Isospin effects in $^{40,48}\text{Ca} + ^{40,48}\text{Ca}$ collisions and future directions


- Motivation and background
- Experimental Results
- Future Directions: (probing higher densities)
- Summary and outlook
Basic ideas driving the experimental program

- Use energy spectra and two-particle correlation functions to probe isotopic effects and transport phenomena in heavy-ion collisions
- Allows investigation of interesting transport properties:
  - Symmetry energy, which accelerates protons and neutrons or positive and negative pions in opposite directions ⇒ probe density dependence of symmetry energy.
  - Isospin dependent cross sections, which damp these flows ⇒ probe isospin dependence of in-medium cross sections.
  - Nucleon effective masses, which influence these accelerations ⇒ probe isospin dependence of nucleon effective masses.
- Today’s talk will focus on
  - proton-proton correlations (relevant to $\rho<\rho_0$)
  - pion production (relevant to $\rho>\rho_0$)
Tool: two proton correlation functions

\[ C(\vec{q}) = \frac{\sum_{E, \phi} Y_{12}(\vec{p}_1, \vec{p}_2)}{\sum_{E, \phi} Y_1(\vec{p}_1)Y_2(\vec{p}_2)} \]

... correlated particle pairs yield
\[ Y_{12}(\vec{p}_1, \vec{p}_2) \]
... single particle yield
\[ Y_A(\vec{p}_A) \]

Correlation function related to the space-time information of the emitting source.

**Koonin-Pratt equation:**
\[ C(\vec{q}) = \int d^3r |\Phi_\vec{q}(\vec{r})|^2 S(\vec{r}) \]
\( \Phi_\vec{q}(\vec{r}) \) is wfn., with \(^1S_0\) FSI

Correlations are large when emitted mechanisms are localised and short-lived.
Influence of symmetry energy on emission times.

**Stiff EoS** ($\gamma=2$) ⇒ greater pressure & faster emission times,

- correlation maximum larger: p’s and n’s emitted at similar times

**Soft EoS** ($\gamma=0.5$) ⇒ smaller pressure & later emission times,

- correlation maximum smaller: p’s emitted after n’s
Secondary decay causes correlation height to be ambiguous

3 sources with same $R(q=20\text{MeV/c})$, but different radii and secondary decay contributions.

- Height is misleading; it reflects both source size and dilution due to secondary decays
  (*secondary decay contributions significantly reduce peak height*)

- Width of correlation function reflects better the size of the emitting source (illustrated later)
  => measurements of pairs with $q<15$ desirable
  => need for detectors with high angular resolution ($\sim0.1-0.2^\circ$)

- Fit entire shape of the correlation function.

Source shapes deduce from Chen calc.
Imaged sources for $^{36}$Ar+$^{45}$Sc collisions $E/A=80$ MeV

G. Verde et al., PRC 67, 034606 (2003)

- Strong dependence of correlation function on 2 proton total momentum.
  - higher momenta $\Leftrightarrow$ earlier times
- Correlation function fit by adjusting shape of two proton source (imaging).
- Description of measured source by BUU requires reduction of in-medium nucleon-nucleon cross sections.
  - isospin dependence?

$$\sigma(\rho, \eta) = \eta \rho^{-2/3} \tanh\left(\frac{\sigma_{\text{free}}}{\eta \rho^{-2/3}}\right)$$
New: correlation functions for $^{40,48}\text{Ca}+^{40,48}\text{Ca}$ collisions

- More precise HiRA data reveal strong angular and momentum dependence
  - more exaggerated angular trends at higher momenta
- backward angles: participant source expands with time
- forward angles: higher momenta dominated by proj. spectator source.
Source sizes decrease with angle; extended freeze-out for PLF.

Trend consistent with that for the maximum of the correlation function.

Corresponding BUU sources are smaller

- effect of cluster production?

Fraction f of the emission that is fast (and contributes to singlet s peak) is somewhat lower at forward angles dominated by projectile remnants.

- Effect of multi-fragmentation freezeout?
Isospin effects: puzzling results?

