Search for Quark Gluon Plasma at RHIC

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Outline of This Talk

• Introduction
  - Scope and primary goal of studies with heavy ion collisions
  - RHIC and the experiments

• Key conditions and signatures of QGP (with selected results)
  - High density
  - Chemical equilibrium
  - Thermal equilibrium
  - Signatures of deconfinement

• Summary and Outlook
Scope of the Research

• Hadrons
  - building blocks of nuclear matter
  - Peculiar property of QCD = Confinement
    • quarks cannot be extracted as single entities
    • we only have baryons and mesons, for sure.

• New forms of hadronic matter
  - Lattice-QCD predicts a new phase of nuclear matter (quark gluon plasma: QGP) at high temperature
    • relevance to Big Bang
  - Phases at high baryon density region
    • relevance to neutron star
Method and Goal of the Research

• Experimental method
  - ultra-relativistic heavy ion collision is a unique tool to create matter with high energy density

• Research Goals
  - realize and evident QGP
  - study its properties
RHIC and the Experiments

RHIC
- 2 independent rings
- 3.83 km circumference
- CMS energy
  - Au + Au: up to 200 A GeV
  - p + p: 500 GeV (polarized)
- two programs: Heavy Ion and SPIN

BRAHMS, PHOBOS
- Small collaborations (~100)
- Large \( \eta \) but small \( \phi \) coverage

STAR, PHENIX
- Big collaborations (~500)
- Small \( \eta \) but large \( \phi \) coverage
Advertisement of Japanese group

- Two Japanese groups have been participating in the PHENIX experiment
  - Heavy ion: Japan-US collaboration in High Energy Physics
  - SPIN: RIKEN SPIN project
RHIC Operation

- The first collision: June 12, 2000
- Year-1 RUN
  - June ~ Sep. 4, 2000
  - Au+Au: $s_{NN}^{1/2} = 132$ GeV
- Year-2 RUN
  - Au+Au, p+p: $s_{NN}^{1/2} = 200$ GeV
- Year-3 RUN
  - Jan. 2003 ~ May 2004
  - d+Au, p+p: $s_{NN}^{1/2} = 200$ GeV
- Year-4 RUN
  - Jan. 2004 ~ May 2004
  - Au+Au, p+p: $s_{NN}^{1/2} = 200$ GeV, 63 GeV
- Year-5 RUN (currently ongoing)
  - Jan. 2005 ~
  - Cu+Cu, p+p: $s_{NN}^{1/2} = 63$ GeV
Key conditions and signatures of QGP

• High density
  - jet quenching

• Chemical equilibrium
  - particle yield

• Thermal equilibrium
  - hydrodynamical behavior
    → elliptic anisotropy $v_2$ in azimuthal angular distribution

• Signatures of deconfinement
  - hadron yield and $v_2$ at medium $p_T$
  - $J/\psi$ yield: suppression and enhancement
  - thermal photons
Probing Partonic Matter with Jets

• Back-to-back Jet Production
  - a hard process common in high energy collisions
  - parton-parton hard scattering
  - parton fragmentation $\rightarrow$ jet
  - high $p_T$ hadrons = mostly leading particles

• In p-A and A-A collisions
  - binary collision scaling
  - nuclear modifications:
    nuclear shadowing & Cronin effect (kT broadening)

• In A-A Collisions
  - new effect = energy loss of partons due to gluon bremsstrahlung
  - a new probe to investigate gluon density

$$\Delta E = \pi C_A C_a \alpha_s^3 \int d\tau p_{\text{glue}}(\tau, r(\tau)) \tau \log \left( \frac{2E_{\text{jet}}}{\mu^2 L} \right)$$
Jet Quenching Effect in Au+Au

- Suppression of yield at high pT in central Au + Au collisions
- Missing of back-to-back angular correlation for high pT particles
Controlled Experiment with d + Au

- Initial state effects cannot be ruled out
  - strong reduction of gluon strength \(\leftrightarrow\) c.f. CGC
  - energy loss of leading baryons due to subsequent collisions

