Heavy-Ion Physics in the Future

Shoji Nagamiya

RIKEN / KEK

1) Past Highlights at RHIC and LHC
2) Tentative Summary and Future Issues
3) Lower Energy Scope
1) Significant Progress since 1970’s.

2) What will be our future?
RHIC and LHC
Temperature vs. Baryon Density

Quark-Gluon Plasma

Hadron Gas

Color Superconductor

Vacuum

Baryon Doping - $\mu_B$(MeV)

Temperature (MeV)

RHIC

LHC
Two Major Discoveries at RHIC

**Dense and Low-Viscous Fluid** is formed in nuclear collisions at RHIC. These results are confirmed at LHC also.

- **Strong Elliptic flow**
  - \( \eta/s \) (Low viscosity/entropy)
  - \( p_T \) suppression

- **Jet Quenching**
  - \( R_{AA} \) vs. \( p_T \) for Au+Au, Pb+Pb(Au), CERN-SPS, CERN-ISR

\[ R_{AA} = \frac{\text{signal}}{\text{no-collision}} \]

\[ p_T \text{ (GeV/c)} \]

\[ v_2 \]

\[ \eta/s \] (Low viscosity/entropy)

High \( p_T \) suppression

- Particle energy was lost through a dense matter like QGP

\[ \text{PHENIX PRL88,022301 (2002)} \]

\[ \text{STAR PRL86,402 (2001)} \]
Extended $R_{AA}$ to $p_T \sim 100$ GeV/c (LHC)

Parameter related to the energy loss in QGP, $\hat{q}$

$\hat{q} = 1.2 \pm 0.3$ GeV$^2$/fm at $T = 370$ MeV (RHIC)

$\hat{q} = 1.9 \pm 0.7$ GeV$^2$/fm at $T = 470$ MeV (LHC)

Jet Modification

Asymmetric di-jets and even mono-jets (!)

$\Delta R > 0.8$

Lost jet energy distributed very widely

$\Delta R > 0.8 \sim \pi/4$, enhancement at low $p_T$

A large jet $E_T$ asymmetry

→ Perhaps, direct evidence of parton energy loss in QGP?
**Elliptic Flow and Quark Number Scaling**

**RHIC**

- Measured Data
- Normalized by # of quarks
- $K_E T/n_q$ scaling works well at RHIC but may not work at LHC.
- Affected by a strong radial flow?? (for protons)

**LHC**

- Pb-Pb events at $\sqrt{s_{NN}} = 2.76$ TeV
- Centrality 20-40%

*ALICE preliminary*
Current RHIC & LHC flow ($v_2,v_3,v_4,v_5$) data are explained. 

$\eta/s$ (LHC) = 0.2 and $\eta/s$ (RHIC) = 0.12 $> 1/4\pi = 0.08$

$\eta/s$ (LHC) $\sim 1.6 \eta/s$ (RHIC)

Gas is mixed to Liquid at an initial stage? (in a gas, $\eta/s$ is large)
Earlier Temperature via Direct Photons

Average temperature at LHC is higher than RHIC, but both are higher than $T_c \sim 160-170$ MeV. Real initial temperature is 30-40% higher than the above?

**Slope = $221 \pm 19 \pm 19$ MeV**

**Slope $\sim 304 \pm 51$ MeV**

**Direct Photons**

Mass = 0 for Electrons
Hadronization Temperature

$T \approx 160$ MeV


Hadronization Temperature $\sim 160$ MeV
Sequential Melting of Quarkonia

Y(2S) more suppressed than Y(1S) in HI

Y(3S) even more suppressed in HI?

Deconfinement observed in HI Collisions?

CMS, PRL 109, 222301 (2012)
New Puzzle in $p+p$ and $p+A$

The above is still a puzzle and there was a special session on this issue at this conference.
Tentative Summary and Future
What Have We Learned from RHIC and LHC and Their Future?

- Energy loss $\hat{q}$, $\eta/s$ Initial temperature $T_{\text{init}}$, $T_C$.

