K. Ozawa (KEK, University of Tsukuba)
for the J-PARC HI collaboration
Studies of Finite Density Matter are remaining frontiers in QCD physics

At J-PARC, several studies related to finite-density medium are on-going!!

J-PARC ACTIVITIES

- Elementary interactions with strangeness
  - Hyperon – Nucleon interactions
    - Hyper-nuclei
    - Direct scattering measurements
  - Kaonic nuclear bound states

- Vector mesons in nucleus
  - $\chi$ sym. restoration in finite density matter

- Explore high baryon density medium in Heavy Ion collisions
Nucleus is a stable object and can have a bound state with hyperons.

If a bound state is observed, we can measure a binding energy.

The binding energy can be interpreted to the strength of interaction between nucleon and hyperon.

This method is a powerful tool to study hyperon interactions and we extend this study to $S=-2$ system.

Measured bound states spectrum by Prof. Nagae

- $U_\Lambda = -30$ MeV
  (c.f. $U_N = -50$ MeV)
PIONEERING RESULTS FOR $S= -2$ SYSTEM

**Nagara event**

$H. \text{Takahashi et al., PRL 87 (2001) 212502}$

$^6_{\Lambda\Lambda} \text{He} \rightarrow ^5_{\Lambda} \text{He} + p + \pi^-$

$\Delta B_{\Lambda\Lambda} = 0.67 \pm 0.17 \text{ MeV}$

$\Lambda-\Lambda$ is weakly attractive

**Kiso event**

$K. \text{Nakazawa et al. PTEP 2015, 033D02}$

$\Xi^- + ^{14}\text{N} \rightarrow \Xi^{15}\text{C} \rightarrow ^{10}\text{Be} + ^5\text{He}$

$B_{\Xi^-} = 4.38 \pm 0.25 \text{ MeV,}$

$\sim 1.11 \pm 0.25 \text{ MeV}$

$\Xi-N$ is attractive!
Two successive two-body reactions

Detection of $\Sigma p$ scattering event by CATCH detector

$\Sigma^\pm$ – PROTON SCATTERING

Physics Motivation:

Systematic study of the $\Sigma p$ interaction
$\Sigma p$ interactions are repulsive and $\Sigma$ hyper-nuclei formation is difficult
Pauli blocking effect between quarks
Origin of repulsive force in $\Sigma^+ p$ interaction
Suggested by HAL QCD Lattice calc.

Half of data is already collected in 2019!

K. Ozawa, SQM 2019, Bari, Italy

J-PARC E40: Prof. K. Miwa (Tohoku univ.)
To study a finite density system, understanding of three-body system is important. Especially, K-NN system is interesting.

Attractive K-N interaction in I=0 is suggested by properties of $\Lambda(1405)$.

A bound state of K-pp system is predicted by several theoretical calculations.

Various predicted values of binding energy and width.

Existing experimental data is not agree with theoretical predictions.

**A new experiment is executed using a new technique!**

J-PARC E15: Prof. Iwasaki (RIKEN)
CLEAR K-PP BOUND STATE IS OBSERVED


Invariant mass distribution of $\Lambda p$

Quasi-Free and Background contributions are evaluated using missing mass information

- Binding energy: $\sim 50$ MeV
- Width: $\sim 100$ MeV
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**

\[
\chi^2/\text{ndf} = 83/50
\]

\[\text{e}^+\text{e}^- \text{ invariant mass}\]

**J-PARC expectation**

\[\phi(1020)\]

\[\text{e}^+\text{e}^- \text{ invariant mass}\]

High Statistics

Better Resolution

~35 MeV
J-PARC E16 EXPERIMENT

- Measurements of $e^+e^-$ pair invariant mass spectra in nucleus
- 10 times larger statistics compared to the KEK experiment
  - $10^{10}$ protons per spill (10 times higher than KEK)
  - Counting rate: 5 kHz/mm$^2$ (maximum)
- Two times better resolution than KEK
  - Larger magnetic field
  - Better Position resolution (~100 μm)

We will start data acquisition in 2020 spring
J-PARC Heavy Ion Program

Only Linac and Booster ring are required for Heavy Ion!

Designed by H. Harada and P.K. Saha
HIGH BARYON DENSITY MATTER AT J-PARC

Energy range: $\sqrt{s_{NN}} = 2$~5 GeV, Maximum interaction rate: $10^8$ Hz
With a collaboration with theorists, we are evaluating achievable baryon density

If we can select “rare event”, higher baryon density can be studied

Max Baryon density distribution (JAM)

Selection of higher baryon density matter
We are looking for suitable valuables e.g. $p_T$ sum of charged particles

Max Baryon density vs $\Sigma p_T$ (JAM)

Statistics-starved “rare event” selection feasible at J-PARC-HI
An issue in this energy region is that theoretical calculations for thermalized phase is not enough.

