indicating a jump in the degrees of freedom.

- $T_c \approx 150$ MeV
- $\epsilon_{SB} \approx 1.0$ GeV/fm$^3$

Does that mean the QGP behaves like an ideal gas of quarks and gluons? Don’t reach the SB limit.

EOS of N=4 Super Yang-Mills may be strongly coupled.
Time evolution of a HIC

1) Prior to collision relativistic nuclei are Lorentz contracted
2) After crossing, particles start to scatter ($\tau \sim 1/p$)
3) After $t \sim 1$ fm, equilibrium is established, giving a thermalized QGP
4) QGP expands and cools until about 10 fm ($3 \times 10^{-23}$ sec!)
5) Hadronization occurs (chemical freeze-out), and shortly after particles stop interacting and free stream towards detectors (kinetic freeze-out)

How does one learn about the fleeting QGP from the mess of final state particles we detect?

Important to understand the initial state, as well as how to draw conclusions from the final state hadrons
A real heavy-ion collision
The role of geometry

Not all heavy-ion collisions are created equal, but rather vary in *centrality*

Some are head-on or “central”

Some are glancing or “peripheral”

Struck nuclei are *participants*, others are *spectators*

Energy density achieved depends on # of participants

Not observable $\Rightarrow$ how can we determine it a posteriori?
The Glauber model

- Attributed to Roy Glauber (2005 Nobel for quantum optics)
- Main assumptions:
  - Probability of nucleon-nucleon scattering independent of previous scatterings
  - Nucleons move in straight-line trajectories undiffracted
- Woods-Saxon distribution of nuclear charge density

\[
\rho(r) = \frac{\rho_0}{1 + \exp[(r - R)/a]}
\]

(spherical case)

- Nuclear thickness function in the optical limit

Define nuclear thickness

\[
T_A(\vec{s}) = \int \rho_A(\vec{s}, z) \, dz \quad \int T_A(\vec{s}) \, d^2s = A
\]

where

Take the product of nucleus A & B, and integrate over s:

\[
T_{AB}(b) = \int T_A(\vec{s}) \cdot T_B(\vec{s} - \vec{b}) \, d^2s
\]
Two key numbers: $N_{\text{coll}}$ & $N_{\text{part}}$

- The total number of inelastic nucleon-nucleon collisions

$$N_{\text{coll}}(b) = T_{AB}(b) \cdot \sigma_{\text{inel}}^{nn}$$

- The total number of participants or “wounded nuclei”, derivation:

  Prob. for a nucleon in nucleus A to scatter with one from nucleus B:

  $$p_{\text{int}} = T_{B}(\vec{s} - \vec{b}) \cdot \sigma_{\text{inel}}^{nn} / B$$

  Prob. for a nucleon in A not to interact: $(1 - p_{\text{int}})^B$

  Prob. for a nucleon in A to interact at least once: $1 - (1 - p_{\text{int}})^B$

  Number of participants from A:

  $$N_{\text{part}}^A = \int T_A(\vec{s}) \cdot \left(1 - \left[1 - T_B(\vec{s} - \vec{b}) \cdot \sigma_{\text{inel}}^{nn} / B\right]^B\right) \, d^2s$$

  Number of total participants: $N_{\text{part}}(b) = N_{\text{part}}^A(b) + N_{\text{part}}^B(b)$
Glauber Monte Carlo

- In MC approach nucleon density discrete rather than continuous
- Sample nucleon positions according to nuclear density distribution
- Nucleons interact if their distance \( d < \sqrt{\frac{\sigma_{nn}}{\pi}} \)
- Fluctuations in overlap geometry will turn out to be important
Centrality

- Centrality is based on an observable, typically event multiplicity, with a monotonic dependence on Glauber quantities, e.g., $N_{\text{part}}$.
- Multiplicity then calculated from Glauber:
  - Nucleon-nucleon multiplicity parameterized by a negative binomial distribution, verified in pp
  - Total AA multiplicity assumed to scale w/ $N_{\text{part}}$ → randomly sample the n.b.d. $N_{\text{part}}$ times
- The multiplicity distributions in data and Glauber then divided into centrality classes, i.e., percentiles of the total cross section.
- While centrality is detector dependent, corresponding Glauber values, e.g., $\langle N_{\text{part}} \rangle$, are approximately experiment independent.
Centrality example: ALICE

