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?

W. Nazarewicz
Constraining symmetry energy with laboratory experiments

Outline:

RIA
NSCL/MSU
HI experiments to study the symmetry energy
Possible experiments at CSR

Lanzhou CSR workshop, July 1-5, 2005, Lanzhou, China

Betty Tsang
The National Superconducting Cyclotron Laboratory
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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**
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

282 employees, incl. 51 undergraduate and 46 graduate students, 24 faculty

User group of over 600 CCF users

(as of March 05)
National Superconducting Cyclotron Laboratory

Coupled Cyclotron Facility (2001)

World’s first superconducting cyclotron (1982)

World’s most powerful superconducting cyclotron (1988)
Rare Isotope Production:

- **Primary beams:** $^{40,48}\text{Ca}$, $^{58,64}\text{Ni}$ and unstable $^{68}\text{Ni}$ and $^{69}\text{Cu}$ beams.
- **Data reveal deficiencies of EPAX parameterization.**
- **Improvement on theoretical understanding of the RI production mechanisms.**
Experimental Areas at NSCL
Constraining symmetry energy with laboratory experiments

The origin of elements → life

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The ultimate goal and major questions of studying heavy-ion reactions induced by neutron-rich (stable and/or radioactive) nuclei

To understand the isospin dependence of the nuclear Equation of State, extract the isospin dependence of thermal, mechanical and transport properties of asymmetric nuclear matter playing important roles in nuclei, neutron stars and supernovae.

Among the currently most interesting topics in isospin physics

1. **EOS of neutron-rich matter, especially the density dependence of symmetry energy** $E_{\text{sym}}(\rho)$ **at high densities.**

2. Momentum-dependence of the symmetry potential and the neutron-proton effective mass splitting $m_n^\ast - m_p^\ast$ in neutron-rich matter

3. Isospin-dependence of in-medium nucleon-nucleon cross sections and the nuclear stopping power in neutron-rich matter

4. Explore the phase diagram $(T, \rho, \delta)$ of neutron-rich matter along the isospin asymmetry $\delta$ axis (e.g., neutron distillation, n-$\Lambda$ phase transition)

5. **Isospin mixing of vector mesons** $(\rho^0, \omega)$ and charge symmetry breaking in neutron-rich matter

The most important question relevant to all of the above: **What is the isospin dependence of the in-medium nuclear effective interactions**
Symmetry Energy in Nuclei

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

Inclusion of surface terms in symmetry
Birth of a Neutron Star

July 4, 1054, China

Crab Pulsar
Size & Structure of Neutron Star depends on EOS

- EOS influence
  - R,M relationship
  - maximum mass.
  - cooling rate.
  - core structure
Heavy ion collisions:

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

\[ \delta = \frac{(\rho_n - \rho_p)}{(\rho_n + \rho_p)} = \frac{(N-Z)}{A} \]

Results from Au+Au flow \((E/A \sim 1-8 \text{ GeV})\) measurements include constraints in momentum dependence of the mean field and NN cross-sections.
Heavy ion collisions:

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


No experimental constraints on the symmetry terms
Extrapolation to neutron stars

\[
E/A (\rho, \delta) = E/A (\rho,0) + \delta^2 S(\rho) \quad \delta = (\rho_n - \rho_p)/(\rho_n + \rho_p) = (N-Z)/A \approx 1
\]

Sensitive observables:

- **At sub-saturation densities**
  - Isospin diffusion
  - Asymmetry of bound residues.
  - Pre-equilibrium n vs. p emission
  - Transverse flow (n.vs.p).
  - Difference between neutron and proton matter radii.

- **At supra-saturation densities (CSR)**
  - Isospin dependencies of pion production.
  - n vs. p emission
  - Transverse flow (n.vs.p).

- Additional measurements are needed to constrain the n,p effective masses and the isospin dependences of the cross sections.

The asymmetry term contributes greater uncertainty than does the symmetric matter EOS.