- Large difference in correlation function ⇒ difference between source size or fast emission fractions.

- $^{40}\text{Ca} + ^{40}\text{Ca}$
- $^{48}\text{Ca} + ^{48}\text{Ca}$

$E_t > 150\text{ MeV and } -0.5 < y_{\text{ cms}} < 0.5$

$1 + R(q)$

$0.6\, \, 0.8\, \, 1\, \, 1.2\, \, 1.4$

$q (\text{MeV/c})$

$0\, \, 10\, \, 20\, \, 30\, \, 40\, \, 50\, \, 60\, \, 70\, \, 80$

$S(r) (\text{fm}^3) \times 10^3$

$0\, \, 0.1\, \, 0.2\, \, 0.3\, \, 0.4\, \, 0.5\, \, 0.6\, \, 0.7\, \, 0.8$

$r (\text{fm})$

$0\, \, 2\, \, 4\, \, 6\, \, 8\, \, 10\, \, 12\, \, 14$

$^{40}\text{Ca} + ^{40}\text{Ca}$

$^{48}\text{Ca} + ^{48}\text{Ca}$

- $^{48}\text{Ca}$ has same $r_{1/2}$ but larger diffuseness
- Neutron rich $^{48}\text{Ca}$ must have a smaller fast emission fraction ⇔ cluster prod.?
Correlation Summary

- Calculations predict significant dependence of p-p correlation functions on density dependencies of symmetry energy and isospin dependence in-medium cross sections.
- Observed a strong isospin dependence of the p-p correlation function:
  - Puzzling insensitivity of source radius $\iff$ both reactions display same radius at half maximum. $^{48}$Ca has smaller fast em. fraction.
- Could we be seeing effects of cluster production?

Future directions $\Rightarrow$ higher densities

- Measurements at NSCL/FRIB
  - n-p spectra and flows (see talk by Famiano)
  - pion production
- Proposed RIBF program at RIKEN
  - pion production
  - n-p spectra and flows
High density probes: pion production, n/p spectral ratios

Example: Pion Production

- Larger values for $\rho_n/\rho_p$ at high density for the soft asymmetry term ($x=0$) causes stronger emission of negative pions for the soft asymmetry term ($x=0$) than for the stiff one ($x=-1$).
- $\pi^-/\pi^+$ means $Y(\pi^-)/Y(\pi^+)$
  
  - In delta resonance model, $Y(\pi^-)/Y(\pi^+)= (\rho_n/\rho_p)^2$
  
  - In equilibrium, $\mu(\pi^+)-\mu(\pi^+)=2(\mu_p-\mu_n)$
- The density dependence of the asymmetry term changes ratio by about 10% for neutron rich system.

This can be explored with stable or rare isotope beams at the MSU, RIKEN, or GSI.

- Highest sensitivity to $S(\rho)$ occurs primarily near threshold in $A+A$
THink more about this. Add figures from last talk.

lynch; 18/08/2009
Future Direction: Pion Production at NSCL and FRIB

- E/A=120-180 MeV; \( \rho/\rho_0 \sim 1.5-1.8 \) MeV.
- Pion ratio shows a strong dependence on the symmetry energy at low incident energies and low pion energies.
- Pion ratio lower at high energy because pion collisions and pion production at later stages dilute the sensitivity to the symmetry energy at high density.

\[
\frac{\pi^-}{\pi^+} \quad \text{for } E/A = 120 \text{ MeV}
\]

\[
\frac{\pi^-}{\pi^+} \quad \text{for } E/A = 400 \text{ MeV}
\]

BUU from: Danielewicz, NPA673, 375 (2000).
Active Target Time Projection Chamber (NSF Funded)

