EXPERIMENTAL STUDY OF FINITE DENSITY MATTER AT J-PARC

K. Ozawa (KEK/J-PARC)
J-PARC (Japan Proton Accelerator Research Complex)

- MR 30 GeV Synchrotron
- Material and Life science Facility
- Nuetrino Experimental Facility
- Hadron Experimental Facility
- RCS 3 GeV Synchrotron
- 400 MeV Linac
FINITE DENSITY MATTER AT J-PARC

- **Nucleus** as a finite density QCD matter
  - Partial restoration of Chiral symmetry

- **Heavy Ion** Physics program at J-PARC
  - Properties of QCD phases and QCD matters
  - Hadron Physics in a finite density matter
CHIRAL SYMMETRY AND “QCD MATTER”

- Chiral symmetry is one of the most important properties to characterize the QCD matter
- Masses of hadrons are generated by the spontaneous breaking of the chiral symmetry
  - $\pi$ mesons can be understood as NG bosons.
- The chiral symmetry in “QCD matter” can be restored in finite temperature and/or density media.
  - Expectation value of the vacuum ($\langle \bar{\psi} \psi \rangle$) is an order parameter of chiral symmetry
- Even at normal nuclear density, we can expect visible restoration of Chiral Symmetry
  - Hadron properties can be changed in nucleus

VECTOR MESONS IN NUCLEUS

- Mass spectra of vector mesons are sensitive to a partial restoration of the chiral symmetry in a finite temperature and/or density media
  - The mass spectra can be modified due to a partial chiral symmetry restoration in a nucleus
- A new experiment is being carried out to measure vector meson mass spectra in pÅ collisions (J-PARC E16)
  - A primary beamline and a new spectrometer are constructed

Reaction

[Graph showing invariant mass distribution]
J-PARC E16 SPECTROMETER

- High beam intensity and large acceptance in target rapidity region to collect huge statistics
  - $10^{10}$ protons per spill
  - Counting rate: 5 kHz/mm$^2$ (maximum)

- Good momentum resolution to detect a small modifications of the mass spectra

- Detectors
  - Silicon Strip Detector: Tracking
  - GEM Tracker: Tracking
  - Hadron Blind Detector: eID (Cherenkov)
  - Lead Glass EM Calorimeter: eID
STATUS OF THE EXPERIMENT

- Commissioning runs: June 2020 and June 2021
  - All detectors, triggers, and DAQ worked well
  - Detector performance in commissioning data

Photo of Spectrometer

Pilot data has been taken
Physics Run in 2024
**NOTE: $\Phi N$ INTERACTIONS AND MASS**

- Mass of $\phi$ meson in a QCD medium can be related with $\Phi N$ interactions also.

- **ALICE** shows the attractive strong interaction between a proton and a $\phi$ meson using two-particle correlations measurements
  - Consistent with LEPS results (W.C. Chang et al., PLB658(2008), 209)
  - Significantly larger than CLAS results (I. I. Strakovsky et al., PRC101(2020), 045201)

- The result suggest a large mass modification of $\phi$ meson
J-PARC HEAVY ION PROJECT

- **Main Physics topics**
  - QCD phase structure in high density region
  - Study of hadron physics in a finite density matter

- **Heavy Ion Beam specifications**
  - Beam Energy: $\sqrt{s_{NN}} \sim 2 - 5$ GeV
  - Species: Up to Uranium
  - Maximum Beam Intensity: $10^{11}$ Hz
FACILITIES TO BE UPGRADED FOR HEAVY ION

- New Heavy Ion Injector (LINAC and BOOSTER)
- New Experimental area and Spectrometers
STAGING PLAN

- On-going
  - pA collisions using existing beam line and spectrometer
    - Main Physics topic: Vector meson measurements in $e^+e^-$ decay modes
    - + Upgrades of the spectrometer for hadron measurements
    - Pilot data for Heavy Ion physics
- Phase I
  - New LINAC and reuse of KEK-PS booster
  - Upgrades of the existing spectrometer
  - Beam Intensity: $10^8$ Hz for Au
- Phase II
  - New Booster and New spectrometer
  - Final configuration