Recently, 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 very well, while cascade only doesn’t
  - It seems we can expect parton fluid phase even at the J-PARC energy

Akamatsu, et.al, PRC98, 024909 (2018)
First step
Interaction rate: $10^6$ Hz
E16 di-electron spectrometer
$\rho, \omega, \phi \rightarrow e^+e^- : 10^4$ events

Second step
Interaction rate: $10^6$ Hz
Dipole hadron spectrometer
Flow, event-by-event fluctuation

Third step
Interaction rate: $10^7$ Hz
Dipole muon spectrometer
Precise low mass vector meson
Heavy Flavor

Final step
Interaction rate: $10^8$ Hz
Rare events: Highest Density matter
Hyper nuclear physics
Strangelet search

A. Andronic, PLB697 (2011) 203

K. Ozawa, SQM 2019, Bari, Italy
DIPOLE HADRON SPECTROMETER

Charged particles + neutrons, $\sim 4\pi$ acceptance
- Silicon Pixel Tracker (SPT) ($\theta < 4\circ$), TPC ($\theta > 4\circ$)
- MRPC-TOF, neutron counter

Rate: $\leq 10^6$ Hz interaction
Centrality: Multiplicity counter + zero-degree calorimeter

Measurements:
Higher order Flow, event-by-event fluctuation
DIMUON SPECTROMETER

Replace TPC by:
- Pb absorbers and GEM trackers
- Dimuon Online Trigger
- 7-layer forward and barrel Silicon Pixel Trackers
- Interaction Rate: $10^7$ Hz

**Top view**

**Beam view**

Measurements:
- Low mass dilepton, Heavy flavor
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, Minbias JAM events
- Reconstruct tracks passing through 4 $\lambda_1$ muon absorbers

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

**Generated cocktail**

$U+U, \sqrt{s_{NN}}=4.5$ GeV, Min-bias (54k)

**Reconstructed spectrum**

**Enough Resolution even in low mass region**
Hypernuclear Spectrometer

- **Hypernuclei at beam rapidity**
  - 1st dipole magnet + collimator $\rightarrow$ Only beam fragments reach 2nd dipole magnet
  - Lifetime and Magnetic moment
  - Interaction Rate: $10^8$ Hz

- **Strangelet search**

Add a sweep magnet and a collimator upstream

SUMMARY

- Several studies related with finite density matter is on-going at J-PARC
  - Hypernuclei
  - Hyperon-Nucleon scattering
  - Kaon bound states
  - Vector mesons in nucleus

- We can have much results in a few years

- Future Heavy ion program at J-PARC is being prepared
  - We need Linac and Booster for heavy ion acceleration
  - First, we can start with di-electron spectrometer, which is being built for a pA experiment
  - Then, further study of high baryon density matter will be done using upgrade detectors
J-PARC-HI COLLABORATION

94 members:

Experimental and Theoretical Nuclear Physicists and Accelerator Scientists

Experiment


Theory


Accelerator


Back up
<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>K1.1</td>
<td>$\pi^\pm, K^\pm$</td>
<td>$&lt; 1.1$ GeV/c</td>
<td>$\sim 10^4$ Hz for $K^+$</td>
</tr>
</tbody>
</table>

**New Beamline**

<table>
<thead>
<tr>
<th>Species</th>
<th>Energy</th>
<th>Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>proton</td>
<td>30 GeV</td>
<td>$\sim 10^{10}$ Hz</td>
</tr>
<tr>
<td>Unseparated</td>
<td>$&lt; 20$ GeV/c</td>
<td>$\sim 10^8$ Hz</td>
</tr>
</tbody>
</table>
IM(Λp) vs. Momentum Transfer $q_{Kn}$

- **Fit with 3 components**
  - **Bound state**
    - centroid DOES NOT depend on $q_{Kn}$
    - BW*(Gauss form-factor)
      \[ f_{K_{pp}}(M, q) = \frac{A_{K_{pp}} (\Gamma_{K_{pp}}/2)^2}{(M - M_{K_{pp}})^2 + (\Gamma_{K_{pp}}/2)^2} e^{-\left(\frac{q}{2\Gamma_{K_{pp}}}\right)^2}, \]
  - **Quasi-elastic $K^-$ abs.**
    - centroid depends on $q_{Kn}$
    - Followed by $Λp$ conversion
      \[ M_F(q) = \sqrt{4m_N^2 + m_K^2 + 4m_N \sqrt{m_K^2 + q^2}}, \]
- **Background**
  - Broad distribution
The J-PARC E16 spectrometer

- PbGd Calorimeters
- Beam coil
- Target
- Return yoke
- GEM tracker
- Csl + GEM
- Cherenkov

Magnet (used for KEK E325)

SSD: Tracking
GTR: Tracking
HBD: eID (Cherenkov)
LG: eID (Calorimeter)

26 modules in total. 8 for the 1st physics run.

