Heavy Ion Physics
Lecture 1: Introduction to Heavy Ion Physics

HUGS 2015

Bolek Wyslouch

Borrowing heavily from Yen-Jie Lee(MIT), Gunther Roland(MIT) and Tom Hemmick (StonyBrook)
Plan of lectures

• Lecture 1: Introduction to heavy ion physics
• Lecture 2: Accelerators and experiments
• Lecture 3: Particle production
• Lecture 4: Elliptic flow and correlations
• Lecture 5: Parton energy loss: jets
• Lecture 6: Quarkonia and heavy quarks
Fundamental Interactions

Gravity Force

Electromagnetic force

Strong force

Weak force
Constituents of matter

### FERMIONS

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### BOSONS

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<td>W⁺</td>
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<tr>
<td>Name</td>
<td>Mass GeV/c²</td>
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<td>g</td>
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Color confinement in Strong interactions

- Different from EM or Weak Interaction

- Typical hadrons:
  - **Mesons**: contain a quark and an anti-quark
    
    \[ \pi^+ \quad \pi^0 \]
    
    - **Baryons**: contain 3 quarks
      
      \[ p \quad n \]

- What will happen if we increase the temperature and density? **Can we "melt" hadrons?**

Quark-Gluon Plasma (QGP)
Asymptotic Freedom

Gross, Politzer, Wilczek 1973: Strong interactions are weak at short distances (high momentum transfers)

Strong Coupling Constant \( \alpha_s \)
Matter in unusual conditions!

Enrico Fermi’s lectures on statistical physics ~1953
This was one of the original motivations for the field of Relativistic Heavy Ion Collisions. Interestingly, the Nature decided that it wants to do something else with quarks and gluons…
Phase diagram of quark and gluon matter

1 eV \sim 12000 \text{ K}
100 \text{ MeV} \sim 1.2 \times 10^{12} \text{ K}

Big questions of our field:
What is the nature of the phase transition?
What are the properties of the melted phase?

\sim \text{equal number of baryons and anti-baryons}
dominated by baryons
Where could such matter be produced?

• Present understanding holds that all matter and energy of the universe sprang from a single point:
  – Extremely Dense; Extremely Hot
• Since that epoch, the history of the universe is dominated by cooling:
  – Today the universe is mostly ~2.7 K.
  – Exceptions exist in hot spots (like our solar system)
• As the universe cooled, different phases of matter and different forces of nature played the dominant role.
Quarks and Gluons in the Universe

Key:
- w, Z: bosons
- photon
- quark
- gluon
- electron
- muon
- tau
- neutrino
- meson
- baryon
- ion
- atom
- star
- galaxy
- black hole

Particle Data Group, LBNL, © 2002
DOE and NSF
Quarks and Gluons in the Universe

History of the Universe

Cosmic Microwave Background

© 2000. Supported by DOE and NSF
Quarks and Gluons in the Universe

Predicted by lattice QCD
Critical temperature ~ 170 MeV
~ 2 x 10^{12} K
~ 5000 x

Extreme high density & temperature
How do we reproduce this world?
Making Plasma in the Laboratory

• Extremes of temperature and density are necessary to recreate the Quark-Gluon Plasma, the state of our universe for the first few microseconds.
  – Density threshold is when protons/neutrons overlap
    • 4X nuclear matter density = touching.
    • 8X nuclear matter density should be plasma.
  – Temperature/Energy Density threshold:
    • When the temperature exceeds the $mc^2$ of the lightest meson (pion $m=140$ MeV/c²)
    • Several light hadrons per volume of light hadron $\varepsilon_c \sim 1$ GeV/fm³
    • The necessary temperature is $\sim 10^{12}$ Kelvin.
Phase transition

• Count the degrees of freedom of a gas of fermions and bosons.
• Each bosonic degree of freedom contributes to the energy density and each fermionic DOF contributes 7/8 of this:

\[ \varepsilon_{2\text{-flavor}} = \left( 2_f \cdot 2_s \cdot 2_q \cdot 3_c \frac{7}{8} + 2_s \cdot 8_c \right) \frac{\pi^2}{30} T^4 = 37 \frac{\pi^2}{30} T^4 \]

\[ \varepsilon_{3\text{-flavor}} = \left( 3_f \cdot 2_s \cdot 2_q \cdot 3_c \frac{7}{8} + 2_s \cdot 8_c \right) \frac{\pi^2}{30} T^4 = 47.5 \frac{\pi^2}{30} T^4 \]

• A pure pion gas would have only 3 DOF \((\pi^+, \pi^-, \pi^0)\)
• Pressure = \(\varepsilon/3\).
The onset of QGP is far from the perturbative regime ($\alpha_s \sim 1$)

Lattice QCD is the only 1st principles calculation of phase transition and QGP.

