Experimental Nuclear Physics

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The Purpose of Nuclear Structure Physics

Overarching questions that drive research

• What is the nature of the nuclear force that binds protons and neutrons in stable nuclei and rare isotopes?

• What is the origin of simple patterns in complex nuclei?

• What is the origin of the elements in the cosmos?
The Scope of Nuclear Structure Physics

The Four Frontiers

1. Proton Rich Nuclei
2. Neutron Rich Nuclei
3. Heaviest Nuclei
4. Evolution of structure within these boundaries

Terra incognita — huge gene pool of new nuclei

We can customize our system – fabricate “designer” nuclei to *isolate and amplify* specific physics or interactions
What do we know??

About 300 stable nuclei

Goeppert-Meyer and Jensen

Bohr, Mottelson, Rainwater
What do we know??

More than 3000 have been produced
What do we know??

6000-8000 are predicted

[Diagram showing proton and neutron numbers, with annotations for proton and neutron driplines, r-process, and superheavy territory.]
The Theoretical Landscape

Experiment and Theory are NOT separate sciences!!!!!
How big is a nucleus??
Sizes and forces (very basic)

Uncertainty principle

\[ \Delta E \Delta t > \frac{\hbar}{2} \]

Substitute ...

\[ E = mc^2 \quad v = x/t \]

...to give

\[ \Delta m \frac{\Delta x}{c} > \frac{\hbar}{2} \]

Nuclear force - pion exchange

\[ \Delta m \sim 140 \text{ MeV} \]
\[ \frac{\hbar c}{2} \sim 10^{-13} \text{ MeV} \cdot m \]

\[ \Delta x \sim 10^{-15} m \]

or

\[ \Delta x \sim 10^{-13} cm \]
Sizes and forces (very basic)

Electron Scattering and Nuclear Structure

Robert Hofstadter

University, Stanford, California

to the Weizsacker semiempirical formula, and, in the case of the heaviest elements, on the energies and half-lives of alpha activities. All approaches led to the same general range of values of the nuclear radii for a uniformly charged sphere, which was taken universally as the appropriate model of the nucleus. The results can be summarized in a well-known formula for the radius of a uniform sphere

\[ R = r_0 A^{1/3} \times 10^{-18} \text{ cm.} \]  

Henceforth, we shall measure all distances in terms of $10^{-18}$ cm as a unit and shall call this unit the fermi. For example, this formula puts the edge of the nuclear sphere of gold at a distance of 8.45 fermis from the center of the nucleus, if the constant $r_0$ is given a good

\[ \rho = \frac{A}{V} = \text{const} \]

\[ V \sim A \sim R^3 \]

\[ R = R_0 A^{1/3} \]
Choosing the right probe

Energy of probe related to size of probee and production device

What's as big as a nucleus??

Another nucleus !!

![Graph showing electromagnetic spectrum with wavelengths and frequency ranges for gamma rays, X-rays, ultraviolet rays, infrared rays, radar, FM, TV, shortwave, and AM bands.](image)
Shopping List

- Beam/Reaction
- Channel Selection
  - Detectors
  - Data Analysis
  - Theory
Schematic view of nuclear reactions

- Gamma ray
- Neutron
- Light charged particle
- Heavy ion
- Radioactive decay
Reactions

Transfer reactions (d,p), (p,t)

(HI,xn)

(40Ca,4n)

Fragmentation

Deep inelastic

208Pb(76Ge,X)

Coulomb excitation

“Soft” grazing

Fusion

“Hard” grazing

Distant
Heavy Ions at the Coulomb barrier: VERY Classical

What does it take to get two nuclei to fuse?