<table>
<thead>
<tr>
<th></th>
<th>$\hat{q}$</th>
<th>$\eta/s$</th>
<th>$T_{\text{init}}$</th>
<th>$T_C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>RHIC 200 GeV</td>
<td>1.2 ± 0.3</td>
<td>0.12</td>
<td>&gt; 300 MeV</td>
<td>~160 MeV</td>
</tr>
<tr>
<td>LHC 2.67 TeV</td>
<td>1.9 ± 0.7</td>
<td>0.2</td>
<td>&gt; 400 MeV</td>
<td></td>
</tr>
</tbody>
</table>

- GeV$^2$/fm, Ratio = 1.6 From Photons $T = 220$ MeV & >300 MeV

RHIC and LHC Plans

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>RHIC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LHC</td>
<td>6.5–7.0 TeV Protons $p+p$, $p+Pb$, $Pb+Pb$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Future Issues

- LHC has definitely >10 years for the future programs in association with the energy recovery and the HL-LHC.
  - Study of QGP properties at high $T \sim 3T_c$ by three experimental groups with various probes, such as sequential quarkonia melting, $v_2$ to $v_5$ (or even higher order) flows, jets, heavy flavors, $J/\Psi$ melting vs. recombination, chiral magnetic effects, etc.

- RHIC will complete its scientific mission by mid-2020’s.
  - Complete the study of QGP blow $T_c$ to $\sim 2T_c$.
  - BES-II to complete the search for Critical Point
  - sPHENIX run to study jets at $T\sim 2T_c$

- Also, $pA$ or $pp$ puzzle must be solved.

- eRHIC?

- Lower energy HI to probe higher density region?
Temperature vs. Baryon Density

- LHC
- RHIC
- STAR's BES
- FAIR NICA? J-PARC?
- Neutron star
Comparison: Collider vs. Fixed Target

Comparison between collider and fixed target experiments

Collider (Pb+Pb or Au + Au): $10^{27} \sim 10^{28}$ cm$^{-2}$s$^{-1}$ for RHIC and LHC
If $10^{28}/($cm$^2$/s ) for Au + Au $\rightarrow 10^{28} \times 7$ barn $= 7 \times 10^4$/s $= 70$ kHz
… 50 kHz data rate is a future challenge at both RHIC and LHC.

Fixed Target Equivalent : $\sim$ Currently, $10^9$ per bunch at AGS for RHIC
If, an interaction rate of 1% target order
$\rightarrow$ for Au + Au collisions, $10^9 \times 0.01 = 10^7 = \sim 10$ MHz/bunch
$\rightarrow$ If 1 pulse = 5 bunches and 5 seconds = 1 pulse,
per bunch is almost equal to per second.

$\sim 10^{10-11}$ beams/s on a fixed target, 1% target implies
100MHz to 1GHz collision rate $\rightarrow$ A new physics may come out with high intensity heavy ion beams on a fixed target, and this direction could be interesting.
Variance: $\sigma^2 = <(\Delta N)^2> \sim \xi^2$
$[\chi^{(2)}/\chi^{(1)}]$  
Skewness: $S\sigma = <(\Delta N)^3>/\sigma^2 \sim \xi^{5.5}$
$[\chi^{(3)}/\chi^{(2)}]$  
Kurtosis: $K\sigma^2 = <(\Delta N)^4>/\sigma^2 - 3\sigma^2 \sim \xi^9$
$[\chi^{(4)}/\chi^{(2)}]$  

The 3rd and 4th-order fluctuations are sensitive to critical point and phase boundary. Detailed studies at lower energies are, thus, challenging & interesting.
FAIR, NICA? and J-PARC?
Possibility for High Density Formation

\[ \rho = \rho_0 \]


\[ \rho = 2 \gamma_{cm} \rho_0 \]

Assume no transverse kick

At AGS, \( \gamma_{cm} \approx 3 \), \( \rho \approx 6 \rho_0 \)

\[ \varepsilon \equiv \frac{E}{V} = 2 \gamma_{cm} mc^2 \rho_0 / (1/\gamma_{cm}) = 2 \gamma_{cm}^2 mc^2 \rho_0 \]
Multi-Strangeness Hypernuclei?

\[ |S| \geq 3 \text{ Hypernuclei} \]

- Full intensity beam of \(10^{11}/s\) is \(\sim 10\) MHz central collisions
- \(10^{-5}\) for \(10^6\) events means \(dN/dy = 10^{-4}\)
  \[ \rightarrow 0.3 \text{ events/hour} \]
  \[ \rightarrow \text{Very marginal but not impossible} \]

