Selected Topics from Experimental Studies at RHIC

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Hadrons and Quarks

Hadrons

• Building blocks of matter in our universe
• Strong interaction; described by QCD
• Composite particles of quarks (anti-quarks)
  – baryon: p, n,…(three quarks)
  – meson: p, K,…(quark + anti-quark)
  – recent discovery of a new particle = penta-quark; a new class of hadrons?
Remaining Basic Problems of QCD

- confinement of quarks --- today’s topic
- chiral symmetry and origin of hadron mass

\[ V(r) = \kappa r \]

\( \kappa \sim 1 \text{ GeV/fm} \)

Gluon is fragmented, and quark and anti-quark pairs are produced.

No way to isolate quarks.

Strong interaction.
Prediction by Lattice-QCD

• Rapid increase in energy density and pressure around a certain temperature
  = increase of degeneracy due to deconfinement of quarks and gluons
    – quark: 3 (flavour) x 2 (spin) x 3 (color)
    – gluon: 8 (color) x 2 (spin)
    – $\pi$ mesons: 3 (isospin)

study QCD matter
  = a new approach to study basic properties of QCD such as confinement
Physics Scope of Hot QCD matter

Strong motivation
= QCD property: confinement

- Property of QCD matter
- Recreation and understanding of early universe

- Equarks and gluons are confined
- Beginning of universe with normal matter

Strong motivation
- QCD property: confinement

- Phase transition: $10^{-6} \sim 10^{-5}$ sec
- Equarks and gluons are confined
- Beginning of universe with normal matter

- $T_C \sim 150$ MeV
- Quark-gluon plasma: QGP
- Hadron phase
- CFL, 2CS
- Endpoint
- Big Bang

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CNS Summer School
Create an Early Universe in a Laboratory

High energy heavy ion collision is a unique tool to produce hot and dense QCD matter

CMS energy/nucleon vs Year when collision of heavy-mass nuclei became available
Why do we need high energy?

- In general, collision process is very dynamic and complex
  - very difficult to describe the evolution of the system
- In the limit of complexity, everything gets simpler
  - hydrodynamics is applicable to describe the evolution of the colliding system

- High energy collision → a system with high complexity
- Questions is: “How high energy is really needed?”

![Diagram showing estimated energy density with CMS energy/A vs. √s [GeV]]
RHIC

• The first colliding-type accelerator for heavy ion study
• Brookhaven National Laboratory
  Long Island, New York, USA
• Two independent rings with superconducting magnets
  – circumference: 3.83 km
  – asymmetric-mass collisions
  – 106 ns crossing time
• Maximum energy $\sqrt{s} \approx \frac{Z}{A} (500 \text{ GeV})$
  – 500 GeV for p-p
  – 200 A *GeV for Au-Au
• Luminosity (designed values)
  – Au-Au: $2 \times 10^{26} \text{ cm}^{-2} \text{ s}^{-1}$
  – p-p : $2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$
    (polarized)
Experimental Runs at RHIC

• The first encounter of Gold ions
  – June 12, 2000: Au + Au collisions at $s_{NN}^{1/2} = 56$ GeV

• Year-1 Run
  – Au + Au at $s_{NN}^{1/2} = 130$ GeV
  – middle of June, 2000 ~ Sep. 4, 2000
    • ~5 M minimum-bias events

• Year-2 Run
  – $s_{NN}^{1/2} = 200$ GeV
  – Au + Au: Aug. 17, 2001 ~ Nov. 25
    • ~100 M minimum-bias events

• Year-3 Run
  – $s_{NN}^{1/2} = 200$ GeV
    • The first asymmetric nuclear collisions in the colliding-type accelerators
  – pol-p + pol-p: May 2 ~ May 17, 2003
Experiments at RHIC

PHENIX

STAR

BRAHMS

PHOBOS
PHENIX (*Pioneering High Energy Ion eXperiment*)

- ~430 from 41 institutions, 11 countries
- Measure photons, electrons, muons as well as hadrons
  = unique among the four experiments
- Cover many observables
Japanese Group at PHENIX

Supported by MONKA-sho’s “US-J Collaboration in Science and Technology in the field of high energy physics”

**Primary contributions = PID**

**RICH**: electron identification

CNS, KEK, Waseda, NIAS, BNL, FSU, KEK, SUNY/SB, ORNL

**TOF**: hadron identification

Tsukuba, Columbia

**AEROGEL**: Tsukuba, CNS, BNL

**BBC**: TOF start, event trigger

Hiroshima, Columbia
Topical Results from RHIC

• **Gross feature of heavy-ion collisions**
  – Participant-spectator model

• **Initial conditions**
  – azimuthal anisotropy and particle yield ratio
  – Basic question is: whether at RHIC thermal and chemical equilibrations are achieved?

• **High p_T particle – single and correlation**
  – Jet quenching; to probe hot matter with high density

• **J/ψ measurement**
  – THE probe of deconfinement
Participant-spectator model

- Classical description works
- Collision geometry is determined by impact parameter
- It works when collision time is short compared to a typical time scale of internal motion of nucleons inside nucleus
Topical Results from RHIC

• Gross feature of heavy-ion collisions
  – Participant-spectator model

• Probing “initial conditions”
  – azimuthal anisotropy and particle yield ratio
  – Basic question is: whether at RHIC thermal and chemical equilibrations are achieved?

