Reaction Studies @ NSCL

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

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The National Superconducting Cyclotron Laboratory @ Michigan State University
Lansing is the capital of Michigan. Michigan State University is located in East Lansing.
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
National Superconducting Cyclotron Laboratory

Coupled Cyclotron Facility (2000)

World’s first superconducting cyclotron (1982)

World’s most powerful superconducting cyclotron (1989)
Example Fragment Separation Technique (NSCL)

100 pnA $^{86}$Kr
5 kW Beam power

D = 5 cm/%
R = 2500 p/$\Delta p$

65% of the $^{78}$Ni is transmitted

Wedge location

$\Delta p = 5\%$

8 msr

production target
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
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)

Use of statistical or phase space model to understand the fragmentation process

Mass measurements of rare isotopes
Sensitivity ~TOF
**Exploration of drip-line**

*Existence of $^{40}\text{Mg}$ but non-existence of $^{39}\text{Na}$ establishes the n-drip line at $N=28$*
Calibrating transfer reactions

- Reaction theory (J. Tostevin):
  - Three-body transfer model; global optical potentials.
  - Fixed neutron potential well
- Excellent agreement with Large Basis Shell Model (LBSM) (B.A. Brown).
Excited-state Spectroscopic Factors of sd shell nuclei

Excited-state SFs of rare nuclei:

- $rp$ process calculations
- $X$-ray burst simulations

Not available in experiment

→ from SM predictions

- SFs for excited states are very small (< 0.1)

→ Test the predictive power of Shell Model

→ Use nuclei in sd shell where the interaction (USDB) is well understood.

Agreement with Shell Model better than 30%

Similar to experimental uncertainties

Analyzed ~ 794 angular distributions
Application: Determination of Spin assignments from Systematics

$J^\pi$ assignment

$^{27}$Mg (NUDAT): (3/2, 5/2)$^+$

Expt

SM

5.627
(3/2, 5/2)

5.454, 3/2

5.404, 5/2
Neutron Spectroscopic Factors for Ni isotopes

- $^{56}$Ni core, in fpg model space
- New $T=1$ effective interactions (derived for $^{56}$Ni-$^{78}$Ni region)

Data uncertainties: 20-30 % ➔ Interactions for gfp shell still need improvements

SF values agree to factor of 2 ➔ cannot distinguish between two interactions

• $^{40}$Ca core, in fp model space
• GXFP1A interaction
• No $^{56}$Ni shell closure requirement
• CPU intensive

M. Horoi

Complete Basis

Analyzed ~ 400 angular distributions
Isospin Dependence of the Nuclear Equation of State

\[ E/A (\rho, \delta) = E/A (\rho, 0) + \delta^2 \cdot S(\rho) \]
\[ \delta = (\rho_n - \rho_p)/ (\rho_n + \rho_p) = (N-Z)/A \]
\[ P = \rho^2 \frac{\partial (E/A)}{\partial \rho} \bigg|_{s/a} \]

- The density dependence of symmetry energy is largely unconstrained.
- Pressure, i.e. EOS is rather uncertain even at \( \rho_0 \).
Size & Structure of Neutron Star depends on EOS

- EOS influence
  - R,M relationship
  - maximum mass.
  - cooling rate.
  - core structure

Crab Pulser is calling
Heavy ion collisions:

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

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

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 \( dS/d\rho|_{\rho=\rho_0} \)
  – 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 \( d^2S/d\rho^2|_{\rho=\rho_0} \)

• Sensitive to \( \rho \sim \rho_0 \)

• Isoscaling, \( Y_1(N,Z)/Y_2(N,Z) \propto \exp(\alpha N+\beta Z) \)
  – Sensitive to sequential decays
Probes of the symmetry energy

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

• 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

Li et al., PRL 78 (1997) 1644

\[ V_{asy} \text{ (MeV)} \]

\[ u = \rho / \rho_o \]
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, \(^3\text{He}, \ldots\))
Double Ratios (central collisions)

- Role of isoscaler $\alpha$ emission:
  - Effect of cluster production clear and theoretically reproduced by QMD.