A. Andronic, PLB697 (2011) 203
Mystery of neutron star matter

- Final form of matter evolution in the universe
  - Produced by supernova explosion, observed as X-ray pulsars

- Highest density matter in the universe
  - $M = 1\sim2\ M_{\odot}$, $R \sim 10\sim20$ km
  - Density of the core = $3\sim10\rho_0$ ($1\sim3$ Btons/cm$^3$)
  - $\rho_0$: nuclear density

- Various forms of matter made of almost only quarks

Strange Hadron Matter
- High density nuclear matter with hyperons (strange quarks)

Nuclear “Pasta”

Neutron Matter
- Superfluid

Quark Matter
- Deconfined quarks
- Color superconductivity

High density formation may help multi-strangeness production
Possible Ideas for Fixed Target

- Primary Beam
  - Lepton pairs
  - Many other ideas
  - Search of strangeness related objects
  - Detector for stable object
  - Primary Protons
  - Primary Neutrons

- Search for lepton pairs
  + Many other ideas
Current Plan for FAIR

FAIR Exp. Programs:
M1: APPA
M1: CBM/HADES
M2: NUSTAR
M3: PANDA, APPA, NUSTAR

<table>
<thead>
<tr>
<th>Facility</th>
<th>Particle</th>
<th>Energy</th>
<th>max. Intensity [s⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIS100</td>
<td>U28+</td>
<td>2.7 GeV/u</td>
<td>3.0E11</td>
</tr>
<tr>
<td>SIS100</td>
<td>Proton</td>
<td>29 GeV</td>
<td>5.0E12</td>
</tr>
</tbody>
</table>

Fully stripped up to ~10 AGeV?

From K. Langanke - September 9 / 10, 2015
Future Plan for FAIR

on top of SIS 100:
SIS 300 in the same accelerator tunnel
- serves as stretcher ring for very slow extraction, thereby increasing the event rates of experiments, e.g. NUSTAR
- provides higher energies for exploring the QCD phase diagram (CBM)
- ultimate advantage: parallel operation of the full FAIR accelerator facility benefiting all scientific pillars

From K. Langanke - September 9 / 10, 2015
Superconducting accelerator complex **NICA**

*(Nuclotron based Ion Collider fAcility)*

- Fixed target experiments area (b.205)
- Extracted beams from Nuclotron
- KRION-6T and HILac (3.5 MeV/u)
- SPP and LU-20 (5 MeV/u)
- Booster (3-660 MeV/u) inside Synchrophasotron yoke
- Nuclotron 0.6-4.5 GeV/u
- Spin Physics Detector (SPD)
- Cryogenics
- HV e-cooler
- Multi-Purpose Detector (MPD)

**Strong Lol exists (2015)**
Possibility of HI at J-PARC

HI LINAC

$^{35+}$U $\rightarrow$ $^{30+}$U
20.0 $\rightarrow$ 19.9 MeV/u

$^{55+}$U $\rightarrow$ $^{56+}$U
19.9 $\rightarrow$ 67.0 MeV/u

$^{66+}$U $\rightarrow$ $^{86+}$U
67.0 $\rightarrow$ 62.3 MeV/u

$^{86+}$U $\rightarrow$ $^{92+}$U
735.2 $\rightarrow$ 727.0 MeV/u

$^{80+}$U $\rightarrow$ $^{92+}$U
62.3 $\rightarrow$ 735.2 MeV/u

$^{92+}$U $\rightarrow$ 11.15 GeV/u

MR

Already existing and working

Serious studies for U at $10^{11}$ beams/s by the accelerator group
HI Linac and HI Booster

Nuclear Experimentalists and Accelerator Physicists (According to H. Sako)

S. Nagamiya (RIKEN/KEK/JAEA)
H. Harada, P. K. Saha, M. Kinsho, J. Tamura (J-PARC/JAEA)
K. Ozawa, K. Itakura, Y. Liu (J-PARC/KEK)
T. Sakaguchi, M. Okamura (BNL)
K. Shigaki (Hiroshima Univ.)
M. Kitazawa, A. Sakaguchi (Osaka Univ.)
T. Chujo, S. Esumi, B. C. Kim (Univ. of Tsukuba)
T. Gunji (CNS, Univ. of Tokyo)
H. Tamura, M. Kaneta (Tohoku Univ.)
K. Oyama (Nagasaki Institute of Applied Science)
H. Masui (Wuhan Univ.)
Joint Project between KEK and JAEA