$^{112}\text{Sn} + ^{112}\text{Sn}, 150 \text{ A MeV, } b=2\text{fm}$

- **Combines active target and time projection chamber**
  - **Fixed Target Mode** with target wheel inside chamber:
    - Scientific Program » **Constrain Symmetry Energy at** $\rho>\rho_0$
  - **Active Target Mode**:
    - Provides a thick target ($\text{H}_2, \text{D}_2, ^3\text{He}, \text{Ne}, \text{etc.}$) while retaining high resolution and efficiency
    - Scientific Program » **Transfer & Resonance measurements, Astrophysically relevant cross sections, Fusion, Fission Barriers, Giant Resonances**
AT-TPC project

- LBL: I-Yang Lee, Larry Phair
- LLNL: Mike Heffner
- Notre Dame: Umesh Garg, Jim Kolata
- NSCL MSU: Abigail Bickley*, Bill Lynch, Wolfgang Mittig, Fernando Montes, Gary Westfall
- St. Mary's (Canada): Rituparna Kanungo
- WMU: Michael Famiano

Diameter: 0.6 m
Drift: 1.2 m
Field: Solenoid
Max Field: 2 T
Pad size: 0.5x0.5 cm²
Number of pads: 10000

Twist Solenoid delivered in 2008
Uses AGET electronics: development will be complete in 2012:

Twist Solenoid at MSU
Puzzles at higher energies from Fopi data

- Calculations suggest that the $\pi^- / \pi^+$ ratios for Au+Au Fopi data are consistent with a very soft symmetry energy at $\rho > 2\rho_0$ (vanishes at $3\rho_0$).
- To separate effects of Coulomb and symmetry energies, measurements with rare isotope beams would be useful. Such experiments can be preformed at the RIBF in RIKEN.

- A particularly interesting observables is the pion double ratio. The double ratio removes sensitivity to differences between $\pi^-$ and $\pi^+$ acceptances.

$$R\left(\frac{\pi^-}{\pi^+}\right) = \frac{Y\left(\pi^-=132\text{+124}\right) / Y\left(\pi^+=132\text{+124}\right)}{Y\left(\pi^-=112\text{+112}\right) / Y\left(\pi^+=112\text{+112}\right)}$$

Zhigang Xiao et al., LANL arXiv:0808.0186

Yong et al., PRC 73, 034603 (2006)
A TPC has been proposed for the SAMURAI dipole at RIKEN

GEANT simulation

\(^{132}\text{Sn}+^{124}\text{Sn}\) collisions at \(E/A=300\) MeV

- Good efficiency for pion track reconstruction is essential.
- Initial design is based upon EOS TPC, whose properties are well documented.

### SAMURAI TPC parameters

<table>
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<tr>
<th>Parameter</th>
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<td>11664 (108 x 108)</td>
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Summary and outlook

• Calculations predict significant dependence of p-p correlation functions on density dependencies of symmetry energy and isospin dependence in-medium cross sections.

• Observed a strong isospin dependence of the p-p correlation function:
  – Puzzling insensitivity of source radius ⇔ both reactions display same radius at half maximum. \(^{48}\text{Ca}\) has smaller fast em. fraction.
  – Could we be seeing effects of cluster production?

• \(\pi^+\) vs. \(\pi^-\) production, neutron/proton spectra and flows may provide constraints at \(\rho \approx 2\rho_0\) and above.

• The availability of fast stable and rare isotope beams at a variety of energies at MSU, RIKEN and GSI allows the exploration of the symmetry energy at a range of densities.

• Devices are being planned and developed to realize these possibilities.
Probes of the symmetry energy

\[ E/A(\rho, \delta) = E/A(\rho, 0) + \delta^2 S(\rho) ; \quad \delta = (\rho_n - \rho_p)/(\rho_n + \rho_p) = (N-Z)/A \]

- **Desirable features for probes**
  - Vary isospin of detected particle
  - Vary isospin asymmetry \( \delta = (N-Z)/A \) of reaction.
- **Low densities** \( (\rho < \rho_0) \):
  - Neutron/proton spectra and flows
  - p-p and n-p correlation functions
  - Isospin diffusion
  - Fragment isotopic distributions: Neutron, proton radii, E0 and E1 collective modes.
- **High densities** \( (\rho \approx 1.5-2\rho_0) \):
  - Neutron/proton spectra and flows
  - \( \pi^+ \) vs. \( \pi^- \) production, k, hyperon production.