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

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

Non-isospin transport effects are “cancelled”??
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 \( S(\rho) \).
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 and Outlook I

Fragmentation systematics

- Measured ~2000 cross-sections with stable and unstable beams
  - Bench-mark systems for fragmentation models
  - Systematics with B/A allows extrapolation of rare isotope cross-sections at tail of distributions.
  - mass measurement of similar sensitivity as TOF methods
- Future: Fragmentation Fission
Test of validity of shell model calculations
Many more unmatched SF’s

*single particle states*

*evolution of shell structure*
Summary and Outlook II: Transfer Reactions

**Inverse kinematics at 35MeV/A**

\[ p^{(34}\text{Ar},d)^{33}\text{Ar} \; \& \; p^{(46}\text{Ar},d)^{45}\text{Ar} \]

study the SF quenching for n-rich and n-deficient systems

\[ p^{(86}\text{Kr},d)^{85}\text{Kr} \; \& \; p^{(84}\text{Se},d)^{83}\text{Se} \]

Evolution of \(N=50\) shell

\[ p^{(56}\text{Ni},d)^{55}\text{Ni} \; \& \; d^{(56}\text{Ni},^3\text{He})^{55}\text{Co} \]

Structure of double magic \(^{56}\text{Ni}, N=Z=28\)
The High Resolution Array (HiRA)

*A State-Of-The-Art Silicon Detector Array for studying transfer reactions, resonance spectroscopy, interferometry, ...*
Summary and Outlook III: EOS of asymmetric matter

The EOS of dense asymmetric matter is of fundamental importance to nuclei and neutron stairs. Calculations suggest a number of promising observables that can probe the density dependence of the symmetry energy.

- Isospin diffusion is providing some constraints at $\rho \leq \rho_0$.
- $\pi^+ \text{ vs. } \pi^-$ production, Kaon and $\Sigma$ hyperon production, neutron/proton spectra and flows may provide constraints at $\rho \approx 2\rho_0$ and above.

There are model dependencies of the isospin dependent in-medium cross sections and effective masses that must be better constrained.
Neutron Spectroscopic Factors
Jenny Lee¹, M.B. Tsang¹, W.G. Lynch¹, S.C. Su¹,², B.A. Brown¹, M. Horoi³, J.A. Tostevin⁴

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Isospin Diffusion Observables in heavy ion reactions


Department of Chemistry and IUCF, Indiana University, Bloomington, IN 47405, USA,

Department of Chemistry, Washington University, St. Louis, MO 63130, USA

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

M. S. Wallace¹,², *, M. A. Famiano³,², M. -J. van Goethem², A. Rogers², W. G. Lynch², J. Clifford², J. Lee², S. Labostov², M. Mocko², L. Morris², B. E. Nett², D. J. Oostdyk², R. Krishnasamy², M. B. Tsang², R. D. de Souza², S. Hudan², L. G. Sobotka², R. J. Charity², J. Elson², G. L. Engel²
Stable Neutron excess

Excitation energy

Gas phase

Giant resonance

(stable beam)

(RI beam)

Fragmentation

ISOL

In-flight (low energy)

Disappearance/Appearance of magicity

Egg

Skin

Halo

N\ll Z

N=Z Stable

N\gg Z

Neutron star

Explosive hydrogen burning

Heavy element synthesis

Neutron excess
Nuclear Reaction Study
Sky is the limit

N < Z  Stable

N = Z  Giant resonance

N >> Z  Neutron star

Excitation energy

Separation energy

Disappearance/Appearance of magicity

Cluster correlation

Soft mode

2n correlation

Halo

Skin

Egg

Gas phase

Explosive hydrogen burning

Heavy element synthesis

Neutron excess

June 2007
Fragmentation of stable and unstable isotopes

- $^{58}\text{Ni}$; N/Z=1.07
- $^{64}\text{Ni}$; N/Z=1.28
- $^{68}\text{Ni}$; N/Z=1.43

- Fragmentation of unstable nuclei is similar to stable nuclei.
- Facilitates development of fragmentation codes
Excitation Energy, Hot and cold fragments

Sequential decays wash out pre-fragment information?

Monte-Carlos of dynamic and statistical models – inadequate to predict productions of rare isotopes
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 $\pi$ 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 $^7$Li & $^7$Be from $^{124}$Sn+$^{112}$Sn; E/A=50 MeV

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

$Y(^7$Be) enhanced from $^{112}$Sn
A Non-isospin transport effects are cancelled!

Study of $R_i$ as function of $y$ and $b$

Transport model calculations
HiRA Collaborations
Asymmetry term studies at $\rho \approx 2\rho_0$

- Densities of $\rho \approx 2\rho_0$ can be achieved at $E/A \approx 400$ MeV.
  - Provides information about direct Urca cooling in proto-neutron stars, stability and phase transitions of dense neutron star interior.

Summary and Outlook

• The EOS of dense asymmetric matter is of fundamental importance to nuclei and neutron stairs and can be addressed experimentally.
• Fast rare isotope beams such as those envisioned in the ISF concept are essential for such studies.
• U.S. scientists presently lead the field
• A collaboration has been formed involving scientists from U.S., Japan and Europe to perform complimentary measurements at MSU, RIKEN and GSI.
  – Present MSU or future ISF measurements focus on measurements at $E/A \leq 200$ MeV, Riken at $200 \leq E/A \leq 350$ MeV and Fair at higher energies up to $E/A \approx 1$ GeV.
  – First measurements at CCF and Letter of Intent to RIKEN in 2006.
Excited-state Spectroscopic Factors of sd shell nuclei

Excited-state SFs of rare nuclei:

- rp process calculations
- X-ray burst simulations

Not available in experiment → from SM predictions

- SFs for excited states are very small (< 0.1)

→ Test the predictive power of Shell Model

→ Use nuclei in sd shell where the interaction (USDB) is well understood.