- VZERO are scintillators at forward $\eta$, collected charged proportional to multiplicity
- Centrality typically measured at forward $\eta$ to be independent from mid-rapidity measurements
- Glauber-based fit provides an excellent description of the VZERO charge distribution
Multiplicity

Multiplicity can also be used to constrain the energy density created in HICs

Notice the flat (pseudo)rapidity dependence near mid-rapidity
This \textit{longitudinal boost invariance} emerges naturally in a commonly used space-time picture of heavy-ion collisions

1.7k charged particles per unit $\eta$ at mid-rapidity
The Bjorken picture

Consider nuclei as relativistic pancakes, which cross at the speed of light
- Beam remnants continue at forward y
- Mid-y dominated by produced particles

Main assumptions of the model:
- Homogenous expansion of cylinder in z direction, i.e., 1D ideal hydrodynamics
- Particles materialize at formation time $\tau_0$ in their rest frame

Velocity in this system: $\beta = \frac{z}{t}$
$\tau = \frac{t}{\gamma}$

$$\epsilon = \frac{E}{V} = \frac{1}{A} \frac{dE}{dz} \bigg|_{z=0} = \frac{1}{A} \frac{dy}{dz} \bigg|_{z=0} \frac{dE}{dy} \bigg|_{y=0} = \frac{1}{A \cdot \tau_0} \frac{dE}{dy} \bigg|_{y=0}$$

Standard relation for rapidity
$$\sinh y = \beta \gamma = \frac{z}{\tau}$$
From multiplicity to $E_T$

Although $E_T$ is measurable with calorimeters, heavy-ion experiments typically measure charged particle multiplicity

$$\frac{dE_T}{d\eta} \approx \langle m_T \rangle \frac{3}{2} \frac{dN_{ch}}{d\eta}$$

$m_T^2 = m^2 + p_T^2$

About 0.65 GeV for pions at the LHC

Mass isn’t known unless particles are identified $\rightarrow$ need a correction

$$\frac{dE_T}{dy} = J(y, \eta) \frac{dE_T}{d\eta}$$

$J(y,\eta) \approx 10\%$
Estimating energy density

\[ \epsilon = \frac{1}{A \cdot \tau_0} \left. \frac{dE_T}{dy} \right|_{y=0} \]

A = \pi R^2 = \pi (7 \text{ fm})^2 \text{ for lead}

Traditionally assumed that \( \tau_0 \sim 1 \text{ fm} \)
We’ll see later that short formation time is justified

\( \frac{dE_T}{dy} \big|_{y=0} \sim 2 \text{ TeV} \) in central collisions at the LHC

\[ \rightarrow \epsilon = 13 \text{ GeV/fm}^3 \]

Well in excess of \( \epsilon = O(1) \text{ GeV/fm}^3 \)
for phase transition from lattice QCD
Statistical hadroproduction

What determines the abundance of different hadron species?

- Hadronization is non-perturbative
- Various pheno. models for elementary collisions (cluster, string, etc.)
- For heavy ions instead appeal to thermodynamics
- Postulate that QGP cools into an equilibrated gas of hadrons; Particle number conserved only over entire volume, not locally \( \rightarrow \) grand canonical ensemble
- Particle density given by derivative of the partition function

\[
n_i = \frac{N}{V} = -\frac{T}{V} \frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2 \, dp}{\exp((E_i - \mu_i)/T)} \pm 1
\]

- Each conserved quantum number gives a chemical potential \( \mu_i \), e.g., charge, baryon number, etc.
- Temperature can be obtained by a fit to the abundance of states
Statistical description of data

$T_{cf} = 156.5 \pm 1.5 \text{ MeV}, \mu_b = 0.7 \pm 3.8 \text{ MeV}$ and $V = 5,280 \pm 410 \text{ fm}^3$.

Fit to the heavy-ion data gives a $T$ of 156 MeV close to the predicted critical temp. Also work for $e^+e^-$, but with canonical ensemble (local, not global equilibrium).

Statistical production appears to be a generic feature of hadronization.

However, an extra chemical potential $\gamma_s$ is needed in $e^+e^-$ for strange particles.

