Exploring the Equation of state of neutron-rich matter with Heavy Ion Reactions

Outline:
NSCL/MSU
Reaction programs @ NSCL
  Rare Isotope Productions
  Transfer Reactions
Equation of state of neutron-rich matter – current experimental status
  Refining reaction theories
    Fragment systematics
    Transport Equation simulations
Summaries and Outlooks

International Workshop on Nuclear Dynamics on heavy ion reactions and neutron stars, July 10-14, 2007, Beijing, China

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The National Superconducting Cyclotron Laboratory
Michigan State University
A national user facility for rare isotope research and education in nuclear science, astro-nuclear physics, accelerator physics, and societal applications

~ 300 employees, incl. 50 undergraduate and 50 graduate students, 25 faculty

User group of over 600 CCF users
Nuclear Physics @ the K500⊗K1200 Facility (CCF)

Accelerator Physics
- RIA related research

Nuclear Structure:
- Accessibility of driplines
- Physics of weakly bound nuclei
- Isospin dependence of nuclear properties
- Evolution of shell structures
- etc

Nuclear Reactions:
- Rare Isotope Productions
- Transfer Reactions
- Equation of state of neutron-rich matter
- Refining reaction theories

Nuclear Astrophysics
- Synthesis of elements
- Evolution of supernovae
- Neutron star physics
National Superconducting Cyclotron Laboratory

World’s first superconducting cyclotron (1982)

World’s most powerful superconducting cyclotron (1989)

Coupled Cyclotron Facility (2000)
**Rare Isotope Production Mechanism**

- **Primary beams:** $^{40,48}$Ca, $^{58,64}$Ni at 140 MeV per nucleon; unstable $^{68}$Ni, $^{69}$Cu and $^{70}$Zn beams at 90 MeV per nucleon and $^{86}$Kr at 64 MeV per nucleon

- ~2000 cross-sections

- EPAX over-predicts isotopes at the p/n extremes

- Study of production model suggests that sequential decays wash out the details of the prefragment stage of the reactions
Relation between cross-sections and average binding energy (BE/A)

Can be described with the use of statistical or phase space model

Mass measurements of rare isotopes
Sensitivity ~TOF
Extrapolation of cross-sections to n-rich and dripline isotopes
Symmetry Energy in Nuclei

\[ B = a_v A - a_s A^{2/3} + \delta - a_c \frac{Z(Z-1)}{A^{1/3}} - a_{\text{sym}} \frac{(A - 2Z)^2}{A} \]

\[ (a_v^{\text{sym}} A - a_s^{\text{sym}} A^{2/3}) \frac{(A - 2Z)^2}{A^2} \]

Inclusion of surface terms in symmetry

Proton Number Z

Neutron Number N

Crab Pulsar

Hubble ST
Size & Structure of Neutron Star depends on EOS

EOS influence
✓ R,M relationship
✓ maximum mass.
✓ cooling rate.
✓ core structure
Birth of a Neutron Star

July 4, 1054, China

July 5, 1054, N. America

Crab Pulsar
Heavy ion collisions:

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

Results from Au+Au flow (E/A~1-8 GeV) measurements include constraints in momentum dependence of the mean field and NN cross-sections.
Isospin Dependence of the Nuclear Equation of State

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

- The density dependence of symmetry energy is largely unconstrained.
- Pressure, i.e. EOS is rather uncertain even at \( \rho_0 \).
Nuclei and the density dependence of the symmetry energy
Constraints and possible measurements

- Surface symmetry energy in mass formulae:
  - Difficult to disentangle from Coulomb and bulk symmetry energy.

- Energies of GDR and pigmy dipole resonances:
  - Extraction is model dependent.

- Difference between neutron and proton rms radii in nuclei:
  - Sensitive to \( \frac{dS}{d\rho}\big|_{\rho=\rho_0} \)
  - Accuracy of present results are disputed.
  - PREX experiment at JLAB.
    - (limited precision: \( \delta_{\text{rms},n} \approx 0.06 \text{ fm} \))

- Asymmetry dependence of isoscaler GMR:
  - Sensitive to \( \frac{d^2S}{d\rho^2}\big|_{\rho=\rho_0} \)

- All above observables are sensitive to \( \rho \sim \rho_0 \)

- Isoscaling in Heavy Ion collisions: \( Y_1(N,Z)/Y_2(N,Z) \propto \exp(\alpha N + \beta Z) \)
  - \( \alpha \propto 4(C_{\text{sym}}/T)\Delta(Z/A)^2 \)
  - Sensitive to sequential decays
Probes of the symmetry energy with HIC

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

- Low densities ($\rho < \rho_0$):
  - Neutron/proton spectra and flows
  - Isospin diffusion
  - Fragment isotopic distributions
  - Neutron, proton radii, E1 collective modes.

- High densities ($\rho \approx 2\rho_0$):
  - Neutron/proton spectra and flows
  - $\pi^+$ vs. $\pi^-$ production, $k$, hyperon production.

Sign in $V_{asy}$ is opposite for n vs. p

\[ F_1 = 2u^2/(1+u) \]
\[ F_2 = u \]
\[ F_3 = \sqrt{u} \]
n/p Experiment $^{124}\text{Sn}+^{124}\text{Sn};\:^{112}\text{Sn}+^{112}\text{Sn};\ E/A=50\ \text{MeV}$
N-detection – neutron wall
p-detection: Scattering Chamber

WU MicroBall (b determination)

~6in

3 particle telescopes (p, d, t, $^3\text{He}$, …)
n/p Double Ratios (central collisions)

Double Ratio

\[
\frac{^{124}\text{Sn}+^{124}\text{Sn}; Y(n)/Y(p)}}{^{112}\text{Sn}+^{112}\text{Sn}; Y(n)/Y(p)}
\]

• Role of isoscaler \( \alpha \) emission:
  – Effect of cluster production clear and theoretically reproduced by QMD.