K. Ozawa, SQM 2019, Bari, Italy
Silicon Strip Detector

• Run0
  • Existing 6 SSDs used for another J-PARC experiment.
    • ATLAS sensor
    • Sensitive area: 61 mm x 62 mm
    • Strip pitch 80 um. (1D)
    • Timing Resolution 4ns
    • It has large unwanted frame.
    • The readout ASIC is APV-25

• Run1
  • Starting collaboration with FAIR-CBM
    • CBM developed sensor
    • Sensitive area: 60 mm x 60 mm
    • Strip pitch 50um (Double sides)
    • Almost no frame
    • The readout ASIC is a CBM special chip
      • Developed for the streaming DAQ, however it can be used for a triggered DAQ
GTR (GEM Tracker)

- Ionization electrons in the drift gap are collected and amplified by GEMs.

- Charge collected on to 2D strip readout.
  - X: 350um pitch
    - Sensitive to bending direction.
    - 100 um resolution required.
  - Y: 1400um pitch

- Assembly works are on-going.
GTR Performance

- Center Of Gravity (COG) Method
  - Ordinal analysis method
  - ~ 60 μm @ 0 degree of incident angle
  - Worse results for inclined tracks

- Timing method
  - Distance in drift field dir. Can be obtained using flight time like mini-TPC
  - ~ 100 μm for all tracks

- 2D fit (COG + Timing)
  - Timing method
  - COG method
  - 2D fit
HBD
(Hadron Blind Detector)

- Based on PHENIX HBD.
- CF4 serves as radiator and amplification gas
  - Radiator 50 cm. / p.e. ~ 11
- Gas Electron Multiplier (GEM) for amplification
- CsI is evaporated on top GEM
  - Photocathode (> ~6eV)

15/June/2019
K. Ozawa, SQM 2019, Bari, Italy
LG (Lead Glass Calorimeter)

- Reuse from TOPAZ
  - ~300 at the 1\textsuperscript{st} stage.
  - ~1000 in total
  - We have all we need.

- Expected Rejection Power
  - ~25 offline (energy dep. th.)
  - ~10 online (fixed th.)

We’ve got all we need.
Beam Energy Consideration

• Currently, main ring of J-PARC has a beam energy of 30GeV for a proton acceleration.
  • It is the same as SIS100/FAIR.
    • For HI, 11AGeV, $\sqrt{s_{NN}} = 4.9$GeV
  • Original designed energy of the ring is 50GeV for proton
    • For HI, 19AGeV, $\sqrt{s_{NN}} = 6.2$GeV

• Original designed energy should be recovered
  • Highest density expected at $\sqrt{s_{NN}} = 8$GeV
    • Randrup, PRC74(2006)047901
  • Significant increasing of charm production cross section
  • Seamless connection to SPS/RHIC BES

• New power supply is required
J-PARC HI Project

Acceleration Scheme for Uranium case (Proposed by H. Harada, J-PARC)

New LINAC and Booster for HI must be constructed.
HI acceleration scheme in nutshell

- **World’s highest intensity** \( \sim 10^{11} \text{ Hz} \), Interaction rate \( \sim 10^8 \text{ Hz} \)
- \( E_{\text{lab}} = 1-19 \text{AGeV}, \sqrt{s_{\text{NN}}} = 1.9-6.2 \text{GeV} \) (U)
- Ion species: p, Si,..., Au, U

K. Ozawa, SQM 2019, Bari, Italy
Available beam and rate

Assumed beam rate: $10^{11}$ Hz

0.1% $\lambda_1$ target $\rightarrow$ Event rate: 100MHz

In one month experiment:

- $\rho,\omega,\phi \rightarrow ee$: $10^{10} - 10^{12}$
- Hypernuclei: $10^4 - 10^{12}$
- Strangelets: $1 - 10^2$

A. Andronic, PLB697 (2011) 203


Statistics

1 year at AGS = 5 min at J-PARC-HI
What’s expected at J-PARC energy?