Need to overcome the Coulomb barrier

\[ R = R_0 A^{1/3} \]

\[ V \sim \frac{1.24 * Z_b Z_t}{(A_b^{1/3} + A_t^{1/3})} \]
$^{40}\text{Ca} + ^{96}\text{Ru} \rightarrow ^{136}\text{Gd}^*$

(Arrnost) Always leads to proton-rich nuclei
Calculating the reaction yield

\[ \text{# of reactions/sec} = N_{\text{beam}}N_{\text{target}}\sigma \]

Typical beam current \(\sim 1-100\ \text{enA}\)

\[ N_{\text{beam}} = \frac{10\times 10^{-9}}{1.6\times 10^{-19}} \to 10^{10} \text{ particles/sec} \]

\[ N_{\text{target}} = \left( \frac{N_A}{A} \right) \times \text{thickness} \]

Typical target thickness \(\sim 0.1 - 10\ \text{mg/cm}^2\)

\[ N_{\text{target}} = \left[ \frac{6\times 10^{23}}{100} \right] \times 1\times 10^{-3} \to 6\times 10^{18} \text{ particles/cm}^2 \]

**Looks like we are winning ...**
Calculating the reaction yield

\[ \text{# of reactions/sec} = N_{\text{beam}}N_{\text{target}}\sigma \]

- \(N_{\text{beam}} = 10^{10} \text{ particles/sec}\)
- \(N_{\text{target}} = 6 \times 10^{18} \text{ particles/cm}^2\)

Cross section: remember the size of a nucleus

- Probability of “hitting” the nucleus \(\sim \pi R^2\)
- 1 barn (b) = \(10^{-24} \text{ cm}^2\)

Typical fusion cross sections are in the mb’s

\[ \text{# of reactions/sec} = 10^{10} \times 6 \times 10^{18} \times 100 \times 10^{-27} \]

\[ \text{# of reactions/sec} = 6000 \]
A nice tool for planning experiments ...

- Designed for fragmentation reactions
- Lots of good basic calculators

http://lise.nscl.msu.edu/lise.html
Cross-sections (PACE4)

Evaporation - Compound nucleus $^{136}\text{Gd}$, Mode 1
Excitation energy 65.8 MeV
Compound nucleus formation cross section: 7.15e+02 mb
Coulomb and interaction-barrier heights, and interaction radii and 'half-density' distances for heavy-ion collisions, (corresponding to contact at 1/10 and 1/2 densities, respectively). Two values for C.B. are given: the 'practical' one and the value due to Bass [Ba80]. do not use for Z < 2.

Colliding nuclei

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Z1</td>
<td>20</td>
</tr>
<tr>
<td>A1</td>
<td>40</td>
</tr>
<tr>
<td>Z2</td>
<td>44</td>
</tr>
<tr>
<td>A2</td>
<td>96</td>
</tr>
</tbody>
</table>

Coulomb barrier ("practical") = 110.02 MeV
Coulomb barrier (Bass) = 110.40 MeV
Interaction barrier = 111.37 MeV
Interaction radius = 11.38 fm
"Half-density" distance (Bass) = 8.48 fm
Decay of the Compound Nucleus

Heavy beam:
• Need high energy
• Brings in high angular momentum

Light beam:
• Can use lower E
• Brings in less angular momentum
Gamma-Ray Emission

Possible decay modes:
- $\beta$ decay
- $p,n$ emission
- $\alpha$ emission
- Internal conversion
- Fission
- $\gamma$-ray emission

Gamma-ray emission is usually the dominant decay mode

- Energy
- Spin, Parity
- Magnetic, quadrupole moment
- Lifetime
- ...
Gamma rays tell you something about shape

Evolution of nuclear structure
(as a function of nucleon number)

Magic
(sph. vib.)

Mid-shell
(ellipsoidal)

Magic
(sph. vib.)

$R_{4/2} = 2.0$

$R_{4/2} = 3.33$

$R_{4/2} < 2$
Partial Level Scheme of $^{152}\text{Dy}$

... as an example of the richness of $\gamma$-ray spectroscopic information
Gamma-ray interactions with matter

Photo effect — photoelectron is ejected carrying the total $\gamma$-ray energy

Compton Scattering — Elastic scattering of $\gamma$ ray off an electron. A fraction of the $\gamma$ ray energy is transferred to the electron

Pair production — In the Coulomb field of the nucleus, a positron-electron pair can be formed. The pair has $\gamma$-ray energy minus $2m_e c^2$
Gamma-ray interactions with matter

