Overview of J-PARC Heavy-ion Project

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for J-PARC Heavy-Ion Collaboration
Reimei workshop 2015, Tokai, 2015/1/20

Outline
1. Introduction
2. Acceleration scheme
3. Physics goals
4. Experimental design and simulation
5. Summary and prospect
J-PARC HI Collaboration

Experimental and Theoretical Nuclear Physicists and Accelerator Physicists

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Goals of J-PARC HI Project
- physics of extremely dense matter -

RHIC/LHC discovered QGP at high T and low \( \rho \)

No direct evidence for the critical point and phase boundaries discovered.

The highest density matter in the lab is created at J-PARC.

5-10 \( \rho_0 \)
~ neutron star core

Goals at J-PARC

- Studies of phase structures
- Hadron properties at high density related to neutron star structures
- Search for strange quark matter

Utilizing world’s highest intensity HI beams
HI experiments for high density physics

Aiming at world’s highest rate of $10^8$ Hz:
Beam rate $4 \times 10^{11}$ / cycle

• Ion species
  – p, Li, C, Si, Ar, Cu, Xe, Au(Pb), U
• Beam energy
  – 1-19 A GeV

Extremely important as accelerator science

Collision energy $\sqrt{S_{NN}}$ [GeV]
Interaction rate [Hz]

Highest baryon density

FAIR SIS-100 (2021-)
CBM
SIS ~

NICA (2017-)

NICA (Collider) (2020-)

J-PARC

Talk by P. Senger (20th)

RHIC BES II (2019-2020)
HI accelerator scheme

- **HI Linac**: 0.4 GeV
  - **HI booster**
  - **HI accelerator scheme**

- **U^{35+}**
  - 20 AMeV
  - **H⁻ Linac**: 0.4 GeV
  - **U^{35+} → U^{66+}**
    - 20 → 67 AMeV

- **HI Linac**: 0.4 GeV
  - 61.8 AMeV stripping
  - **U^{66+} → U^{86+}**
  - 0.4 → 3 GeV

- **RCS**
  - **(H⁻ → p)**
  - 61.8 → 735.4 AMeV

- **U^{86+}**
  - 0.727 AGeV stripping
  - **U^{86+} → U^{92+}**
    - 0.727 → 11.15 AGeV

- **MR**
  - 3 → 30 GeV (p)
  - **MLF**

- **p/HI to HD**
  - **p to NU**

- **HI (under planning)**
  - **p to HD**

- **Figures: Not to scale**

- **Talk by P.K. Saha (20th)**
- **Talk by H. Harada (21st)**
Observable for QCD phase structures

• Dileptons
  • Penetrating probes of dense matter
    – Modification of $\rho/\omega/\phi$ linked to chiral symmetry restoration

• Hadron measurements (high statistics)
  – Event-by-event fluctuations
  – (Multi-)strange hadrons, hypernuclei, strangelets

• Charm
  – $J/\psi$, D,...
    • Sensitive to initial dense matter?

• Photons
  – Thermal radiations from QGP
Low-mass dileptons

Maximum low mass enhancement around J-PARC energies?

- **Dielectron**
  - $\gamma$ conversion at low mass (background)

- **Dimuon**
  - $\pi,K \rightarrow \mu$ decay (background)
  - Higher rate beam can be used

- **High statistics at J-PARC**
  - Moment analysis
    \[ \int dm_{ee} N(m_{ee})m_{ee}^n \ (n = 1, 2, \ldots) \]
  - Direct comparison to theoretical models (e.g. QCD sum rules, related to quark and gluon condensate)

Hayano and Hatsuda, RMP**82**, 2949
Net-proton fluctuations

Ebe fluctuations: Probe to search for the critical point w/ higher-order fluctuations

Enhancement of 4th-order fluctuations at low energies

Indications of the critical point?

Talk by X. Luo (20th)
Talk by K. Morita (20th)

J-PARC

M.A. Stephanov, PRL107, 052301 (2011).

STAR Preliminary

X. Luo, Quark Matter 2015
Event selection

Advantage of J-PARC HIC program:
high-luminosity/statistics → various event selections

Example: event selection by

1. Net-baryon number
2. Total-strange number

High $\mu$ region can be studied by selecting baryon rich events

average transverse energy

courtesy of M. Kitazawa

Talk by M. Kitazawa (21th)
Talk by T. Sakaguchi (21th)
Extension of Hadron nuclear physics with to high density at J-PARC

Normal nuclear density

Talk by M. Naruki (20th)

Neutron star density

Meson beam experiment

Exotic hadron
Pentaquark (E19)
H-dibaryon (E42)

Hypernuclei
\(|S|\leq 2\) (E10, E13)

Kaonic nuclei: \(K^{-}pp\) (E27)

Chiral restoration in \(p+A\) (E16)

YN YY interactions

Neutron Star

EOS

HI experiment

Exotic hadron structure

\(|S|\geq 3\) hypernuclei

Neutron-stardust

\(A^*\) Cluster
strangelet (strange quark matter)

HBT

Collective flow

Talk by T. Yamazaki (20th)

Chiral restoration in \(A+A\)