- Baryon is highly stopping at mid-y, at AGS (=J-PARC) energy
  - \( \rightarrow \) **High density matter.** Nucleons pass through each other at SPS and above

- \((K^+, \Lambda, \Xi,)/\pi\) ratio have maximum at \( \sqrt{s_{NN}} \sim 5 \text{GeV} \)
  - \( \rightarrow \) **Strangeness fraction is largest at J-PARC energy.** (\( \pi \) is a proxy of multiplicity)

\[ \text{Au+Au: } \sim 6 \rho_0, \text{ U+U: } \sim 8.6 \rho_0 \]
No dilepton measurement at $\sqrt{s_{NN}}$~5GeV

- Very low mass region ($<100\text{MeV}$)
  - Soft mode associated with phase transition

- Low mass region: $\rho/\omega/\phi$ ($\sim 10^{-3}$)
  - Chiral symmetry restoration study by spectra shape analysis with high statistics
    $$\int dm_{ee} N(m_{ee}) m_{ee}^n (n = 1, 2, ...)$$
  - Comparison to models with q/g condensation (Hayano and Hatsuda, RMP82, 2949)

- Intermediate mass
  - Thermal radiation. c-bar free at J-PARC energy

- High mass region: $J/\psi$?
  - Fully exploiting high luminosity at J-PARC

K. Ozawa, SQM 2019, Bari, Italy
Observables: Event-by-event fluctuation

- Event-by-event fluctuations of conserved charge:
  - Observable to shoot the critical point

- 4\textsuperscript{th}, 6\textsuperscript{th}, 8\textsuperscript{th} baryon number fluctuations
  - Sensitive to chiral transition (even for crossover)
  - 2-order more statistics required with 1-order higher fluct.

B. Friman et al., EPJ C 71 (2011) 1694

X. Luo, Quark Matter 2015

K. Ozawa, SQM 2019, Bari, Italy
Observables: Flow (constraining EOS)

- Sign of $v_1$ slope changes around phase transition
- Measurement of $dv_1/dy$ is a key to understand EOS
- Higher order flow ($3^{rd}$, $4^{th}$, $5^{th}$) is of great interest
  - 1-order higher flow $\rightarrow$ 1 order higher statistics

$dv_1/dy < 0$ : softening of EOS (due to phase transition?)

Assuming phase transition (crossover), JAM becomes closer to data.

A. Ohnishi, Reimei HI, Aug 2016

Y. Nara, KEK Theory group Workshop, Feb 2017

K. Ozawa, SQM 2019, Bari, Italy
More observables...

- **Λ–Λ correlation**
  - Baryon-baryon interaction measurement in high density matter?

- **Ω–Ω bound states?**
  - A recent Lattice result suggests a weak bound-states (B.E.=1.6MeV) of two Ω’s

- **More exotics?**
  - Λ(1405), Dibaryon (H-dibaryon,...)
  - Kaonic nucleus (K-pp,...), Strangelet..
  - 6, 8, 10 quark states?

- ⋯

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K. Ozawa, SQM 2019, Bari, Italy
Strategy for high-rate measurements

- **10MHz DAQ system**
  - Continuous readout + online data reduction
  - Online triggers (Centrality, dimuon, ...)

- **High rate detectors**
  - Silicon pixel trackers

- **Large acceptance (~4π)**
  - E-b-e fluctuations, etc.

New design of Dipole magnet spectrometer

As beam intensity increases;
1. Dipole hadron spectrometer (10^6 Hz)
2. Dipole dimuon spectrometer (10^7 Hz)
3. Hypernuclear spectrometer (10^8 Hz)
Basic spectrometer Performance

- Detector simulation using GEANT
- $U+U \sqrt{s_{NN}}=4.5$ GeV, MinBias JAM events

$y$-$p_T$ Acceptance

Protons, $\pi^+$, $K^+$

PID with TOF

PID with TPC $dE/dx$

K. Ozawa, SQM 2019, Bari, Italy

15/June/2019
**Status and plan**

- **Accelerator side**
  - JAEA and J-PARC are positive for building an ion source, a linac and a booster (~$140M)
  - We are documenting a project proposal for the Masterplan of Science Council of Japan (5 year-plan starting 2019)

- **Facility side**
  - Identified location for detectors on the high-momentum beamline

- **R&D and Phase-0 experiment**
  - Continuous readout and online tracking
    - At J-PARC E16 exp.

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**Hadron Experimental Facility**

- **Extended area** (will start in few years)
- **J-PARC-HI Spectrometer location** (planned)

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9/27/2018