Germanium
The “best” gamma-ray detector

HPGe detector

Clover detector

This happens about 70% of the time!!
Compton Suppression
Compton Suppressed Arrays

For the last ~ 15 - 20 years, large arrays of Compton-suppressed Ge detectors such as EuroBall, JUROBALL, GASP, EXOGAM, TIGRESS, INGA, Gammasphere and others have been the tools of choice for nuclear spectroscopy.
γ-γ coincidence: a must in constructing a level scheme
Channel Selection for gamma-ray spectroscopy: Finding a needle in a haystack

Detection of Light Charged Particles (a,p,n)

PLUS Efficient, flexible, powerful.....inexpensive.

MINUS Countrate limited, Contaminant (Carbon etc, isotopic impurities) makes absolute identification of new nuclei difficult.

CROSS SECTION LOWER LIMIT ~100μb that is, ~10^{-4}

Detection of Residues in Vacuum Mass Separator

PLUS True M/q, even true M measurement. With suitable focal plane detector can be ULTRA sensitive. Suppresses contaminants.

MINUS Low Efficiency

CROSS SECTION LOWER LIMIT ~100nb that is ~10^{-7}

Detection of Residues in Gas Filled Separator

Improves efficiency of vacuum separators, at cost of mass information and cleanliness. In some cases (heavy nuclei) focal plane counters clean up the data for good sensitivity.
Microball charged particle detector

95 CsI(Tl) detectors

Nearly $4\pi$ coverage
Microball charged particle detector

Counts/(2 keV)

$E_{\gamma}$ (keV)

(a) 1442 1442 1693 1714 1947 217 217 217 2281 2440 2742 2593 2742 2859
(b) 1442 1442 1693 1714 1947 217 217 2281 2440 2742 2593 2742 2859
(c) 1442 1442 1693 1714 1947 217 217 2281 2440 2742 2593 2742 2859
(d) 1442 1693 1714 1947 217 2281 2341 2440 2593 2742 2859
Recoil Separators

Works on basic principle of charged particle moving in magnetic or electric field

\[ B \rho = \frac{mv}{Q} \]

Very useful in heavy mass region (and superheavies) where fission dominates the cross section
**RECOIL DECAY TAGGING METHOD**

1. **Beam** enters the target.
2. A **recoil** event occurs.
3. The recoil is detected by the **FMA**.
4. The recoil is then tracked through the **PPAC**.
5. The recoil is finally detected by the **DSSD**.

**Timeline**:
- **Reaction Occurs**: $10^{-12} - 10^{-9}$ s
- **Gamma-Ray Detected**: 0.5 - 2.0 µs
- **M/Q Measured**: 30 ns
- **Recoil Implant in DSSD Pixel ($X, Y$)**: 20 µs - 5 s
- **Alpha or Proton Decay Occurs in Pixel ($X, Y$)**

**Prompt $\gamma$-rays**
- Correlated with M/Q and ($X, Y$) position of recoil in DSSD

**Decay Proton or Alpha**
- Identifies nucleus that emitted the $\gamma$-rays
Measure recoil in DSSD
Recoil proton energy in same pixel
$\gamma$-ray spectroscopy of the odd-odd $N = Z + 2$ deformed proton emitter $^{112}$Cs


![Diagram of energy level scheme for $^{112}$Cs with transitions labeled.]
RDT Instrumentation at JYFL

GREAT
Focal plane spectrometer

RITU
Gas-filled recoil separator
Transmission 20-50 %

JUROGAM
43 Ge + BGO
Eff. 4%

TDR
Total Data Readout
Triggerless data acquisition system
In-beam spectroscopy with intense ion beams: Evidence for a rotational structure in $^{246}$Fm


$\sigma = 11$ nb
<table>
<thead>
<tr>
<th>Year Range</th>
<th>Era:</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1896-1898</td>
<td>The beginning:</td>
<td>Becquerel and Curie make first discovery of radioactivity</td>
</tr>
<tr>
<td>1910-1938</td>
<td>Discovery Era:</td>
<td>Nuclear size, Neutron, Isotopes, Masses, Binding Energy</td>
</tr>
<tr>
<td>1939-1945</td>
<td>Fission Era:</td>
<td>Fission....and activity leading to bombs &amp; nuclear power</td>
</tr>
<tr>
<td>2002-20??</td>
<td>RIB Era:</td>
<td>Neutron Rich “Terra Incognita”</td>
</tr>
</tbody>
</table>
The future

Nuclear Landscape

Fewer than 300 nuclei

Super Heavies

Proton Drip Line

Neutron Drip Line

known nuclei

terra incognita

neutron number N
How Many ions/s do you need for Physics?

