The $S\pi$RIT and pion detectors in RIKEN for the experimental study of symmetry energy with heavy ion collisions

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Heavy Ion Collision to study density dependent symmetry energy

- Large uncertainty on nuclear symmetry energy at $\rho \gg \rho_0$ compared with that for $\rho \leq \rho_0$ region.
- Heavy ion collision is currently unique way to produce high dense matter in the laboratory.
- It is challenging to extract the information related to EoS because of complicated nuclear collision dynamics.
One of the high density probes for $E_{sym}$: pion production

- Larger values for $\rho_n/\rho_p$ at high density: softer Esym causes stronger emission of negative pions.
- In delta resonance model, $Y(\pi^-)/Y(\pi^+) \approx (\rho_n/\rho_p)^2$
- In equilibrium, $\mu(\pi^+)-\mu(\pi^-)=2(\mu_p-\mu_n)$
Pion Calculation and Symmetry energy

- Pion Calculations by some models
  - B. A. Li, PRL 88 (2002) 192701 : IBUU
  - Z. Xiao, B. A. Li, L. W. Chen, G.-C. Yong, and M. Zhang, PRL102 (2009) 062502 : IBUU04
  - Z. Q. Feng and G. M. Jin, PLB 683 (2010) 140 : ImQMD
  - J. Hong and P. Danielewicz , PRC90 (2014) 024605 : pBUU
  - N. Ikeno, A. Ono et al., PRC93 (2016) 044612 : AMD+JAM
  - Wen-Mei Guo, Gao-Chan Yong and Wei Zuo, PRC90 (2014) 044605 ... etc.

- Pion ratio in central Au+Au collisions: Theory vs. Exp. Data
  - Model predictions do not agree.
  - Relation $\pi^-/\pi^+ \cong N^2/Z^2$ does not hold.
  - Code Comparison Project is on going.
  - J. Xu et al., PRC93 (2016) 044609.
  - Need to understand the dynamics as well as pion production.
Series of HIC experiments under GeV energy beam in Japan

• Most of previous experimental studies use mass symmetric collisions so far.

• It is useful also to study with mass-asymmetric collision to distinguish different moving source like NN, participant-participant and nucleus-nucleus.

• HIC experiment with RI-beam
  • SPiRIT project at RIKEN

• Pion experiments using stable beam
  • Pilot experiment of SPiRIT at HIMAC
  • RI-beam → require large acceptance
  • Stable beam → small acceptance detector still works.
HIC experiment at HIMAC

- HIMAC: Heavy Ion Medical Accelerator in Chiba
- Synchrotron type accelerator for medical usage
- C, Si, Xe projectile can be utilized
- Up to sub-GeV/A beam energy

Collaborators
- M. Sako1;2
- T. Murakami1;2
- Y. Nakai2
- Y. Ichikawa1
- K. Ieki3
- S. Imajo1
- T. Isobe2
- M. Matsushita3
- J. Murata3
- S. Nishimura2
- H. Sakurai2
- R.D. Sameshima1
- E. Takada4

1 Kyoto Univ.
2 RIKEN
3 Rikkyo Univ.
4 NIRS
Pion range counter for detecting pions

- Target: In \(\sim 390 \text{ mg/cm}^2\)
- Typical Intensity: \(\sim 10^7 \text{ ppp}\)
- Range Counter: 14 layers (+2) of Sci.
- measured angle \((\theta_{\text{lab}})\): 30, 45, 60, 75, 90, 120 degree
- solid angle: 10 msr

<table>
<thead>
<tr>
<th>Beam</th>
<th>(^{28}\text{Si})</th>
<th>(^{132}\text{Xe})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy(AMeV)</td>
<td>400, 600, 800</td>
<td>400</td>
</tr>
</tbody>
</table>
Pion Detection Principle

\[
\pi^+ \rightarrow \mu^+ + \nu
\]

- \(\mu^+\): Energy \(\sim 4\) MeV
- Range \(\sim 1\) mm

\(\sim 400\text{MeV/u}\) beam energy → Pion’s are rare

* less than 1/100 of protons
Result of pion production
\( \rightarrow \) It well overlaps with moving source frame.