Observables in HI collisions

Assume \( E_{\text{sym}}(\rho) = C_{\text{cym}}(\rho / \rho_0)^\gamma \)

Heavy Ion Collisions:

Central collisions (isospin fractionation)

\[
n/p \text{ ratios; } <E_n>, <E_p> \]

The symmetry term affects the emission of n and p.

\[
n/p(\text{stiff } \gamma \sim 1.1) < n/p(\text{soft } \gamma \sim 0.6)\]
Studies of emitted n and p

- Direct measurements of n vs. proton emission rates and transverse flows - probes the pressure from asymmetry term at saturation density and below.
  - Predictions for emission rates:
  - Clusters can be addressed within coalescence invariant analyses

- Double ratio is less sensitive to energy calibration and neutron efficiency uncertainties.
n/p Experiment $^{124}$Sn+$^{124}$Sn; $^{112}$Sn+$^{112}$Sn; E/A=50 MeV
N-detection – neutron wall
p-detection: Scattering Chamber

WU MicroBall
(b determination)

~6in

beam

3 particle telescopes
(p, d, t, \(^{3}\)He, …)

# of charged particles

Impact parameter
n/p Double Ratios (central collisions)

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

minimize systematic errors

There will be improvements in both data (analysis) and BUU (1997) calculations.
Isotope Distribution Experiment

MSU, IUCF, WU collaboration

Sn+Sn collisions involving $^{124}$Sn, $^{112}$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)
Measured Isotopic yields

Central collisions

Multifragmentation

Similar distributions

$R_{21}(N,Z) = \frac{Y_2(N,Z)}{Y_1(N,Z)}$

$Xu et al., PRL, 85, 716 (2000)$

$T.X Liu et al. PRC 69, 014603$
Isoscaling from Relative Isotope Ratios

\[ R_{21}(N,Z) = \frac{Y_2(N,Z)}{Y_1(N,Z)} \]

\[ \alpha = 2C_{\text{sym}}[\Delta \delta(1-\delta)]/T \]

In statistical and dynamical models, \( \alpha \) is related to the symmetry energy and asymmetry of the emitting source.

Tsang et al, PRL, 86, 5023 (2001)  MB Tsang et al. PRC 64,054615
Isospin Diffusion

\[ R_i = \frac{2\delta - \delta_{PP} - \delta_{TT}}{\delta_{PP} - \delta_{TT}} \]

- symmetry energy will act as a driving force to transport the \( n \) or \( p \) between projectile to target.

Difference between projectile and target spectator asymmetry, \( \delta = (N-Z)/(N+Z) \), measures the isospin diffusion which can be used to extract information about symmetry energy.
Comparisons to data

- Diffusion occurs within \( \approx 120 \text{ fm/c} \).
- More mixing with soft \( S(\rho) \)
  - consistent with large \( E_{sym} \) at \( \rho < \rho_0 \).
- Less mixing with stiff \( S(\rho) \).
- Explicit secondary decay correction gives same result.
- Stiff \( S(\rho) \) favored.
- Momentum-isospin dependence?
Constraints on symmetry term in EOS from isospin diffusion

\[ E(\rho, \delta) = E(\rho, 0) + E_{\text{sym}}(\rho)\delta^2; \quad \delta = (\rho_n - \rho_p)/(\rho_n + \rho_p) \]

Assume \( E_{\text{sym}}(\rho) \propto (\rho / \rho_0)\gamma \)

**BUU+m*: Transport theory based on Boltzmann Equations & include momentum dependence in mean field.

Need further constraints from n/p ratios and correlation experiments.

Sn+Sn DATA

**112,124Sn+ 112,124Sn**

E/A=50 MeV

Peripheral collisions

Tsang et al., PRL 92, 062701(2004)
Chen et al., PRL 94, 032701(2005)
Future plans: S2 reconfiguration

- Objectives are to constrain $S(\rho)$, $m^*_n$, $m^*_p$, $\sigma_{pp}$ and $\sigma_{np}$.