Remember that with a stable beam we had $10^{10}$ particles/sec

Well, it depends on what physics you want to do...

**STOPPED BEAMS**......Decays, masses, moments, harvesting.
(could be few/minute, or lower.. to macroscopic amounts [$>10^{20}$ atoms])

**LOW ENERGY** (~2MeV/u) .... Astrophysics and reactions.
(needs $10^8$ p.p.s. .... or more)

**RE-ACCELERATED** (5-10 MeV/u) .... Structure.
(From $10^4$ and upwards)

**FAST** (50-200MeV/u) .... Existence, whatever structure is possible.
(From few/week and up)
Production of Rare Isotopes in Flight

$E > 50 \text{ MeV/nucleon}$

1. Accelerate heavy ion beam to high energy and pass through a thin target to achieve random removal of protons and neutrons in flight

2. Cooling by evaporation

E.g., NSCL/FRIB (USA), RIKEN (Japan), GSI (Germany)
Example: $^{86}$Kr $\rightarrow 78$Ni

Neutron-Rich: Revealing New Physics

Neutron-Rich: Revealing New Physics

Well Developed Deformation in $^{42}$Si

$^{44}$S beam produced in fragmentation of $^{48}$Ca
Two proton knockout to reach $^{42}$Si
Few nucleon transfer reactions
Inverse kinematics

- Argonne
- Notre Dame
- Florida State
### Neutron-Rich: Testing Ab-initio Calculations

**Structure of $^7$He by proton removal from $^8$Li with the ($d$, $^3$He) reaction**


1Physics Department, Western Michigan University, Kalamazoo, Michigan 49008-5252, USA

<table>
<thead>
<tr>
<th>Element</th>
<th>Nucleus</th>
<th>Energy</th>
<th>Photons</th>
<th>Stability</th>
<th>Beta-</th>
<th>Beta-</th>
<th>Beta-</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^7$Li</td>
<td>STABLE</td>
<td>7.58%</td>
<td>92 MeV</td>
<td>STABLE</td>
<td>99.9%</td>
<td>100.0%</td>
<td>100.0%</td>
</tr>
<tr>
<td>$^8$B</td>
<td>0.54 MeV</td>
<td>100.0%</td>
<td>100.0%</td>
<td>STABLE</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
</tr>
<tr>
<td>$^1$B</td>
<td>STABLE</td>
<td>10.0%</td>
<td>150 MeV</td>
<td>STABLE</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
</tr>
<tr>
<td>$^2$Be</td>
<td>5.57 eV</td>
<td>100.0%</td>
<td>100.0%</td>
<td>STABLE</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
</tr>
<tr>
<td>$^3$Be</td>
<td>53.24 MeV</td>
<td>100.0%</td>
<td>100.0%</td>
<td>STABLE</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
</tr>
</tbody>
</table>

- Start with $^7$Li beam
- ($d$, $^3$He) to make $^8$Li
- ($d$, $^3$He) to make $^7$He
Neutron-Rich: Testing Ab-initio Calculations

![Graphs showing angular distributions for various reactions.](image)