\[ f_-(E_{\text{mov}}) = N_- \exp\left(-\frac{E_{\text{mov}}}{E_0}\right), \]

\[ f_+(E_{\text{mov}}) = N_+ P(E_{\text{mov}}) \exp\left(-\frac{E_{\text{mov}}}{E_0}\right), \]

\[ E_{\text{mov}} = \gamma_{\text{mov}} \left( E_{\text{lab}} - \beta_{\text{mov}} p_{\text{lab}} \cos \theta_{\text{lab}} \right), \]

\[ P(E_{\text{mov}}) = \frac{\Delta B_c}{E_{\text{mov}} \ln\left(1 + \exp\left(\frac{(E_{\text{mov}} - B_c)/\Delta B_c}{E_{\text{mov}}}ight)\right)}. \]

\[ 1 + a_2 \cos^2 \theta_{\text{mov}} \]

\[ p_{\text{mov}} \cos \theta_{\text{mov}} = \gamma_{\text{mov}} \left( p_{\text{lab}} \cos \theta_{\text{lab}} - \beta_{\text{mov}} E_{\text{lab}} \right) \]
Differential $\pi^-/\pi^+$ ratio

weak angular dependence
clear energy dependence

$\pi^-/\pi^+$ supports $(N/Z)^2$
Heavy RI Collision experiment @RIKEN-RIBF

→ SPiRIT project

• Experimental project to give a constrain on the density dependent symmetry energy main for higher dense region.

• Systematic measurement in same $Z$ but different $N$ system realized with heavy RI beam.
  • Scaling with $\delta$.
  • $\rho \sim 2\rho_0$ nuclear matter at RIBF energy (E/A=270MeV).

<table>
<thead>
<tr>
<th>Primary</th>
<th>Beam</th>
<th>Target</th>
<th>$E_{beam}/A$</th>
<th>$(N-Z/A)_{sys}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{238}\text{U}$</td>
<td>$^{132}\text{Sn}$</td>
<td>$^{124}\text{Sn}$</td>
<td>270</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td>$^{124}\text{Sn}$</td>
<td>$^{112}\text{Sn}$</td>
<td>270</td>
<td>0.15</td>
</tr>
<tr>
<td>$^{124}\text{Xe}$</td>
<td>$^{108}\text{Sn}$</td>
<td>$^{112}\text{Sn}$</td>
<td>270</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td>$^{112}\text{Sn}$</td>
<td>$^{124}\text{Sn}$</td>
<td>270</td>
<td>0.15</td>
</tr>
</tbody>
</table>

• Successfully finished.
  • 2016 Apr. – Jun.
Collaboration for New Exp. at RIBF: SPIRIT

SAMURAI Pion Reconstruction and Ion Tracker

International Collaboration aiming to study density dependent symmetry energy through **Heavy RI Collision** experiments.
SPIRIT Collaboration (2009~)

**SAMURAI Pion Reconstruction and Ion-Tracker**


**Kyoto Univ.**: T. Murakami, N. Nakatsuka, M. Kaneko


**TAMU**: A. Mchintosh, S. Yennello

**TITech**: T. Nakamura, Y. Kondo, Y. Togano

**IFJ-PAN**: J. Lukasik, P. Pawlowski

**Jagiellonian Univ.**: P. Lasko, K. Pelczar

**Korea Univ.**: B. Hong, G. Jhang, J.W. Lee

**IBS**: H.S. Lee, Y.J. Kim

**Tsinghua Univ.**: Z. Xiao, R. Wang, Z. Yan

**Tohoku Univ.**: T. Kobayashi

**Rudjer**: I. Gasparic

**GSI**: K. Boretzky, Y. Leifels

**Darmstadt**: T. Aumann, H. Toernqvist, H. Scheit, A. Horvat, L. Atar, D.M. Rossi
Intense (80 kW max.) H.I. beams (up to U) of 345 AMeV at SRC
Fast RI beams by projectile fragmentation and U-fission at BigRIPS
Operation since 2007
Super Ring Cyclotron
To accelerate Uranium ion.
High-resolution beam line F0-F11: 125.983m