Talk by Y. Nara (20th)
Particle production rates

Beam: $10^{10}$ Hz
0.1% target
→ Min-bias event rate
10MHz

In 1 month experiment:
\[ r, w, f \rightarrow ee \]
$10^3 - 10^{11}$

Hypernuclei

Hypernuclei


Measurements and Search

$10^{-13}$ sensitivity at J-PARC

A. Andronic, PLB697 (2011) 203
Search for strangelet at AGS-E886
\(~10^{-7}\) sensitivity \(\sim y_{\text{beam}}\)

PID of fragments is done with TOF and Z measurements

\[\text{dE}/\text{dx vs } \beta \text{ relation}\]

AGS D6 Beamline (30m)

\(p=1.8\text{GeV/c}\)

J-PARC Hadron hall

Hadrons/nuclei

HI beam
Experimental challenges

• High rate capability
  – Fast detectors
    • Silicon trackers, GEM trackers, ...
  – Pixel size < 3x3mm$^2$
    (at 1m from the target, $\theta<$2deg, 10% occupancy)
  – Extremely fast DAQ
    • Min-bias event rate = 10MHz
      → Triggerless DAQ

• Large acceptance ($\sim 4\pi$)
  – Coverage for low beam energies
  – Maximum multiplicity for e-b-e fluctuations

• Electron measurement
  – Field free region for RICH near the target

Toroidal magnet spectrometer
Beam View

Muon Tracker

Neutron counter

EMCAL

RICH

JHITS
J-PARC Heavy Ion Toroidal Spectrometer

Coils = insensitive area

12-fold coils
$B \phi$ variations $\sim +{-20\%}$

Toroid coils
3.2m Neutron counter
EMCAL
ZCAL
Beam
RICH
4m
1.4m
Top View
15 Toroid coils
0.25m 0.5m
1.90m
1.90m
R=1m
SVD 0.25m
C$_5$F$_{12}$ radiator
p<3.4GeV/c
e-π separation
μ-π separation
Fe absorbers +trackers
Multiplicity counter
GEM trackers
Neutron detector
EMCAL (e,γ ID)
PbWO$_4$, 15$X_0$
JHITS
ZCAL
MC + ZCAL
Central MC + ZCAL
Centrality
JHITS
Spectrometer performance

U+U at 10AGeV/c with JAM + GEANT4
- Assumption for simplicity
  - Half-spherical toroidal shape
  - Uniform B_φ field
  - No dead area due to coils
- Acceptance >= 78 %
- π/K separation 2.5GeV/c (2.5σ)

Assuming TOF resolution of 50 ps

Forward trackers

H. Sako, B.C. Kim
Reconstructed dilepton spectra

**Dielectrons**

\[ \theta_{ee} > 5^\circ \]
\[ 2^\circ < \theta < 80^\circ \]
\[ p_T > 0.1 \text{ GeV/c} \]

e^+e^- cocktail (8.6 M events)
No \( \gamma \) external conversion

**Dimuons**

\[ \theta_{ee} > 2^\circ \]
\[ 2^\circ < \theta < 80^\circ \]
\[ p_T > 0.1 \text{ GeV/c} \]

\( \mu^+\mu^- \) cocktail (500 M events)
No \( K,\pi \) weak decays

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**Signal**

- \( \pi^0 \rightarrow ee \gamma \)
- \( \eta \rightarrow ee \gamma \)
- \( \rho \rightarrow ee \)
- \( \omega \rightarrow \pi^0 ee \)
- \( \omega \rightarrow ee \)
- \( \phi \rightarrow ee \)

Very Preliminary

**Like-sign pairs**

**Like-sign mixed**

**Generated**

**Reconstructed**

B/S~23 (CERES)
B/S~4 (J-PARC)
Hypernuclear spectrometer

- Hypernuclei in ion collisions
  - $|S| >= 3$ Hypernuclei
  - Strangelet
- Hypernuclear measurement at $y_{beam}$
  - Life time
  - Magnetic moment

JHIPER

$^{12}$C Target
$^{12}$C Beam
Collimator (W) 1m
Dipole magnet
0.5m Charge counter
1.5m Precession magnet

Trigger counter for decay $\pi^-$

C+C at 15 AGeV/c
JAM-1.622 (RQMD/S mode) + GEANT4

BdL = 6Tm $\rightarrow$ Precession angle $\sim 68^\circ$
(assuming $\mu_\Lambda$)

Ideas based on
M. Asakawa et al, KEK Report 2000-11
T. R. Saito et al, HypHI Letter of Intent, 2005

At $10^7$ Hz interaction rate
$\rightarrow$ Track rate in TPC : $9.3x10^6$ Hz
$\rightarrow$ Trigger rate : $4.0x10^3$ Hz
Experiment with full beam rate may be feasible!
Summary and Prospect

- Rich and precise physics for phase structures and at high density at J-PARC
- Acceleration at $4 \times 10^{11}$/cycle by adding a linac and a booster to RCS and MR
- Large acceptance toroidal spectrometer for lepton and hadron measurements
- Hypernuclear spectrometer utilizing full beam intensity

Prospects

- Accelerator R&D of booster, linac, and ion source
- Detector R&D with the high-p beamline experiments at J-PARC (E16, E50) and heavy-ion experimentalists
  - MRPC-TOF (Tsukuba, JAEA, KEK) in J-PARC E16 (p+A)
  - DAQ (JAEA, Nagasaki IAS)
- Discussions in J-PARC and in nuclear physics community started

Collaborations from the world and from hadron/nuclear physics desired

We proceed with the project with strong collaboration of experimentalists, theorists, and accelerator scientists!

Goal: start within 10 years