Lattice Calculations indicate:

- $T_C \sim 170$ MeV
- $\varepsilon_C \sim 1$ GeV/fm$^4$
How can we “melt” nuclear matter in the laboratory?

Collisions of energetic, large nuclei

Collisions of relativistic, large nuclei

Lorentz contraction

$V << c$

$V \sim c$
Energy is usually released in collisions.

Some Serious Melting

Fused bullets: French and Russian, Crimean War, 
~1853-1856
• Energy deposited in the collision region results in large multiplicity of produced particles.

Spectator particles, protons and neutrons from the original nuclei

New particles, created out of the vacuum
Visualization of the collision

MIT Heavy Ion Event Display: Au+Au 200 GeV

Heavy Ion

Particles before hadronization (Quark gluon plasma)

Meson

Baryon

Heavy Ion Group @ MIT
Yen-Jie Lee, Andre S. Yoon and Wit Busza

Time = -10.0 fm/c
Stages of the heavy ion collision

- Initial state: parton distributions inside nuclei
- Hot and dense, expanding medium: energy density
- Final state: fragmentation of partons into hadrons, experimental detection
More detailed sequence of events

- At first an out-of-equilibrium, high density state is created, expands longitudinally
- The system undergoes rescattering, achieves local thermodynamic equilibrium, cools and expands like a fluid (hydrodynamically)
- When the temperature drops to below $T_c \sim 170$ MeV system is in hadron gas phase
- Hadron gas undergoes freeze-out and particles stream towards the detector
Kinematic Variables

Rapidity:
\[ y = \frac{1}{2} \ln\left( \frac{E + P_Z}{E - P_Z} \right) \]

Pseudo-rapidity:
\[ \eta = \frac{1}{2} \ln\left( \frac{P + P_Z}{P - P_Z} \right) = -\ln\left( \tan \frac{\theta}{2} \right) \]

Transverse Momentum:
\[ p_T = \sqrt{p_X^2 + p_Y^2} \]

Transverse Mass:
\[ m_T = \sqrt{p_T^2 + m_0^2} \]
Kinematics of Au-Au collision at 200 GeV/A

Before Collision

After Collision

Rapidity $y = \frac{1}{2} \ln \left( \frac{E + p_z}{E - p_z} \right)$

Measures longitudinal velocity

Logarithmic: CMS region is magnified

Lorentz-boost in beam-direction: Shift in $y$
Pseudorapidity “cheat sheet”

\[ \eta = \frac{1}{2} \ln\left( \frac{P + P_Z}{P - P_Z} \right) = -\ln\left( \tan \frac{\theta}{2} \right) \]
Heavy Ion Collision Recorded by the CMS Detector (2010)
Geometrical cross section:
\[ pp \pi r^2 = \pi (1 \text{fm})^2 = 32 \text{ mb} \]

Au+Au Collisions (200 GeV):
\[ R_{\text{Au}} = 1.2 A^{1/3} = 6.98 \text{ fm} \]
\[ \pi b_{\text{max}} = \pi (2R)^2 = 6 \text{ barn} \]

Pb+Pb (2.76 TeV) 7.7 barn

1 barn = 10^{-24} \text{ cm}^2
Orders of magnitude

• To study “matter” it would be nice to have a substantial chunk of “stuff” with well defined temperature, volume, pressure: thermalized matter
• Typical hadron has radius of ~1 fm, fills effectively about 5-6 fm$^3$ volume so hadronic matter density is about n~0.2 1/fm$^3$
• Typical cross section of hadron interaction at high energies is about 50 mbarn (5 fm$^2$) or more
• Collisions of heavy ions increase the density by at 1-2 orders of magnitude to n~O(10) 1/fm$^3$
• Mean free path $\lambda \sim \left( n\sigma \right)^{-1}$ is about 0.02 fm!
• Expect multiple hadronic interactions within the collision volume: thermalization!
Energy Density (Bjorken)

