p-n interactions

Estimating the properties of nuclei

and

The study of exotic nuclei
Drivers of structural evolution, the emergence of collectivity, shape-phase transitions, and ellipsoidal shapes

Many ingredients but the dominant one is the valence proton-neutron interaction
Valence Proton-Neutron Interaction

Development of configuration mixing, collectivity and deformation – competition with pairing

Changes in single particle energies and magic numbers

Partial history: Goldhaber and de Shalit (1953); Talmi (1962); Federman and Pittel (late 1970’s); Casten et al (1981); Heyde et al (1980’s); Nazarewicz, Dobacewski et al (1980’s); Otsuka et al (2000’s); Cakirli et al (2000’s); and many others.
The idea of “both” types of nucleons – the p-n interaction

Lower energies imply correlations and collectivity – mixing of IPM wave functions due to residual interactions (esp. p-n)
Second effect of p-n in shifts of single particle energies themselves. Monopole effect. Migration of magicity
One of the most important effects of the valence p-n interaction is in shifting single particle level energies. Monopole shift of proton s.p.e. with neutron number. Tensor interactions.

Monopole shift of proton s.p.e. with neutron number. Tensor interactions.

Competition of the valence p-n interaction and pairing interactions drives the onset of deformation. Can we estimate this and the locus in (Z,N) of shape changing regions?
Fragility of magicity

No shell closure for N=8 and 20 for drip-line nuclei; new shells at 14, 16, 32...
Estimating the properties of nuclei

We know that $^{134}$Te (52, 82) is spherical and non-collective.

We know that $^{170}$Dy (66, 104) is doubly mid-shell, very collective.

What about: $^{156}$Te (52, 104) $^{156}$Gd (64, 92) $^{184}$Pt (78, 106) ???

All have 24 valence nucleons. What are their relative structures??
If p-n interactions drive configuration mixing, collectivity and deformation, perhaps they can be exploited to understand the evolution of structure.

**A simple toy model of the evolution of structure (including predictions of behavior far from stability). Hundreds of supercomputer hours or multiplying two small integers.**

Let's assume that all p-n interactions have the same strength. This is not realistic, since the interaction strengths are orbit-dependent but, maybe, on average, OK.

How many valence p-n interactions are there? \(N_p \times N_n\). If all are equal then integrated p-n strength should scale with \(N_p N_n\).
Valence Proton-Neutron Interactions

Correlations, collectivity, deformation. Sensitive to magic numbers.

N_p N_n Scheme

Highlight deviant nuclei
The $N_p N_n$ scheme: Interpolation vs. Extrapolation

$^{142}$Xe (54, 88) ?

- $^{156}$Te (52, 104)  $^{156}$Gd (64, 92)  $^{184}$Pt (78, 106).
- $N_p N_n$ :  
  - $2 \times 22 = 44$
  - $14 \times 10 = 140$
  - $4 \times 20 = 80$

$N_p N_p = 4 \times 6 = 24$
Competition of p-n interaction with pairing:
simple estimate of evolution of structure with N and Z

\[ P = \frac{N_p N_n}{N_p + N_n} \sim \frac{p-n}{\text{pairing}} \]

p-n / pairing

p-n ~ 200 - 300 keV, pairing int. ~ 1 – 1.5 MeV

<table>
<thead>
<tr>
<th>Isotopes</th>
<th>Energy (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>^{210}\text{Pb}</td>
<td>0.8</td>
</tr>
<tr>
<td>^{134}\text{Te}</td>
<td>1.28</td>
</tr>
<tr>
<td>^{92}\text{Mo}</td>
<td>1.69</td>
</tr>
</tbody>
</table>

\( N_p N_n \) pairing interactions per pairing interaction
Competition of p-n interaction with pairing: simple estimate of evolution of structure with N and Z

\[ P = \frac{N_pN_n}{N_p + N_n} \sim \frac{p-n}{\text{pairing}} \]

\( p-n \sim 200 - 300 \text{ keV} \), \( \text{pairing int.} \sim 1 - 1.5 \text{ MeV} \)

Hence takes \( \sim 5 \) p-n int. to compete with one pairing int.
Comparing with the data
Masses Reflect Nucleonic Interactions
Mass differences; interaction filters (double differences)

Total mass/binding energy: Sum of all interactions

Mass differences: Separation energies, shell structure, phase transitions, collectivity

Double differences of masses: Interaction filters

- Shell structure: \( \sim 1 \text{ MeV} \)
- Quantum phase transitions: \( \sim 100\text{s keV} \)
- Collective effects: \( \sim 100\text{s keV} \)
- Interaction filters (e.g., p-n): \( \sim 10-15 \text{ keV} \)
- Fundamental Interactions: \(< 1 \text{ keV} \)

We will look at a specific double difference of masses that gives the p-n interaction below. First some remarks on its importance.
Valence p-n interaction: Can we measure it?
Use nuclear masses which reflect all interactions

$$\delta V_{pn} (Z,N) = - \frac{1}{4} \left[ \{B(Z,N) - B(Z, N-2)\} - \{B(Z-2, N) - B(Z-2, N-2)\} \right]$$