ZeroDegree

SAMURAI
Field integral = 7Tm

BigRIPS
Max. rigidity = 9Tm

Control Z and N of beam

SHARAQ by U. of Tokyo
Max. rigidity = 6.8Tm max.
SAMURAI Spectrometer

Superconducting Analyzer

High-resolution beam line

IRC

F0-F11: 125.983m

ZeroDegree

SHARAQ by U. of Tokyo

SAMURAI

BigRIPS

Max. rigidity = 9Tm

Field integral = 7Tm

SAMURAI Spectrometer

Superconducting Analyzer for Multi particles from Radio Isotope Beams

B < 3T

R: 1m

Gap: 80cm

Install

Time Projection Chamber

High-resolution beam line

SHARAQ by U. of Tokyo

Max. rigidity = 6.8Tm max.
New Device: SPIRIT-Time Projection Chamber

- Based on Bevalac EOS TPC.
- Wire amplification with P10 gas (1 atm).
- Target at the entrance of chamber.
- ~12000 readout pads.
- Multiplicity: 10~100.

- Beam passes through chamber as well.

![Diagram of SPIRIT-Time Projection Chamber](image-url)
Readout Electronics for TPC: GET

• GET: novel readout system for TPC
  • Integrated system from Frontend to DAQ.
  • Developed by France-USA Collaboration.

• Configurable even after the installation
  • gain can be selected pad by pad: 120fC~10pC
  • Shaping T, Sampling rate

• Ch. by ch. hit registering \(\rightarrow\) Selective digitization
2015 Aug.: Installation of electronics finished

Pedestal RMS for all of pads

AsAd standalone $\rightarrow \sim 2.5$
SPIRIT experimental setup: beam line + TPC + trigger + NeuLAND

- Sn beam
- STQ
- Chamber in SAMURAI magnet B=0.5T
- Beam Tracker
- MWPC type
  - Time Proj.
  - Chamber 12k channel
Functionality of each devices

• **Main devices for produced particle measurement:**
  • TPC
    • Measure charged particles produced in collision
    • R. Shane et al., NIM A 784 (2015) 513
    • G. Jhang et al., Jour. of Korean Phys. Soc. 69-2 (2016) 144
    • S. Tangwancharoen et al., NIM A 853 (2017) 44
  • NeuLAND
    • Measure neutrons produced in collision

• **Event characterization:**
  • Beam line detector (BigRIPS)
    • Identify projectile colliding with Sn target.
  • Trigger array
    • Trigger “central” collision events.
    • NIM A 856 (2017) 92
First Physics Run at 2016 spring

  - Beam rate: 10kHz, trig. rate: 70Hz
  - ~30M Events: 60Hz, 7MB/eve $\rightarrow$ 420MB/sec
  - 250TB/2week (no selective digitization, no zero-suppression)

1 pixel: 1 pad
Dead channels along beam trajectory

What is these pads? Black means dead.

- Seen along beam trajectory $\rightarrow$ due to $\delta$-ray?
  $\rightarrow$ but $\delta$-ray is supposed to be suppressed with B-field.
- Could not be seen in the case of cosmic
- Varies event by event
How signal from heavy ion would be seen with high gain for the measurement of protons

Top view

Beam signal is not seen.

Spread over neighboring pads through C between the pads.