Phase 1
Reused Booster Ring

Phase 2
HI Booster Ring
HEAVY ION: PHASE I EXPERIMENT AND SPECTROMETER UPGRADES

- Physics Goal of phase I experiment
  - Hadron interactions in dense medium
  - Search for a quark phase
    - Flow, Two particle correlations
    - Di-electron

- Heavy Ion beams
  - Species: Au
  - Intensity: $10^8$ Hz

- Detector Upgrades
  - Hadron measurements
    - It will be partially installed for pA experiment
  - Additional detectors in forward region

Schematic view of spectrometer

Forward Additional Detectors

Original acceptance

Time Of Flight
EQUATION OF STATE (DIRECTED FLOW)

- Particle emissions (flows) are basic observables in heavy ion collisions
  - Example:
    - Directed Flow
      - Sensitive to the Equation-Of-State
      - First harmonic coefficient: $v_1$
      - $f(\phi; y, p_t) \propto 1 + 2 \sum v_n (y, p_t) \cos(n\phi)$

Data: STAR PRL 1708.0713; PLB 2108.00908
Calc: Y. Nara et al., PRC 106 (2022)4, 044902
Temperature measured by radiation of di-electrons

- Expected $e^+e^-$ mass spectrum with radiation

Non-monotonic behavior shows a phase transition

- Temperature as a function of collision energies

P. Senger, CBM, Particles 2020, 3(2), 320-335;
Event by Event fluctuation of conserved variables have a sensitivity for the phase transition
- correlation length, critical point

Higher order fluctuations are essentially important
- Need huge statistics and uniform acceptance
PHASE II: SPECTROMETER

- Experiment with High-intensity beam ($10^{11}$ Hz)
- Large acceptance and low $p_T$ tracking detector
  - higher flows, fluctuations, charmed hadrons
  - Detailed detector designs are still under discussion
- Current plan
  - Hadron Spectrometer
    - Dipole + TPC
    - Large Acceptance for Correlations, Fluctuations
  - Hyper-nuclei Spectrometer
    - Closed configuration
    - Hadron Spectrometer + Sweeping magnet

Schematic view of Hyper-nuclei spectrometer
We are performing experimental studies of finite density matter at J-PARC
- pA experiments
- Future Heavy Ion experiments

We are performing a new experiment to study mass spectra of vector mesons in nucleus, since mass spectra of the vector mesons can be modified due to a finite density effects.
- Hadron mass is dynamically generated by a spontaneous breaking of chiral symmetry in the medium and closely related with properties of QCD medium

Future Heavy ion experiments at J-PARC are planned to study hadron physics and high-density matter

Significant Facility upgrades are required for Heavy Ion experiments
- We need Linac and Booster for heavy ion acceleration
- New Spectrometer and new experimental area
MEASUREMENTS OF VECTOR MESONS

Vacuum

Quark Condensates

$\phi$ meson, which contains quark and anti-quark

$e^-$ $e^+$ $e^-$

Reconstruct

Change of quark condensates and modifications of mass spectrum

Nucleus (Finite Density)

Spectral Change: (Partial) Restoration of chiral symmetry

$e^+$ $e^-$

Reconstruct

Invariant Mass

In vacuum

In Nucleus
EXAMPLE: NEUTRON STAR EOS

- Basic information of the interactions can be measured at the current J-PARC
- Extrapolation to the higher density region is necessary
  - $\chi$EFT
  - Linear (causal) EOS
  - Chiral Functional Renormalization Group
    - M. Drews, W. Weise, PNP 93(2017) 69
  - Constrains from GW and multimessenger data
    - E. Annala et al., Nature Phys. 16 (2020) 907
- Experimental information at the high-density region is essential
Many particles including short-lived resonances are produced

Measurements of hadrons can give fruitful information about hadron interactions
- Properties of emitted hadrons are determined by their interactions

Correlation analysis which are performed at “High Energy” heavy ion collisions can be done

In addition, study of interactions in a finite density circumstance can be done

A. Andronic et al., PLB697 (2011) 203

Expected Hypernuclei production

J-PARC
Polarization and mass shift

H. Kim and P. Gubler, PLB805 (2020)135412

Chiral partner through interferences

M. Harada and C. Sasaki, PRC 80 (2009)054912

Mass of $\phi$ meson v.s. Momentum

Mass spectrum of $e^+e^-$
OBSERVABLES: PARTICLE CORRELATIONS

- Two particle correlation function:
  - \( C(q) \sim \int d^3 r S(r) \left| \varphi^{(-)}(q, r) \right|^2 \)
  - \( C = C(qR, R/a_0) \)
    - \( a_0 \): Scattering length

