本新学術領域：実験・観測・理論 連携

“クォークの物質科学” 創始

中性子星全体の内部構造の解明

“核物質EOS”を決定

日本が誇る
世界最高の2大加速器
と天文衛星

大強度陽子加速器
J-PARC

X線天文衛星
ASTRO-H

X線天文観測
⇒中性子星の半径

冷却原子ガス
⇒中性子物質の物性

中性子過剰核物理

不安定原子核工場
RIBF

→核物質EOS

ストレンジネス核物理

⇒ハイペロン粒子の間の力

大強度陽子加速器
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⇒ハイペロン粒子の間の力
A Time Projection Chamber (TPC) is being built in the US to measure $\pi^+ / \pi^-$ & light charged particles in RIKEN

Funded by DOE
NuSym Collaboration: International collaboration to determine the symmetry energy over a range of densities.
Strategies used in Heavy Ion collisions to determine the EoS

- Vary the energies and N/Z compositions of projectile (RI beams in RIKEN) and N/Z of stable targets.
- Measure N/Z compositions of emitted particles ($n$, $p$, $t$, $^3He$, $\pi^+$, $\pi^-$) -- TPC

Observables:
- $n/p$ & $t/^3He$, $\pi^-/\pi^+$, single and double ratios
- $n/p$ & $t/^3He$ & $\pi^-/\pi^+$ flow
- Excitation functions of the above observables.

Supra saturation densities

B.A. Brown, PRL 85(2000)5296
Tsang et al, PRL 102, 122701 (2009)
Strategies used in Heavy Ion collisions to determine the EoS

- Vary the energies and N/Z compositions of projectile (RI beams in RIKEN) and N/Z of stable targets.
- Measure N/Z compositions of emitted particles (n, p, t, $^3$He, $\pi^+$, $\pi^-$) -- TPC
- Simulate collisions with transport models (underway)
  - Find the symmetry energy density dependence that describes the data.
  - Constrain the relevant input transport variables

Supra saturation densities

![Graph showing supra saturation densities](image-url)
Important issues influencing the EoS of high density asymmetric matter

Large uncertainties in the symmetry energy at high density.

At $\rho>\rho_0$ density, mass splitting increases with density and asymmetry.
Importance of 3-body neutron-neutron force in the Equation of State of pure neutron matter

Model calculations with and without 3nn forces:

**BHF**: PRC80,045806 (2009)
Brueckner-Hartree-Fock

**DBHF**: arXiv:1111.0695
Dirac Brueckner-Hartree-Fock

**CEFT**: PRL105,161102(2010)
Chiral Effective Field Theory

**QMC**: PRC85,032801R(2012)
Quantum Monte Carlo

Summary of $^{208}$Pb n-skin thickness constraints

Pressure ($10^2$ bar) vs. Density ($\rho/\rho_0$)

- **BHF**
- **DBHF**
- **QMC**

Tsang et al. PRC (in print)
arXiv:1204.0466

neutron star

$^{208}$Pb

Tsang et al. PRC (in print)
arXiv:1204.0466
SAMURAI-TPC EoS program

• **Need to vary mass of RI projectile and stable target** in order to change the relative role of compression and other transport effects: in-medium NN cross-sections; isospin dependence of NN cross-sections, momentum dependence of mean field, etc.

• **Compare reactions** with very asymmetric, n-rich systems (eg. $^{132}\text{Sn} + ^{124}\text{Sn}$) to reactions with nearly symmetric, n-poor system (eg. $^{108}\text{Sn} + ^{112}\text{Sn}$).

• **Need at least two beam energies** to disentangle symmetry energy effects from nucleon effective masses etc.

• **Proposed programs** (not an exhaustive list):
  
  – Collisions of heavy systems with same Z: $^{A}\text{Sn} + ^{112,124}\text{Sn}$
  
  – Collisions of heavy projectile and light target with same Z: $^{A}\text{Sn} + ^{58,64}\text{Ni}$
  
  – Collisions of light systems with same Z: $^{A}\text{Ni} + ^{58,64}\text{Ni}$
  
  – Collisions of heavy systems with same A: $^{102}\text{Zr}, ^{102}\text{Ru} + ^{96}\text{Zr}, ^{96}\text{Ru}$
    
    • Isotracing → similar to isospin diffusion or stopping at high density

• **All beams and energies are unique to RIKEN**
Heavy Ion Collisions at high density with RIB

First Experiments (to be proposed in Dec PAC)

<table>
<thead>
<tr>
<th>Beam</th>
<th>pro</th>
<th>tgt</th>
<th>N/Z(beam)</th>
<th>N/Z(tgt)</th>
<th>N/Z(CN)</th>
<th>N/Z diff</th>
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<tbody>
<tr>
<td>132Sn</td>
<td>RI</td>
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<td>1.64</td>
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</table>
Heavy Ion Collisions at high density with RIB

First experiments:
Largest asymmetry differences

Need references for one energy. Explore reactions with same A

Heavy projectile on light target; light projectile on light target to constrain transport parameters

Isotracing: stopping

<table>
<thead>
<tr>
<th>Physics experiments:</th>
<th>200 MeV &amp; 300 MeV</th>
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**Commissioning experiment for SAMURAI-TPC**

**Considerations:**
1. High beam energy to optimize pion production.
2. Beam charge ($Z \approx 50$) to replicate the space-charge effects expected for later experiments
   - For example: $^{124}\text{Xe}$ beam
3. Test coupling and response of Nebula for such heavy ion reactions.

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<td>$^{124}\text{Xe}$</td>
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## Summary (proposed reactions in Dec PAC)

### Commission experiments

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### Physics experiments: 200 MeV & 300 MeV

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To measure neutron spectra with Nebula array and proton spectra with hodoscope

**Advantage:**
- Can perform high rate experiment not possible with SAMURAI TPC
- Provide actual in-beam experience with SAMURAI and Nebula array

**Technical Issues:**
- Need a device to provide event selection
  - microball and associated mechanical and electronic problems
  - Cannot determine reaction plane to measure flow.
- Need to simulate placements of beam stops, proton and neutron detector.

Possible Interim experiments currently under discussions (Not ready for Dec PAC)
A Time Projection Chamber (TPC) is being built in the US to measure $\pi^+ / \pi^-$ & light charged particles in RIKEN.
To determine density dependence of symmetry energy between $\rho_0$ and $2\rho_0$

On track for experiments in 2014

- Time-projection chamber (TPC) will sit within SAMURAI dipole magnet
- Setup will include auxiliary detectors for heavy-ions and neutrons, and the trigger array.