*Li et al., PRL 78 (1997) 1644*
Choice of beams and facilities for pion ratios

- Choice of facility is governed by availability of beams and equipment.
- Sensitivity to symmetry energy is larger for neutron-rich beams.
  - Largest sensitivity requires rare isotope beams such as $^{132}\text{Sn}$ and $^{108}\text{Sn}$.
- Sensitivity increases with decreasing incident energy.
- Most sensitive measurements of $\pi^-/\pi^+$ ratios at FAIR would be with beams available at RIBF.
- Measurements require floor-space and a magnet suitable for a TPC; this is not currently within the FAIR project.
Available Observables:

- Most models predict pion spectral ratios to be sensitive to symmetry.
- Double ratio removes sensitivity to differences between $\pi^-$ and $\pi^+$ acceptances.

$$R\left(\pi^-/\pi^+\right) = \frac{\begin{bmatrix} Y\left(\pi^-\right)_{132+124}/Y\left(\pi^+\right)_{132+124} \\ Y\left(\pi^-\right)_{112+112}/Y\left(\pi^+\right)_{112+112} \end{bmatrix}}{\begin{bmatrix} Y\left(\pi^-\right)_{132+124}/Y\left(\pi^+\right)_{132+124} \\ Y\left(\pi^-\right)_{112+112}/Y\left(\pi^+\right)_{112+112} \end{bmatrix}}$$

- Most models predict the differences between neutron and proton flows and $t$ and $^3$He flows to be sensitive to the symmetry energy and the $n$ and $p$ effective mass difference.
- In this prediction, the flows out of plane show a significant sensitivity.
Propose to build a TPC for use within the gap of the SAMURAI dipole. The SAMURAI TPC would be used to constrain the density dependence of the symmetry energy through measurements of:

- Pion production
- Flow, including neutron flow measurements with the nebula array.

The TPC also can serve as an active target both in the magnet or as a standalone device.

- Giant resonances.
- Asymmetry dependence of fission barriers, extrapolation to r-process.
### Research program

<table>
<thead>
<tr>
<th>Probe</th>
<th>Devices</th>
<th>$E_{\text{lab}}/A$ (MeV)</th>
<th>Part./s</th>
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<th>Possible Reactions</th>
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<tr>
<td>$\pi^+\pi^-, p, n, t, ^3\text{He}$</td>
<td>TPC Nebula</td>
<td>200-300, 350</td>
<td>$10^4$-$10^5$</td>
<td>$E_{\text{sym}}$, $m_n^<em>$, $m_p^</em>$</td>
<td>$^{132}\text{Sn}+^{124}\text{Sn}$, $^{105}\text{Sn}+^{112}\text{Sn}$, $^{52}\text{Ca}+^{48}\text{Ca}$, $^{36}\text{Ca}+^{40}\text{Ca}$, $^{124}\text{Sn}+^{124}\text{Sn}$, $^{112}\text{Sn}+^{112}\text{Sn}$</td>
<td>2013 - 2014</td>
</tr>
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<td>$\pi^+\pi^-, p, n, t, ^3\text{He}$</td>
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<td>200-300</td>
<td>$10^4$-$10^5$</td>
<td>$\sigma_{\text{nn}}, \sigma_{\text{pp}}, \sigma_{np}$</td>
<td>$^{100}\text{Zr}+^{40}\text{Ca}$, $^{100}\text{Ag}+^{40}\text{Ca}$, $^{107}\text{Sn}+^{40}\text{Ca}$, $^{127}\text{Sn}+^{40}\text{Ca}$</td>
<td>2015 - 2017</td>
</tr>
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- Typical rates at $10^4$/s are 3-4 pions/s of each charge and about 5 n’s/s
  - Goal is to run up to $10^5$/s
- Ideal would be to run 3-4 weeks/y. This corresponds to two experiments that each measure two pairs of systems: e.g. $^{132}\text{Sn}+^{124}\text{Sn}$, $^{105}\text{Sn}+^{112}\text{Sn}$ at one incident energy.
- Initial experiments would occur in 4 years. Sequence of measurements will depend on both the physics and technical situations at the start of commissioning.
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**TPC properties**

- Good efficiency for pion track reconstruction is essential.
- Initial design is based upon EOS TPC, whose properties are well documented.