For more details on statistical hadronization see the Nature article handout.
The strange quark

Light quark ("dressed") mass dynamically generated by QCD
Heavy quark mass directly from the Higgs mechanism
Strange quark is special: both mechanisms contribute
  – Bare mass ~ 100 MeV
  – Kaon mass ~ 500 MeV

- Because $T_c$ in excess of the strange quark mass, expect thermal production
- In elementary collisions strangeness is locally conserved
  $\rightarrow \gamma_s$ reflects this "canonical suppression"
- In an equilibrated QGP, expect conservation only over global volume ($\gamma_s = 1$)
Strangeness enhancement

\[ \lambda_s = \frac{2\langle s\bar{s}\rangle}{\langle u\bar{u}\rangle + \langle d\bar{d}\rangle} \]

Strangeness indeed enhanced by 2x in AA, compared to elementary collisions. Larger enhancement factor for multi-strange hadrons (~7x for \( \Xi \), ~15x for \( \Omega \)).

Supports picture of QGP as an equilibrated state over a large volume.
Heavy-ion experiments
• The first HI collider, after many years of fixed target expt’s
• First collisions in 2000, continues to operate today
• STAR searching for the critical point with a beam energy scan
• PHENIX currently being upgraded to sPHENIX for ~ 2023
The LHC @ CERN

Collides heavy ions for ~ 1 month per year (PbPb, pPb, ArAr so far)
In operation, since 2010
ALICE dedicated to HI program, but interesting things can also be done with HEP detectors (ATLAS, CMS, and recently LHCb)
Ion beams

Max energy determined by bending power of magnets

Using the Mandelstam variable \( s = (p_1 + p_2)^2 \), can derive the equivalent COM beam energy for heavy-ion beams

\[
E \propto \frac{Z}{A}
\]

4-vectors

LHC

Early Run 1, max pp \( \sqrt{s} = 7 \text{ TeV} \) → PbPb \( \sqrt{s_{NN}} = 2.76 \text{ TeV (7Z/A)} \)
Later Run 1, max pp \( \sqrt{s} = 8 \text{ TeV} \) → pPb \( \sqrt{s_{NN}} = 5.02 \text{ TeV (8Z/√A)} \)
Run 2, max pp \( \sqrt{s} = 13 \text{ TeV} \) → PbPb \( \sqrt{s_{NN}} = 5.12 \text{ TeV (13Z/A)} \)
\( \rightarrow pPb \sqrt{s_{NN}} = 8.16 \text{ TeV (13Z/√A)} \)

At RHIC, AuAu \( \sqrt{s_{NN}} = 200 \text{ GeV} \) → pp \( \sqrt{s} = 500 \text{ GeV (polarized!)} \)
HEP detectors

- Fast & triggerable for huge luminosity
- Precision silicon tracking + high B field, e.g., for b-tagging
- Hermetic calorimeters for jets and missing $E_T$
- Isolated photons and leptons for EW bosons, Higgs, top

Ex: ATLAS, CMS
Also sPHENIX follows HEP model
Heavy-ion detectors

- Tracking w/ gaseous detectors for high occupancy, e.g., TPCs (STAR, ALICE)
- Low $p_T$ reach is essential for “bulk” observables
- Emphasis on particle ID, e.g., TOF, dE/dx, RICH
- Low $p_T$ photons and leptons important, often forward $\eta$ muon detectors independent from barrel system (ALICE, PHENIX)
## Probes of the QGP

<table>
<thead>
<tr>
<th>Observable</th>
<th>Property of the QGP</th>
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<tbody>
<tr>
<td>Strangeness enhancement</td>
<td>Chemical equilibrium</td>
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<tr>
<td>Jet quenching</td>
<td>Density</td>
</tr>
<tr>
<td>Quarkonia melting</td>
<td>Temperature</td>
</tr>
<tr>
<td>Particle correlations</td>
<td>Collectivity, Viscosity</td>
</tr>
<tr>
<td>Thermal photons</td>
<td>Temperature</td>
</tr>
<tr>
<td>Hanbury Brown Twiss correlations</td>
<td>Size</td>
</tr>
</tbody>
</table>

And many more…
Summary of today’s lecture

• Heavy-ion collisions used to explore QCD at high energy density
• Matter crosses over to a deconfined state, the quark-gluon plasma
• Collision centrality related to observables via a Glauber model
• Energy density estimated from mid-rapidity multiplicity in Bjorken’s picture
• Extended QGP alters chemical composition of produced matter, increasing strangeness
• Currently colliding heavy ions at RHIC & LHC w/ various detectors

Tomorrow
Select phenomena / observables for heavy ions: collective flow, jet quenching and quarkonia melting