Similar program can be implemented at CSR HiRA.
The High Resolution Array (HiRA)

- Flexible easily reconfigured array with 20 independent telescopes (can be expanded).
- High resolution:
  - $\pm 0.1^\circ$ at 50 cm.
  - High resistivity silicon; $\Delta E \approx 35$ KeV FWHM, per signal.
Silicon Detectors

- 62.3 x 62.3 mm$^2$ Active Area
- Pitch 1.95 mm
- 1024 Pixels per telescope

- Bulk material is n type
- Interstrip on junction side is 25 µm
- Interstrip on ohmic side is 40 µm
  - P+ implant for better interstrip isolation
- Depletion voltage for 1.5 mm detector < 500 V
- 10 guard ring structure on periphery (2mm dead area region)
Laser Based Alignment System

• Designed for precision measurement of detector positions relative to target.
• Adaptable to various configurations and other devices.
• Computer controlled.

Resolution:
• ±0.005° for angular stages.
• 100 microns for distance.
Electronic Readout

Developed at Washington University (St. Louis)

With 2000 channels to readout, cost of “traditional” readout is prohibitive.

Design Includes:
• Multiple Preamps
• Shapers
• Discriminator
• Time to amplitude converters

This chip board + one VME module replaces 32 pre-amp’s, 32 Shapers, 32 TDCs and 32 ADCs

Application Specific Integrated Circuit
HiRA Electronics Setup Behind Detectors in Vacuum Chamber
Beam Tracking Using Micro Channel Plate Detectors

MCP 2D Position Spectrum

Schematic Construction and Operating Principle of MCP

Magnet

Foil

Beam

MCP

e-

INPUT ELECTRON

INPUT SIDE ELECTRODE

CHANNEL WALL

OUTPUT ELECTRODE

OUTPUT ELECTRONS

STRIP CURRENT

V_D
The S800 Spectrograph

2 experiments scheduled in July & August
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TPC’s maybe the best way to attack $E_{\text{sym}}(\rho,\delta)$

1) Have element and isotope resolution for light particles (FLOW + PE)
2) Can determine the reaction plane (FLOW)
3) Can measure $\pi^+$ and $\pi^-$ spectra
4) Can handle interaction rates of up to $\sim 100$ events/second

BUT

5) Require external:
   - n-detectors (n-FLOW)
   - MUSIC for heavier fragments at forward angles [Deflection (flow) of projectile spectators, projectile fragmentation and multifragmentation]

6) They require a good trigger!

Issues:
1) Magnet Design: Solenoid or Dipole? Size and shape of the magnet?
2) Geometry at forward angles:
   - Access for neutron detection.
   - DYNAMIC RANGE: Thresholds and resolution for fragment and projectile residue detection.
3) Complexity and cost of trigger.
4) Suppression of beam space-charge: issue for dipole design
**Solenoidal design**

Solenoidal drift chamber. Open forward geometry covered by TOF wall.

**Advantages:**
*Azimuthal symmetry favors elliptical flow analyses.*

**Disadvantages:**
*At forward angles: poor momentum res. & high detection thres.*

**Dipole design**

Rectangular TPC. Open forward geometry providing access for TOF wall, neutron detector and MUSIC.

**Advantages:**
*Good momentum res. at forward angles. Possibly lower detection thres. at forward angles.*

**Disadvantages:**
*Beam is perpendicular to magnetic field making beam line problematic.*

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[Images of solenoidal and dipole designs]
Some observations

1. Radioactive Beams → have the highest discovery potentials.
   Large numbers of isotopes waiting to be discovered → impact on Astrophysics.

2. HI collisions
   Isospin Physics is the focus of the global HI communities.
   CSR has a window of opportunity in this area with the availability of >400 MeV/nucleon heavy beams while the rest of the world is still building.
   Requires “Simple” detectors, n, p (charged particle), π, simple impact parameter selection detectors.

3. State of art detectors include R&D in electronics and data analysis – Investments in these areas should not be neglected.