- Information on hadron interactions can be extracted
  - Interactions of exotic hadrons or short-lived resonances
  - Interactions in low momentum limit

Y. Kamiya et al., PRL 124(20)13, 132501
APPLICATIONS: PARTICLE CORRELATIONS

- Interactions in a finite-density matter
  - Vector meson and nucleon interactions
    - Mass modifications and chiral symmetry restorations
  - Pseudo-scalar and nucleon interactions
    - Changes of scattering amplitude in a matter discussed by Dr. Y. Ichikawa

- Hadron Structure
  - Combined with binding energy data, hadron internal structure (compositeness) can be discussed
    - Example: $\Xi\alpha$ interaction discussed by Dr. Y. Ichikawa
  - When the thermalization of the matter is achieved, statistics of productions can provide the structure information
    - cf: ExHIC collaboration, PPNP 95(2017) 279

ALICE, PRL 127 (2021), 172301
DIRECT STUDY OF HIGH-DENSITY MATTER

- Search for QCD Phase structures
  - 1st order phase transition
  - Color superconductor
    - Di-quark correlations

- Properties of dense matter
  - EOS, transport properties (viscosity), etc.
  - Chiral symmetry

JAM2 Calculation by Y. Nara:
https://gitlab.com/transportmodel/jam2

Calculated Temperature and Density

![Diagram showing temperature and density relationships]

K. Ozawa - ISMD 2023
PHASE TRANSITION AND OBSERVABLES

- Generated matter has dynamical trajectory on the QCD phase diagram
- When the matter cross the phase boundary, significant changes of measurements can be expected
- Quark-Hadron Phase transition
  - Temperature
  - Particle Fluctuation
- Color-superconductivity
  - Low mass di-electron emissions
PHASE TRANSITION AND COLOR SUPERCONDUCTIVITY

- **Color Superconductivity**
  - Di-quark correlations in a high-density matter

- **Realistic signatures of the existence of the superconductivity phase are still under discussion**

- **One promising signature is an enhancement of dilepton mass spectra**
  - “Soft-mode” photon self-energy due to dynamical diquark fluctuation develop near the phase boundary
  - Discussions for measurements lead by Dr. Y. Morino

**Calculated $e^+e^-$ mass spectrum with the phase transition**

T. Nishimura, M. Kitazawa, T. Kunihiro, PTEP 2022, 093D002

$T = 90$ [MeV], $\mu = 350$ [MeV]
HADRON MEASUREMENTS CAPABILITIES

- Enhance the rapidity region with forward detectors

Proton acceptance in A+A

Momentum vs. Mass

Enough particle ID capabilities
PHASEII: UPGRADES OF EXPERIMENTAL AREA

Current Experimental Hall

Upgrade Plan of the Experimental Hall

New Production target & New beamlines

[Diagram showing current and upgrade plans for the Experimental Hall, highlighting new production target and beamlines.]
PHASE II: HADRON MEASUREMENTS

- Identified charged particles for $\sim 4\pi$ acceptance
  - Silicon Pixel Tracker (SPT) ($\theta < 4^\circ$)
  - TPC ($\theta > 4^\circ$)
  - MRPC-TOF for particle identifications
- Trigger-less DAQ and high-rate counting

- Enhance the physics capabilities for rare events, fluctuations, higher order flows.
J-PARC-HI Collaboration

134 members:

Experimental and Theoretical Nuclear Physicists and Accelerator Scientists

Experiment


Theory


Accelerator


J-PARC (Japan Proton Accelerator Research Complex)

- MR
  - 30 GeV Synchrotron
- RCS
  - 3 GeV Synchrotron
- 400 MeV Linac
- Hadron Experimental Facility
### HADRON EXPERIMENTAL FACILITY

**Diagram:**
- **30GeV Main Ring**
- **Primary Proton Beam**
- **New Primary Beam Line (High-p)**
- **Production Target**