Agreement with Shell Model better than 30%

Similar to experimental uncertainties
If you know “your friends” and know yourself, your victory will not stand in doubt.
Isotope Science Facility at Michigan State University
Upgrade of the NSCL rare isotope research capabilities
Summary and Outlook

• Heavy Ion collisions with rare isotope beams can address some compelling issues.
• The EOS of dense asymmetric matter is of fundamental importance to nuclei and neutron stairs.
• Calculations suggest a number of promising observables that can probe the density dependence of the symmetry energy.
  – Isospin diffusion is providing some constraints at \( \rho \leq \rho_0 \).
  – \( \pi^+ \) vs. \( \pi^- \) production, Kaon and \( \Sigma \) hyperon production, neutron/proton spectra and flows may provide constraints at \( \rho \approx 2\rho_0 \) and above.
• The availability of fast rare isotope beams at a variety of energies allows the exploration of the
Isospin transport observable

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

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

Ratio $Y(\text{Li})/Y(\text{Be})$

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)
RIA (The Rare Isotope Accelerator)

2001—The Nuclear Science Advisory Committee Long Range Plan endorses RIA as the highest priority for major new construction.
2004—RIA tied for 3rd place for future scientific facilities supported by the Department of Energy (DOE) to be built in 20 years.
2005—President Bush proposed 3.8% cuts in DOE science.
2005—Congress recommended DOE nuclear science increased by 3.9%

Construction (?) of RIA definitely will be postponed
RIA R&D continue;
Research with existing RI facilities such as NSCL
Cost of RIA ~ one week of war in Iraq

**Window of opportunities for CSR**
Overview of Nuclear Science

Nuclear science addresses the quantum quark/gluon and nuclear many body problems. How do we understand nuclei in terms of their fundamental parts and interactions?
Transport Equation Simulations

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

- Explicit secondary decay correction gives same result.
- Stiff $S(\rho)$ favored.
- Momentum-isospin dependence?
Emission patterns of charged particles e.g. $^7$Li

Observable: $V_\parallel$ vs. $V_\perp$

Acceptance: No detector coverage around beam & detector energy thresholds

Emission from projectile and target residues would create ridges from Coulomb repulsions.
Recent results for EXO 0748 - 676

- EXO 0748 – 676 is a neutron star in a Binary system, which emits bursts of X-rays.
- Recent X-ray observations with XMM-Newton have identified red-shifted lines of O and Fe.
  - red shift ⇒ M/R
- Rules out most EOS's
  - "...If this object is typical, then condensates and unconfined quarks do not exist in the centres of neutron stars." F. Ozel, Nature 441, 1115 (2006).
Recent monopole resonance data

- Yields similar conclusions as for the isospin diffusion
  - $K_{\text{sym}} = - 440\pm 60$ MeV GMR (Garg)
  - $K_{\text{sym}} = - 500\pm 50$ MeV isospin diffusion (Li)

Garg et al., (2007)

needs intense fast rare isotope beams, $E/A \sim 50$ MeV
Isospin Diffusion and the EOS

• In a reference frame where the matter is stationary:
  \[ \bar{\Gamma}_\delta \equiv \left( \rho_n \bar{v}_n - \rho_p \bar{v}_p \right) = -\rho D_\delta \bar{\nabla} \delta \]
  \[ \delta = (\rho_n - \rho_p)/\rho \]
  – \( D_\delta \) the isospin diffusion coef.
• Two effect contribute to diffusion
  – Random walk
  – Potential (EOS) driven flows
• \( D_\delta \) governs the relative flow of neutrons and protons
  – \( D_\delta \) decreases with \( \sigma_{np} \)
  – \( D_\delta \) increases with \( S_{int}(\rho) \)
Calibrating transfer reactions

- Reaction theory (J. Tostevin):
  - Three-body transfer model.
  - Global optical potentials.
  - Fixed neutron potential well.
- Excellent agreement with Large Basis Shell Model (LBSM) (B.A. Brown).
- n-bound geometry and densities constrained by Hartree-Fock Calculations (J. Tostevin).
  - Predicts quenching of SF’s.
- Separation dependence of quenching is not observed with transfer reactions.
Symmetry Energy in Nuclei

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

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

Inclusion of surface terms in symmetry

Proton Number \( Z \)

Neutron Number \( N \)

Crab Pulsar