**TABLE III.** Comparison of experimental and theoretical spectroscopic factors for the \((d, t)\) and \((d, ^3\text{He})\) reactions; \(\sigma\) denotes the cross section at the angular-distribution maximum.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>(\sigma) (Exp) (mb/sr)</th>
<th>(C^2S) (Exp)(^a)</th>
<th>(C^2S) (VMC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^7\text{Li}(d, ^3\text{He})^6\text{He}(0^+))</td>
<td>12.3(2.0)</td>
<td>0.44(6)</td>
<td>0.42</td>
</tr>
<tr>
<td>(^7\text{Li}(d, t)^6\text{Li}(1^+))</td>
<td>41.2(6.0)</td>
<td>0.74(11)</td>
<td>0.68</td>
</tr>
<tr>
<td>(^7\text{Li}(d, t)^6\text{Li}(0^+))</td>
<td>5.6(0.9)</td>
<td>0.19(3)</td>
<td>0.21</td>
</tr>
<tr>
<td>(^8\text{Li}(d, ^3\text{He})^7\text{He}(3/2^-))</td>
<td>4.5(0.9)</td>
<td>0.36(7)</td>
<td>0.58</td>
</tr>
<tr>
<td>(^8\text{Li}(d, ^3\text{He})^7\text{He}(5/2^-))</td>
<td>1.0(0.5)</td>
<td>0.29(15)</td>
<td>0.17</td>
</tr>
</tbody>
</table>

\(^a\) Values obtained from \((\sigma_{\text{Exp}}/\sigma_{\text{DWBA}}) \times 0.32\).
Fission

CARIBU at ANL

Spontaneous Fission Source: $^{252}\text{Cf}$

Univ. of Jyvaskyla

Proton-induced fission of Uranium

Gas Catcher

Isobar Separator

Ion Guide, Mass Separator, Penning Trap
More than 800 nuclides produced in the fission of $^{235}\text{U}$
Neutron-Rich: For Applications

Pandemonium leads to incorrect average $\beta$ and $\gamma$ energies

How do we fix that? Use a detector that “catches” everything

**Total Absorption Gamma Spectrometer (TAGS)**

- Full $4\pi$ coverage
- High efficiency
- Calorimeter
Neutron-Rich: For Applications

Reactor Decay Heat in $^{239}$Pu: Solving the $\gamma$ Discrepancy in the 4–3000-s Cooling Period


![Graph showing feeding vs. $E_x$ [MeV] with different data points and curves.]

![Graph showing $f(t)$ vs. cooling time (s) with isotope symbols and data points.]

Brookhaven Science Associates
Spallation

Removal of protons and neutrons from heavy target by light energetic particles
Spallation

ISOLDE

Two d.o.f. to specify an isotope – N, Z or A, Z

target - ion source

proton beam (1 GeV)

analysing magnet

radioactive ion beams

ISOLDE @ CERN
SPIRAL2 @ GANIL
ISAC @ TRIUMF
Exotic Nuclei: For Other Fields

Studies of pear-shaped n accelerated radioactive b

Exotic Nuclei: For Other Fields
Next generation of $\gamma$-ray spectrometers
Next generation of $\gamma$-ray spectrometers

Current arrays limited by all the other “stuff”

Ideally, want just a sphere of Germanium
Need Compton Tracking

- Fit all permutations with Compton scattering
- Lowest $\chi^2$ gives most probable sequence
Building Gretina

- 36 segments per Ge crystal
- 4 crystals per module
- 30 modules for $4\pi$
Compare GRETA with Gammasphere

- Efficiency (1 MeV): 8% (Gammasphere) vs. 55% (GRETA)
- Efficiency (15 MeV): 0.5% (Gammasphere) vs. 12% (GRETA)
- Peak/Total (1 MeV): 55% (Gammasphere) vs. 85% (GRETA)
- Position resolution: 20mm (Gammasphere) vs. 1 mm (GRETA)
An example related to data evaluators
What do extra neutrons do?

Make a “Nuclear Molecule”?  
B(E2) increases

Make a “N=8” spherical cloud?  
B(E2) decreases
Systematics

Graph showing the relationship between neutron number and energy and transition probability for elements Be and C.
A precise measurement of the $\text{B}(\text{E2}; \; 2^+ \rightarrow 0^+)$ in $^{12}\text{Be}$

Fast, thick target DSAM

- 55 MeV/A $^{12}\text{Be}$ beam
- 3 different targets
- GRETINA + S800

Gretina at MSU/NSCL
Radioactive Ion Beam Facilities Worldwide

Lots of new, exciting data on the horizon!!