- At $t = t_{\text{form}}$, the hatched volume contains all particles with $\beta_{||} < dz/t_{\text{form}}$

$$dN = \frac{dz}{t_{\text{form}}} \frac{dN}{d\beta_{||}} = \frac{dz}{t_{\text{form}}} \frac{dN}{dy}; \quad (dy = d\beta_{||} @ y = 0)$$

- At $y = \beta_{||} = 0 \quad E = m_{r}$, thus:

$$\langle \epsilon(t_{\text{form}}) \rangle = \frac{E}{V} = \frac{dN < m_T >}{dz \cdot A} = \frac{dN(t_{\text{form}}) < m_T >}{dy \cdot t_{\text{form}} \cdot A}$$

- We can equate $dN \langle m_T \rangle$ and $dE_T$ and have:

$$\langle \epsilon_{BJ}(t_{\text{form}}) \rangle = \frac{1}{t_{\text{form}} \cdot A} \frac{dE_T(t_{\text{form}})}{dy}$$

Two nuclei pass through one another leaving a region of produced particles between them.
Number of produced particles $\sim$ max. energy density $\sim$ number of participating nucleons

Most central collisions: impact parameter $(b) \sim 0 \text{ fm}$

Most peripheral collisions: impact parameter $(b) \sim R_{\text{ion}} \text{ fm}$
Estimation of collision centrality: Glauber model

- Monte Carlo technique: generate random positions of constituent nuclei
- Follow their trajectory and count interactions
- Use nucleon-nucleon cross section
Collision “centrality”

“Centrality” usually characterized by percentile, e.g. the “5% most central collisions”

Fraction of the total cross section
• Charged particle multiplicity as a function of pseudorapidity
• Increasing collision energy: 19, 130, 200 GeV/A
• Different centrality: peripheral to central

• Very clear increase in multiplicity with energy and centrality
Charged multiplicity at $\eta=0$ vs $\sqrt{s}$
Charged multiplicity $\eta=0$ vs $\sqrt{s}$
What time do we assume?

- Two values of $\tau_0$:
  - $\tau_{\text{form}} \leq \frac{\hbar}{m_T} (\tau_{\text{form}}) = 0.35 \text{ fm/c}$
  - $\tau_{\text{therm}} \leq 1 \text{ fm/c (hydro)}$

- We derive conservative lower limits on the energy density at formation and thermalization:
  - $\varepsilon(\text{form}) > 15 \text{ GeV/fm}^3$ (RHIC)
  - $\varepsilon(\text{therm}) > 5 \text{ GeV/fm}^3$ (RHIC)
  - $\varepsilon(\text{therm}) > 16 \text{ GeV/fm}^3$ (LHC)

These values are well in excess of $\sim 1 \text{ GeV/fm}^3$ obtained in lattice QCD as the energy density needed to form a deconfined phase.
• Heavy ion collisions clearly produce hot region of space with energy densities sufficiently high to enter the quark-gluon plasma phase
• The mean free path for the ingredients seems to be much smaller than the size of the hot region, implying thermalization
• The hot matter expands and cools very fast, the measurements have to be done very quickly
Techniques to study the plasma

Radiation of hadrons

Azimuthal asymmetry and radial expansion

Energy loss by quarks, gluons and other particles

Suppression of quarkonia
Radiation of hadrons and photons

- Effects dependent on energy density
  - Charged multiplicity
  - Energy distribution
- Measuring the “chemistry” of collision, quark content of the plasma, temperature, speed of expansion
  - Momentum spectrum
  - Particle composition: $\pi$, $K$, $p$, $\gamma$
  - Comparison of particle content in nuclear and proton-proton collisions
Azimuthal asymmetry and radial expansion

• Exploit the fact that there are many peripheral collisions that are azimuthally asymmetric

• The pressure in the hot drop of strongly interacting fluid affects the momentum of emitted particles
Energy loss by quarks, gluons and other particles

• Equivalent of x-ray of the plasma, the loss of energy can tell us about the density, composition and the microscopic structure of the plasma

• We use probes created during the elementary collisions between the initial quarks and gluons
  – Large transverse momentum quarks or gluons appearing as jets
  – Particles that do not interact strongly can be used as a reference: Z, W, photon
Production and suppression of quarkonia

• Bound states of heavy quarks produced inside plasma are being used as an indicator of plasma temperature and density

• Comparison of production of quarkonia between ion-ion, proton-ion and proton-proton collisions show several interesting effects that can be interpreted in terms of plasma properties
  – $J/\psi, \psi'$ suppression and recombination
  – Properties of $\Upsilon$ family