#### Extraction for Hadron Exp.

<table>
<thead>
<tr>
<th>Name</th>
<th>Species</th>
<th>Energy</th>
<th>Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>K1.8</td>
<td>$\pi^\pm, K^\pm$</td>
<td>$&lt; 2.0$ GeV/c</td>
<td>$\sim 10^5$ Hz for $K^+$</td>
</tr>
<tr>
<td>K1.8BR</td>
<td>$\pi^\pm, K^\pm$</td>
<td>$&lt; 1.0$ GeV/c</td>
<td>$\sim 10^4$ Hz for $K^+$</td>
</tr>
<tr>
<td>KL</td>
<td>$K_L$</td>
<td>2.0 GeV/c (Ave.)</td>
<td>$\sim 10^7$ Hz for $K^0$</td>
</tr>
<tr>
<td>New Beamline</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High-p</td>
<td>primary</td>
<td>30GeV</td>
<td>$\sim 10^{10}$ Hz</td>
</tr>
<tr>
<td></td>
<td>Unseparated</td>
<td>$&lt; 20$GeV/c</td>
<td>$\sim 10^8$ Hz</td>
</tr>
</tbody>
</table>
HI ACCELERATION SCHEME AT J-PARC

Proton beam rate (slow extraction)
- $5.5 \times 10^{13}$/cycle (currently)
- $1.2 \times 10^{14}$/cycle (2022)

- HI beam rate $\sim 10^{11}$ Hz
- $E_{\text{lab}}(U) = 1$-12 AGeV
- $\sqrt{s_{NN}}(U) = 1.9$-4.9 GeV
MINIMUM UPGRADES (ACC. PART)

Heavy Ion LINAC
Budget request as a low energy heavy ion project
Reuse of cavities which is used at JAEA Tandem Booster
Reuse of KEK-PS Booster Ring (KEK-BS)

- HI beam rate $\approx 10^{11}$ Hz
- $E_{lab}(U) = 1-12$ AGeV
- $\sqrt{s_{NN}}(U) = 1.9-4.9$ GeV

**Intensity is limited by KEK-BS, which is a small ring and no flexible optics. Space charge effect is at a negligible level because the beam intensity is $10^{-3}$ lower than that of proton beam at present.**
Dielectron measurements in heavy-ion collisions at J-PARC with E16 upgrade
- $10^8$ beam/spill, IR rate ~ 50 kHz with 0.035 mm Au target (~0.1% int. length)

Experimental area will be used as it is

First Proposal is submitted to J-PARC Program Advisory Committee in this July
- Temperature and yield measurements of di-electrons above $M_{ee} > 1$ GeV
  - Search for a (onset of) partonic matter
  - “Caloric curve” to map out the phase diagram below $\sqrt{s_{NN}} < 10$ GeV
The most forward modules should be upgraded to cope with a high hit-multiplicity environment
- Hit occupancy should be reduced and finer segments are required

Tracking device
- The most inner GEM Trackers must be upgraded and replaced with SSDs

Electron identification detectors
- Lead glass calorimeter must be upgraded to finer segmented detectors
  - Lead Tangsten (PWO₄ is a candidate)

Zero degree calorimeter
- New detector for a centrality determination

Readout and DAQ system
- Current system assume 1 kHz event trigger
- New system should be run at 50kHz interactions
~ 6% accuracy of T can be expected from $M_{ee}>1.1\text{GeV}/c^2$ in the case of 150 MeV
~10% accuracy of T can be expected from $M_{ee}>0.9\text{GeV}/c^2$ in the case of 120 MeV
~20% accuracy of integrated excess yield (0.4<$M_{ee}$<0.7GeV/$c^2$)
(sys error from the known resonances is dominated)
**EXPECTED DIMUON SPECTRUM**

We have evaluated performance of our dimuon spectrometer

- Embed $\mu^+\mu^-$ into JAM events and process by GEANT
- $U+U, \sqrt{s_{NN}}=4.5$ GeV, Min. bias JAM events
- Reconstruct tracks passing through 4 $\lambda_1$ muon absorbers

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

**Generated cocktail**

**Reconstructed spectrum**

**Enough Resolution even in low mass region**
Calculations for thermalized phase are being developed by a collaboration of theoretical groups.