- With d + Au collisions, “initial” and “final” state effects can be distinguished
  - no significant final state effects in d + Au collisions
  - “less jets created” versus “jets quenched”
Confirmation of High Density Matter

- Behavior is clearly different between $d + Au$ and $Au + Au$
  - Final state effect (jet quenching) is the main cause of these effects seen in central $Au + Au$ collisions
  - Matter with large gluon density is created in $Au + Au$ collisions
    - A theoretical calculation gives; $\rho = 11.5/fm^3$, $\varepsilon = 8.8$ GeV/fm$^3$ at $\tau = 1$ fm
Chemical Equilibrium

Two Freezeout

- **Chemical Freezeout**
  - End of inelastic interaction
  - Number of particles is fixed

- **Kinetic Freezeout**
  - End of elastic interaction
  - Momentum distribution is fixed

- **Chemical freeze-out model**
  - Assuming thermalization of hadrons consisted from $u, d, s$

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

- $Q_i$: 1 for $u$ and $d$, -1 for $u$ and $d$
- $s_i$: 1 for $s$, -1 for $s$
- $g_i$: spin-isospin freedom
- $m_i$: particle mass

- 4 parameters
  - $T_{ch}$: chemical freeze-out temperature
  - $\lambda_q$: light-quark chemical potential
  - $\lambda_s$: strangeness chemical potential
  - $\gamma_s$: strangeness saturation factor

2005/03/03 "QGP at RHIC" presented at KEKPH 2005
Chemical Fit

- The model reproduce data within (almost) one sigma
  - There are a few exception, but they are OK within 2 sigma

- Tch at RHIC (and SPS) seems to sit on the phase boundary
Centrality ($<N_{\text{part}}>$) Dependence

- $T_{\text{ch}} \sim 160$ MeV; close to $T_{\text{c}}$
- strangeness saturation factor $\gamma_s$
  - introduced to reflect that strangeness production/equilibration is a slow process
  - Increasing with $<N_{\text{part}}>$, and reach $\sim 1$ in central collisions
  - Only at RHIC; $\gamma_s < \sim 0.7$ at AGS and SPS energy
- Implication
  - fast strangeness production/equilibration at RHIC
  - it may only be possible in the deconfined phase
    - two-body process in hadronic phase is too slow
      - a new idea: multi-body interactions
Elliptic Anisotropy $v_2$

\[ \frac{dN}{d\phi} = N \left[ 1 + \sum 2v_n \cos(n\phi) \right] \]

- $\phi$: azimuthal angle for measured particles from a reaction plane
- $v_n$: anisotropy parameter

Large $v_2$ value indicates early thermalization
Large Elliptic Flow at RHIC

- Large $v_2$ is observed at RHIC
- $v_2$ value comparable to 'hydro' for $p_T < \sim 1.5$ GeV/c
- Hydro needs thermalization time $\Delta t$ to be less than $\sim 1$ fm, in order to have large $v_2$ value comparable to the experimental results
Large Proton to Pion Ratio in Mid-rapidity Region

- Large $p/\pi$ ratio at mid-$p_T$ region in central Au-Au collisions
- Different central-to-peripheral ratio ($R_{cp}$) for $\pi$ and $p$

- "Radial flow" is not the answer
  - $R_{cp}$ for $\phi$ is similar to $\pi$, not to proton
  - If it is a "flow effect"
    - slope parameter: $T_0 \sim T + m<\beta^2>
    - $m_\phi \sim m_p$
  - A new scheme of hadron formation
- "recombination" instead of "fragmentation" from the QGP soup
Quark Recombination Model

• A new hadronization scheme other than fragmentation
  - could be a good probe of deconfinement
  - gain is larger for baryons than for mesons
    • large combinatorials in central Au-Au collisions
    • combining three quarks at pT/3 to produce a baryon at pT v.s. two quarks at pT/2 to produce a meson at pT

• v2/n vs pT/n
  - Good example to show validity of this model
Quarkonium in HI collisions

- Novel idea of $J/\psi$ suppression
  - by Matsui and Satz (1986; before experimental results)
  - a good probe of deconfinement
    - suppression due to Debye screening in deconfined phase