J-PARC = Japan Proton Accelerator Research Complex

Nuclear Transmutation (Phase 2)

Materials and Life Science Experimental Facility

Hadron Beam Facility

Neutrino to Kamiokande

Linac (330m)

3 GeV Synchrotron (25 Hz, 1MW)

50 GeV Synchrotron (0.75 MW)

Joint Project between KEK and JAEA
Lower Energy Future Issues

- FAIR is in progress. NICA proposed in 2015. J-PARC LOI is underway (2016) with maximum $10^{10-11}$ beams/s. (1 GHz interactions, but the current detector technology can handle up to 10 MHz)

- High density studies via rare processes (lepton pairs or muon pairs, etc.)

- Search for strangelet, multi-strangeness hypernuclei, etc. if the production probability is $> 10^{-(9-11)}$. If hypernuclei are formed in the projectile frame, then the lifetime is elongated to $\beta_{\gamma\tau}$ which is about 30-60 cm

- Study of hyperon mixing in neutron star?

- Fluctuation studies by the STAR low energy scans.
RHIC played an extremely important role for the discovery and properties of QGP. RHIC will complete its scientific mission by mid-2020's.

LHC has added more surprise and, at least, has > 10 years for future unexpected discoveries.

Puzzle in $p+A$ (or $d+A$) and $pp$ collisions.

Useful to explore high density region with very intense HI beams on the order of $10^{10-11}$/$s$ at selected facilities.
Thank You
Extra Slides
Higher Order Flows measured by ATLAS
## Low-Energy Heavy-Ion Programs

<table>
<thead>
<tr>
<th>Accelerator</th>
<th>Type</th>
<th>Beam energy (AGeV)</th>
<th>C.M. energy vs(AGeV)</th>
<th>Beam rate / Luminosity</th>
<th>Interaction rate (sec⁻¹)</th>
<th>Year of experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>RHIC Beam Energy Scan (BNL)</td>
<td>Collider</td>
<td></td>
<td><strong>7.7-62</strong></td>
<td>$10^{26} - 10^{27}$ cm⁻² s⁻¹ ($\nu_s = 20$ AGeV)</td>
<td>600~6000 ($\nu_s = 20$ AGeV) ($\sigma_{\text{total}} = 6$ b)</td>
<td>2004-2010</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2018-2019 (e-cooling)</td>
</tr>
<tr>
<td>NICA (JINR)</td>
<td>Collider</td>
<td>0.6-4.5</td>
<td><strong>4-11</strong></td>
<td>$10^{27}$ cm⁻² s⁻¹ ($\nu_s = 9$ AGeV Au+Au)</td>
<td>~6000 ($\sigma_{\text{total}} = 6$ b)</td>
<td>2019-2024</td>
</tr>
<tr>
<td></td>
<td>Fixed target</td>
<td></td>
<td>1.9-2.4</td>
<td></td>
<td></td>
<td>2017-</td>
</tr>
<tr>
<td>FAIR SIS100 (CBM)</td>
<td>Fixed target</td>
<td>2-11(Au)</td>
<td>2-4.7</td>
<td>$1.5 \times 10^{10}$ cycle⁻¹ (10s cycle, U⁹²⁺)</td>
<td>$10^5$-$10^7$ (detector)</td>
<td>2021-2024</td>
</tr>
<tr>
<td>J-PARC</td>
<td>Fixed target</td>
<td>1-19(U)</td>
<td>1.9-6.2</td>
<td>$10^{10} - 10^{11}$ cycle⁻¹ (~6s cycle)</td>
<td>$10^7$-$10^8$ (0.1% target)</td>
<td>?</td>
</tr>
</tbody>
</table>

### References
- RHIC: A. Fedotov, LEReC Review, 2013
Example of Lepton Pair Studies

Proposed by Dr. Sako, et. al.
FAIR’s Charm and Beauty in 2020?