ImQMD: Y.X. Zhang
IBUU04: B.A. Li
Isospin Diffusion--Isospin Transport Ratio

Isospin diffusion occurs only in asymmetric systems A+B

No isospin diffusion between symmetric systems

Non-isospin diffusion effects

→ same for A in A+B & A+A ; same for B in B+A & B+B

\[ R_i = 2 \frac{x_{AB} - (x_{AA} + x_{BB})/2}{x_{AA} - x_{BB}} \]

Rami et al., PRL, 84, 1120 (2000)

\( x_{AB}, y_{AB} \) experimental or theoretical observable for AB

\( y_{AB} = a \cdot x_{AB} + b \)

\( R_i(x_{AB}) = R_i(y_{AB}) \)

Non-isospin transport effects are “cancelled”??
Isotope Distribution Experiment

**MSU, IUCF, WU collaboration**

Sn+Sn collisions involving $^{124}\text{Sn}$, $^{112}\text{Sn}$ at E/A=50 MeV

**Miniball + Miniwall**

4 π multiplicity array

Z identification, A<4

**LASSA**

Si strip +CsI array

Good E, position, isotope resolutions

*Xu et al, PRL, 85, 716 (2000)*
Emission patterns of $^7\text{Li}$ & $^7\text{Be}$ from $^{124}\text{Sn} + ^{112}\text{Sn}$; E/A=50 MeV

$Y(^7\text{Li})$ enhanced from $^{124}\text{Sn}$

$Y(^7\text{Be})$ enhanced from $^{112}\text{Sn}$
Isospin transport observable

\[ \frac{Y(^7\text{Li})}{Y(^7\text{Be})} \]

Mainly dominated by Coulomb

\[ V_{\text{\parallel}}(\text{au}) \]

\[ ^{112}\text{Sn} + ^{124}\text{Sn} \]

\[ ^7\text{Li} \]

\[ ^7\text{Be} \]

\[ Y(\text{Li}) \text{ enhanced from } ^{124}\text{Sn} \]

\[ Y(\text{Be}) \text{ enhanced from } ^{112}\text{Sn} \]

Ratio \( \frac{Y(\text{Li})}{Y(\text{Be})} \)

Mainly dominated by Coulomb

How to observe isospin transport?

\[ R_i = \frac{2x_{AB} - x_{AA} - x_{BB}}{x_{AA} - x_{BB}} \]
Coulomb & other (preequilibrium & sequential) effects are “cancelled”

\[ R_i = \frac{2x_{AB} - x_{AA} - x_{BB}}{x_{AA} - x_{BB}} \]

Rami et al., PRL, 84, 1120 (2000)
Transport Equation Simulations

- Diffusion occurs within \( \approx 120 \text{ fm/c} \).
- More mixing with soft \( S(\rho) \) — consistent with large \( E_{\text{sym}} \) at \( \rho < \rho_0 \).
- Less mixing with stiff \( S(\rho) \).

Tsang et al. PRL 92, 062701 (2004)
Transport Equation Simulations

- Explicit secondary decay correction gives same result.
- Stiff $S(\rho)$ favored.
- Momentum-isospin dependence?

Tsang et al. PRL 92, 062701(2004)
Constraints from Isospin Diffusion Data

M.B. Tsang et. al.,
PRL 92, 062701 (2004)

L.W. Chen, C.M. Ko, and B.A. Li,
PRL 94, 032701 (2005)

C.J. Horowitz and J. Piekarewicz,
PRL 86, 5647 (2001)

B.A. Li and A.W. Steiner,
nucl-th/0511064
Summary & Outlook I: Improve measurements on n/p double ratios and transport model calculations

Investigate model dependencies of the isospin dependent in-medium cross sections and effective masses that must be better constrained.

ImQMD: Y.X. Zhang, Z.H. Li
BUU: Y.X. Zhang, P. Danielewicz
Summary and Outlook II: Tightening the constraints at sub-saturation density

- Improving and understanding better the impact parameter determination.
- Changing the incident energy
- Improving the constraints on $S(\rho_0)$, $m^*$?
- Improving the constraints on the isospin dependent in-medium cross sections.
- Investigating with other observables

ImQMD: Y.X. Zhang, Z.H. Li
BUU: Y.X. Zhang, P. Danielewicz
Experiment Correlation functions with HiRA

- Calculations predict the height and width of proton-proton correlations are sensitive to the density dependence of the asymmetry term.
  - width provides more accurate information than height.

Chen et al., PRL 90 162701 (2003).
Verde (2004)
The High Resolution Array (HiRA)

A State-Of-The-Art Silicon Detector Array for studying transfer reactions, resonance spectroscopy, interferometry, ...

Si-E 1.5 mm

Si-ΔE 65 μm

32 strips v. (front)

32 strips h. (back)

32 strips v. (front)

Beam

pixel
Extrapolation of neutron-rich isotope cross-sections from 140 MeV per nucleon $^{48}$Ca and $^{64}$Ni beam


64 MeV per nucleon $^{86}$Kr beam


Isospin fractionation in nuclear multifragmentation

Isospin diffusion observables in heavy ion reactions


The High Resolution Array (HiRA) for rare isotope beam experiments