 δ-rays passing GG wires
GG can not block these δ-rays

Side view

Drift direction
Preamp becomes dead for a certain time due to huge signal

- Output of CSA is kept to be saturated in the case of huge signal
- As long as output is saturated, no signal comes out from following shaper → behaves as dead
- Dead for 2 msec in the case of 10pC charge input
- 10pC corresponds to the charge from Z~35 nuclei

**Table**

<table>
<thead>
<tr>
<th>Z</th>
<th>Q (fC)</th>
<th>deadtime (μ -sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.886751</td>
<td>50</td>
<td>0</td>
</tr>
<tr>
<td>4.472136</td>
<td>120</td>
<td>0</td>
</tr>
<tr>
<td>6.324555</td>
<td>240</td>
<td>65</td>
</tr>
<tr>
<td>6.879922</td>
<td>284</td>
<td>100</td>
</tr>
<tr>
<td>8.944272</td>
<td>480</td>
<td>255</td>
</tr>
<tr>
<td>Sn Beam</td>
<td>28398</td>
<td>22024.52</td>
</tr>
<tr>
<td>87.5595</td>
<td>46000</td>
<td>35800</td>
</tr>
</tbody>
</table>
δ-ray which cannot be blocked with GG

10kHz beam rate: 1 beam per 100 µsec

Part of δ-ray coming from beam passes through GG
→ Make a dead time on the pad

Independent from trigger rate, probability of dead pads increase depending on beam rate

Acceptable beam rate of pads along beam line is limited due to this effect
Increasing dynamic range: pad desaturation

Goal: extend the dynamic range of the TPC
Problem: saturated pads lose charge info

\[ P(x) = \int_{x-w/2}^{x+w/2} \rho(x')dx' \]

Idea: usage of pad response function (PRF)
Integral of the charge distribution over one pad.

How to use:
1) Find the charge center of gravity
2) Calculate the distance of the center of each pad from the c.o.g.
3) Calculate the fraction of charge of the pad over the total charge
4) From the tails of the distribution we can estimate the charge of the saturated pad
Avalanche is directly over pad (i.e. 0mm).
- The fractional charge seen on that pad would be 75% of the total charge.

Center of pad is 8mm from the avalanche
- The fractional charge would be about 10% of the total charge.
Increasing dynamic range: pad desaturation

- Test performed on the E=100-300MeV Z=1-3 cocktail beam
- Preliminary overlap of energy loss calculation (Bichsel curves) with data

Before correction

After correction
2nd way: using signal slope value as deposited charge information

- Scan for steepest bin of a signal.
- Slope of signal shows linearity for higher pulser voltage.
- According to SPICE simulation, linearity can be kept up to 240fC input.
  - i.e. ~2 times wider

120fC D.R.
117 ns Shaping time

- Work in progress for combining two methods.
While we took a long time to establish the sophisticated tracking software..., we finally to move on to the physics analysis!!
Trigger system for high dense matter
#hits(side)>4 && Z<20

- Suppress background events and take “central” collision events
  - The fraction of events that we are interested in is only O(0.1)%
- Sophisticated trigger system to take central collision data: side array + Forward VETO.
The impact parameter triggered by SpiRIT

Clear correlation between number of hits on side array and TPC is seen!

- Trigger efficiency and impact parameter are evaluated with transportation code.
  - Finite resolution of impact parameter (b): Mean of b: 6fm, width of b: 4fm.
- Possible to centrality selection with number of track information.
- Need to evaluate the transportation code itself.

Test by UrQMD $^{132}$Sn$^{124}$Sn, 270 AMeV
- Total events
- KyotoM $\geq 4$ & KATANA Z $\leq 20$

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35
Comparison with several transportation codes

- Number of hit on side array is compared with simulation filtered with trigger acceptance.
- Side array located at mid-rapidity. \(\rightarrow\) Looking particles coming to mid-rapidity.
- AMD w/ cluster shows less multiplicity \(\rightarrow\) Too much cluster in AMD?
Summary

• Experimental projects to study the density dependent symmetry energy is ongoing in Japan.

• Doubly differential cross sections of p+ an p- for the Si+In reactions at 400, 600 and 800 AMeV were measured with Pion range counter.

• First experiment of heavy RI collision, SPiRIT project, was performed at RIKEN-RIBF.

• SPiRIT-TPC + GET
  • We try to understand the detector/electronics response for the simultaneous measurement of light and heavier particles.

• SPiRIT Trigger system for central collision

• Experimental data will come soon. Maybe pion at first. Can we understand what will come?