- History in Brief
  - observation of suppression in S + A at SPS
    → turned out to be similar to p + A
  - anomalous suppression in Pb + Pb
    → a result to evident QGP at SPS
Recent Progress in Theory (I)

- Lattice-QCD told us:
  - confining potential starts to disappear at low temperature far below $T_c$
  - $J/\psi$ does not melt easily
  - Impact to the scenarios
    - Is dissociation dynamical or static?
Recent Progress in Theory (II)

- Enhancement of $J/\psi$ yield
  - recombination of charms becomes effective with increase of charm density
  - a signature of deconfinement
    - recombination of quarks from QGP soup
  - statistical hadronization model
    - coalescence in the final stage
  - kinetic formation model
    - reproduction in QGP + coalescence in the final stage
J/ψ in Au-Au collisions at RHIC

- results from Year-2 RUN
  - very poor

- but is already inconsistent with large enhancement scenarios
  - e.g. kinetic formation model, cf. PRC 63, 054905 (2001)

- In Run-4, 240 μb⁻¹ recorded with improved detector performance
  - ~ 100 times more J/ψ signals expected than in Run-2
Direct photons

- Direct photon is a unique probe, which provides direct information of its birth, because of penetrating property
- Photons can come from every stage of collisions, and can have various origins
- Direct photons = not from “hadron decay”

Diagram:
- Direct photons
  - Non-thermal
    - Initial hard scattering
    - Pre-equilibrium
  - Thermal
    - QGP
    - Hadron gas
- Photons from hadron decay
Quick Look of Various Photon Sources

- for thermal and hard photon measurements, hadron decay is a non-trivial background source
  - strong suppression of high \( p_T \) hadrons would improve the ratio, in particular, for hard direct photons

- a window for QGP thermal photons; \( p_T = 1 \sim 3 \text{ GeV/c} \)
Success in the 1\textsuperscript{st} round

- Direct photon in high pT region in Au+Au collisions
  - suppression of high pT $\pi^0$ yield makes the $\gamma/\pi^0$ ratio larger
  - comparable to a pQCD calculation (Ncoll scaling), which means:
    - no strong initial state effect; modification of structure function
    - $\pi^0$ suppression is the final state effect

- 2\textsuperscript{nd} round $\rightarrow$ thermal photons
Is thermal photon yield suppressed?

- Comparison of the present result with calculations with kT broadening and jet QGP bremsstrahlung
  - fast quarks passing through QGP, which is a significant photon source for \( p_T < 6 \text{ GeV/c} \)
- At present, it is too early to claim anything significant

- Gluon plasma (GP) and photon yield
  - chemically non-equilibrium state; \( GP \rightarrow QGP \)
  - hotter than QGP (\( \leftrightarrow \) smaller degeneracy)
    - hot glue scenario?
  - If GP stays long, it will have impact to photon production in hot matter; photon yield will be related to the evolution from GP to QGP
  - Other way to say: photon suppression is the signature of GP; native no-QGP hadron picture can be ruled out
Summary and Outlook

Key conditions and signatures of QGP

• High density
  - jet quenching \(\rightarrow\) OK

• Chemical equilibrium
  - particle yield \(\rightarrow\) looks fine
    -- need dynamical model

• Thermal equilibrium
  - hydrodynamical behavior \(\rightarrow\) seems OK
    → elliptic anisotropy \(v_2\) in azimuthal angular distribution

• Signatures of deconfinement
  - hadron yield and \(v_2\) at medium \(p_T\) \(\rightarrow\) promising
  - \(J/\psi\) yield: suppression and enhancement \(\rightarrow\) stay tuned
  - thermal photons \(\rightarrow\) need further work
Epilogue

• All the RHIC results suggest realization of a new form of matter, Quark Gluon Plasma, but we still know little about “what is QGP”.

• Data suggests thermalization at very early stage → Idea of sQGP (strongly interacting QGP) came out.
  - Lattice calculations seem to support the idea of strongly interacting matter near Tc
  - at the same time, it is a perfect fluid with very small viscosity, according to hydrodynamics.

• Study of properties of QGP is the next stage of this exciting field
  - RHIC → RHIC-II
  - LHC