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Elliptic Anisotropy in Particle Emission

\[
\frac{dN}{dp_Tdyd\phi} = \frac{dN}{dp_Tdy} \frac{1}{2\pi} \left(1 + 2v_1 \cos(\phi) + 2v_2 \cos(2\phi) + \ldots \right)
\]

• Azimuthal anisotropy in the participant region in non-central collisions
  – if local equilibration is achieved quickly enough,
  – then anisotropy appears in the internal pressure gradient, which produces anisotropic particle flow

• Very large anisotropy at RHIC
  – comparable to the predictions from fluid dynamical calculations
Hydrodynamic model

- early thermalization (~0.5 fm)
- initial state = QGP phase

Thermalization seems to be barely achieved at RHIC
Particle Yield Ratio and Chemical Equilibrium

\[
\rho_i = \gamma_s^{s_i} \frac{g_i}{2\pi^2} T_{ch}^3 \left( \frac{m_i}{T_{ch}} \right)^2 K_2 \left( \frac{m_i}{T_{ch}} \right) \lambda_q Q_i \lambda_s^{s_i}
\]

\[\lambda_q = \exp \left( \frac{\mu_q}{T_{ch}} \right), \quad \lambda_s = \exp \left( \frac{\mu_s}{T_{ch}} \right)\]

Static thermal model reproduces the particle ratio extremely well

- To be noted: \(\gamma_s\): strangeness saturation factor \(\rightarrow \sim 1\)
  - introduced to reflect on slowness of s production in hadron interactions
  - fast strangeness production/equilibration is only possible at QGP
  - It is natural to assume that chemical equilibration is realized at QGP
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Jet

• hard scattering of partons (quarks & gluons) is frequent at high energy collisions
• calculated well with pQCD
• Rutherford scattering in high energy collisions
  – how point-like the partons are:
    \[ p_T = 400 \text{ GeV} \]
    \[ \Delta x \sim 0.5 \times 10^{-3} \text{ fm} \]
Jet quenching

Energy loss of partons (quarks and gluons inside nucleons) in media at high density
-- primarily due to gluon bremsstrahlung

hard-scattered parton from e.g. p+p
cone of hadrons “jet”

hard-scattered parton in Au+Au

Energy loss via strong interaction

High p_T hadrons are fragments of partons

Energy Loss!

Yield [GeV^-1c]

p_T [GeV/c]

π^0 without energy loss
π^0 with energy loss

Gamma

Transverse Momentum Distribution of $\pi^0$

- Compare the yield in Au+Au with that in p+p scaled with $N_{\text{coll}}$
  - should be scaled in hard processes, without nuclear effects
- In Au + Au collisions at CMS energy = 130 and 200GeV
  - peripheral collisions: good agreement with $N_{\text{coll}}$ scaled p+p data
  - central collisions: significant suppression from with $N_{\text{coll}}$ scaled p+p data

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**70-80% Peripheral**

$N_{\text{coll}} = 12.3 \div 4.0$

**0-10% CENTRAL**

$N_{\text{coll}} = 975 \div 94$

Yield Suppressed!
Jets and two-particle azimuthal distributions

\[ p+p \rightarrow \text{dijet} \]

- trigger: highest \( p_T \) track, \( p_T > 4 \text{ GeV/c} \)
- \( \Delta \phi \) distribution: \( 2 \text{ GeV/c} < p_T < p_T^{\text{trigger}} \)
- normalize to number of triggers

Phys Rev Lett 90, 082302
Azimuthal distributions in Au+Au

Near-side: peripheral and central Au+Au similar to p+p

Strong suppression of back-to-back correlations in central Au+Au
Is suppression an initial or final state effect?

Initial state?

- strong modification of Au wavefunction (gluon saturation)

Final state?

- partonic energy loss in dense medium generated in collision

Need of results from d(p) + Au collisions
- large hot region will not be created
  → final state effect will be smaller
- initial state effect will stay
How is it settled?

- Execution of d + Au in Year-3 RUN (2003)
- No effects seen in d + Au collisions
  - effects are intrinsic to central Au + Au collisions
  - final state interaction is dominant
  - strongly suggests the creation of hot matter and significant energy-loss of partons in central Au + Au collisions
Single Electron Spectrum

Major background: $\pi^0$ Dalitz-decay and $\gamma$ conversions
Careful subtraction of the backgrounds $\rightarrow$ single electron

Momentum spectra is in good agreement with the charm spectrum in p+p collisions scaled with $N_{coll}$
$\rightarrow$ Is charm immune to energy loss?
$\rightarrow$ flavor dependence is a keen subject

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J/ψ Measurement at RHIC

- Suppression of J/ψ yields: a signature of QGP
  QGP $\Rightarrow$ Debye screening $\Rightarrow$ J/ψ is dissolved

In Pb+Pb at CERN-SPS, large suppression was observed in the J/ψ - Drell-Yan ratio

- At RHIC with higher T, stronger suppression may be expected
- Measurement in the Year-2 RUN
  - statistics is very poor
Will $J/\psi$ be really suppressed?

- Idea of $J/\psi$ enhancement
  - Results from RHIC suggests thermal and chemical equilibration is achieved at QGP phase
  - In the QGP at high temperature, original $J/\psi$ will be completely dissolved, but $J/\psi$ may be re-created via recombination process in the later (hadronization) stage
  - Probability of recombination increases quadratically with the number of c quarks

- Dedicated Au + Au in the RHIC Year-4 RUN which starts in this winter
  - total suppression or hint of enhancement
  - we will find it out soon

By A.P. Kostyuk
Summary

- Motivation and Scope
  - confinement = basic QCD property
  - hot QCD matter
  - early universe
- RHIC and PHENIX
  - RHIC started operation in 2000
  - Japanese group
- Topical results from RHIC
  - thermal and chemical equilibration
  - Jet quenching
  - $J/\psi$ production

- Results from RHIC have been very exciting, and more will surely come. Please stay tuned.