Example: A Japanese group develops an “unified” hydro-cascade model

- Simultaneously evolve both fluid element and hadrons in time
  - High density hadrons → “parton fluid”
  - Cooled “parton fluid” → hadrons
- Unified model describes data well, while cascade only doesn’t
  - It seems we can expect parton fluid phase even at the J-PARC energy
FLOW MEASUREMENTS

- Using the developed model, significance of flow measurements are evaluated
  - Au+Au events of hydro + JAM cascade model (JAM-1.9043)
  - Higher-order flow can be measured for study of “fluid” properties of generated medium

Higher-order harmonics with 2-particles correlation (4.5 M events)

Higher-order harmonics with Cumulants (54M events)
**E16 UPGRADE: ZERO DEGREE CALORIMETER**

- Centrality is defined with the number of SSD hits and the energy deposit at zero-degree calorimeter (ZCAL)

- **ZCAL**
  - Located at 4.5m downstream from the target (just in front of the beam dump)
  - Dimension: 15cm(x)×30cm(y)×50cm(z)
  - $4.0\lambda_{/11.3X_0}$ Tungsten-MPPA fiber sampling calorimeter (based on RHIC ZDC)
  - Acceptance to avoid positive fragments and beam but detect neutrons
FEASIBILITY STUDIES: INPUTS

- Thermal dielectrons

Dielectrons from hadronic decays

JAM event generator for Au+Au at 10 A GeV/c

- \( \frac{dN_{ee}}{dy} (0.3 < M_{ee} < 0.7 \text{ GeV}/c^2) = 1.2 \times 10^{-5} \times \frac{dN_{\pi^+\pi^-}}{dy} (105) \)
- \( \frac{dN_{ee}}{dM} \propto (M T)^{3/2} \exp(-M/T) \)
- \( \frac{dN_{ee}}{dP_t} \propto \exp(-P_t/T) \)

Two cases studied

- T = 150 MeV (cross-over transition)
- T = 120 MeV (1\textsuperscript{st} order phase transition)

- Dielectron pairs are transported into GEANT4 simulation
- Full E16 acceptance & E16 achieved eID capability considered
- Tracking inefficiency due to high multiplicity effects taken into account

K. Ozawa - ISMD 2023
EFFICIENCIES AND RAW MASS DISTRIBUTIONS

- Pair Efficiencies
  - Multiplicity effects not included

- Raw Mass Distributions
  - Thermal photons
  - Known resonance decay $\pi^0 \rightarrow ee\gamma$, $\eta \rightarrow ee\gamma$, etc..
  - $\gamma$ conversion in the target
  - Miss ID $\pi^+$
  - Combinatorial pairs

$1 \times 10^8$/spill 10 AGeV Au beam x 100 days run
0.035 mm Au target ($\sim$0.1% int. length)
PRODUCTION RATE

A. Andronic, PLB697 (2011) 203
VECTOR MESONS IN NUCLEUS

- Spectral changes of vector mesons in QCD medium provide crucial information on the non-trivial structure of QCD medium
- Spontaneously broken chiral symmetry and its (partial) restoration in a finite density matter.
- Upgrades of the KEK-PS E325 experiment

KEK E325 results

J-PARC expectation

High Statistics
Better Resolution
EXPECTED RESULTS FOR THE FIRST EXP.

- Measurements of changes of hadron properties in a nucleus
  - Hadron mass can be changed in a finite density due to a partial restoration of chiral symmetry
  - Same effects are expected in a high energy heavy ion collisions
  - Much clear measurements can be done in a nucleus
HYPER-NUCLEI SPECTROMETER

- Closed geometry: Sweeping magnet and Collimator
  - Limit the acceptance to beam rapidity
  - Only beam and fragments can reach 2nd dipole magnet
  - Interaction Rate: ~100 MHz
- Lifetime and Magnetic moment of hypernuclei
- Search for new hypernuclei and strangelet

Horizontal Position @ TPC entrance
\[ \propto \frac{Z}{A} \]

Schematic view of Hyper-nuclei spectrometer

No contamination from non-strange nuclei
**AN EXAMPLE OF EXPECTED RESULT:** $^3\Lambda^H$

1. Tag $\pi$- with the track angle and position
2. Identify fragment by $Z$ and $p/Z$
3. Invariant mass of ($\pi$-, fragment) pair

$^3\Lambda^H$ embedded in JAM C+C events

- Horizontal position vs angle
- Fragment ID in TPC
- Reconstructed $\pi^-$-$^3$He invariant mass