GEANT simulation $^{132}$Sn+$^{124}$Sn collisions at E/A=300 MeV
Rational for electronics upgrade

- Initial experiments 2013-2014 would be performed with STAR TPC electronics.
  - Currently used at MSU for S800 spectrograph and tracking detectors.
- STAR ADC is 10 Bit; data rate is <100 events/s.
  - Limits dynamic range of resolved particles
- To increase dynamics range and resolution, new GET electronics, would be installed in 2014.
  - AGET ADC has 12 bit resolution and 1000 event/s readout rate.
  - Self triggering, important for active target applications.
  - Currently testing GET prototype.

Simulated resolution of SAMURAI TPC, neglecting ADC dynamical range problem.
Example: Constraints on symmetric matter EOS at $\rho > 2 \rho_0$.

$$E/A(\rho, \delta) = E/A(\rho,0) + \delta^2 S(\rho)$$

$$\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p) = (N-Z)/A \approx 1$$

Boundary determined by comparing transverse and elliptical flow data to transport calculations.

Flow confirms the softening of the EOS at high density.
Constraints from kaon production are consistent with the flow constraints and bridge gap to GMR constraints.
Note: analysis requires additional constraints on $m^*$ and $\sigma_{NN}$.

- The symmetry energy dominates the uncertainty in the n-matter EOS.
- Both laboratory and astronomical constraints on the density dependence of the symmetry energy are urgently needed.
Why Isospin Diffusion and n/p ratios?

- Supra-saturation and sub-saturation densities are only achieved *momentarily*.
- Theoretical description must follow the reaction dynamics self-consistently from contact to detection.
- Isospin diffusion and n/p ratios:
  - Depends to first order on the single particle distribution function, which can be more accurately calculated in BUU or QMD transport theory.
  - May be less sensitive to uncertainties in (1) the production mechanism for complex fragments and (2) secondary decay.
n/p Experiment $^{124}\text{Sn}+^{124}\text{Sn}; ^{112}\text{Sn}+^{112}\text{Sn}; \text{E}/\text{A}=50\ \text{MeV}$
TPC Budget, Timeline, and Responsibilities

- **Major budget items:**
  - TPC design and construction $740k (requested from DOE)
  - GET electronics upgrade ~ $300k
- **Major responsibilities as defined in DOE proposal:**
  - Japanese collaborators: SAMURAI dipole, the TPC laser calibration system, the TPC gas handling system, TPC mounting hardware, target, beam tracking, TPC electronics and data acquisition and the ancillary trigger scintillation array.
  - U.S. Collaborators: construction and initial testing of the SAMURAI TPC chamber.
- **Current activities:**
Summary and outlook

- Calculations predict that $t-^3\text{He}$ spectra should be able to place constraints on the density dependence of the symmetry energy and on the nucleon effective masses.
  - Investigation of this sensitivity is underway, but not trivial.
- Calculations predict significant dependence of p-p correlation functions on density dependencies of symmetry energy and isospin dependence in-medium cross sections.
- Measurements of p-p correlation functions were performed for $^{40}\text{Ca}+^{40}\text{Ca}$ and $^{48}\text{Ca}+^{48}\text{Ca}$ collisions at E/A=80 MeV.
- Observed a strong isospin dependence of the p-p correlation function:
  - Puzzling insensitivity of source radius $\Leftrightarrow$ both reactions display same radius at half maximum. $^{48}\text{Ca}$ has smaller fast em. fraction.
- Further refinements in gates will allow significant comparisons to transport theory and constraints to be placed transport quantities such as the isospin dependence of the in-medium cross sections.