Int. of last two n with Z protons, N-2 neutrons and with each other

Int. of last two n with Z-2 protons, N-2 neutrons and with each other

Empirical average interaction of last two neutrons with last two protons
Empirical interactions of the last proton with the last neutron

\[ \delta V_{pn}(Z, N) = \frac{1}{4} \left[ B(Z, N) - B(Z, N - 2) \right] - \left[ B(Z - 2, N) - B(Z - 2, N - 2) \right] \]
In terms of proton and neutron orbit filling, p-n interaction

p-n interaction is short range
similar orbits give largest p-n interaction

Largest p-n interactions if proton and neutron shells are filling similar orbits
\[ Z \leq 82 \quad , \quad N < 126 \]

\[ Z > 82 \quad , \quad N < 126 \]

\[ Z > 82 \quad , \quad N > 126 \]
Away from closed shells, these simple arguments are too crude. But some general predictions can be made.

\[ p-n \text{ interaction is short range} \]
\[ \text{similar orbits give largest } p-n \text{ interaction} \]

Largest \( p-n \) interactions if proton and neutron shells are filling similar orbits.
Empirical p-n interaction strengths stronger in like regions than unlike regions.

Empirical p-n interaction strengths indeed strongest along diagonal.
Direct correlation of observed growth rates of collectivity with empirical p-n interaction strengths and the evolution of structure.
Comparison of empirical p-n interactions with the DFT

These DFT calculations accurate only to ~ 1 MeV. \( \delta V_{pn} \) allows one to focus on specific correlations.

New measurements at ISOLTRAP/ISOLDE test DFT

Comparison of empirical p-n interactions with the DFT

These DFT calculations accurate only to ~ 1 MeV. $\delta V_{pn}$ allows one to focus on specific correlations.

New measurements at ISOLTRAP/ISOLDE test DFT

Exotic Nuclei

A new era in nuclear structure, reaction, and astrophysics

Science, Production, Recent results, and Facilities
A field that is energized worldwide
Some themes in the science of exotic nuclei
The ultimate goal of the physics of nuclei is to develop a unified, predictive theory of nucleonic matter.
New Features in Exotic Nuclei

- **Weak Binding**
  - Low density, diffuse, extended, nearly pure neutron amplitudes
  - Spatially extended wave functions
  - Localized nuclear density
  - Diffuse
  - Normal potential
  - Changes in single particle energies, magic numbers

- **Halo/Skin Nuclei**
  - Low density, diffuse, extended, nearly pure neutron amplitudes
  - ¹¹Li

- **Coupling to open channels**

- **Altered Shell Structure**

- **New N/Z ranges**

- **Interaction-induced changes in SPEs**

- **Changes in single particle energies, magic numbers**
$^{11}\text{Li}$: Borromean Halo Nucleus  

$^{19}\text{C}$: The Heaviest Known Halo Nucleus  

$^{208}\text{Pb}$: Well Bound Heavy Nucleus  

The Borromean Rings
Neutron “skins” near the neutron drip line

Skins and Skin Modes
1949 Nuclear Shell Structure

Nobel Prize 1963

N/Z

around the valley of nuclear stability
N/Z ~ 1 - 1.6

neutron-rich nuclei
N/Z ~ 3

126

82

50

Binding Energies of h11/2 and g7/2 Proton States on Sn

- Separation Energy (MeV)
- A

G1/2

G7/2

G9/2

N1/2

P3/2

P3/2

P1/2

P1/2

h11/2

h9/2

f7/2

f5/2

i13/2

A New magic nuclei
A Not magic

Tentative from γ-spectroscopy
Possible trends -- no information
Themes in the new era of Nuclear Structure

• Changing Shell Structure – The nucleonic foundation of nuclear behavior – changing paradigms after half a century

• Nucleonic interactions – Pairing and p-n: new density regimes and the effects of the continuum.

• The evolution of structure – Symmetries, phase transitions, and critical points in complex nuclei

• The heaviest nuclei – Quantal binding

• The limits of nuclear existence

• The links to Astrophysics, and opportunities to test fundamental symmetries
Production and use of Exotic Isotopes

High Energy Heavy Ion Driver → Intense Stable Ion Beam → Fragmentation Target and Ion Separator → Exotic Ion Beam → Fast Beam Experiments

High Energy Proton Driver → Intense Proton Beam → ISOL Target/Ion Extraction → Exotic Ions → Second Accelerator → Exotic Ion Beam → Reaccelerated Beam Experiments

Production and use of Exotic Isotopes

- High Energy Heavy Ion Driver
- Intense Stable Ion Beam
- Fragmentation Target and Ion Separator
- Exotic Ion Beam
- Fast Beam Experiments
- Stopped Beam Experiments (Traps)
- Exotic Ions
- Gas Stopping

Exotic Ion Beam
- Second Accelerator
- Exotic Ion Beam
- Reaccelerated Beam Experiments

Intense Stable Ion Beam
- Fragmentation Target and Ion Separator

Exotic Ions
- Gas Stopping

Production and use of Exotic Isotopes

- High Energy Proton Driver
- Intense Proton Beam
- ISOL Target/Ion Extraction
- Exotic Ions
Facility for Rare Isotope Beams

- 200 MeV/u, 400 kW superconducting heavy-ion driver linac
- Initial capabilities should include fragmentation of fast heavy-ion beams combined with gas stopping and reacceleration
- Capable of world-class scientific research program at start of operation
- Accommodate 100 users at a time, 400-500 per year

Upgrade options:
- Higher driver beam energy
- ISOL production mechanism
- Multiuser operation
- Expanded experimental area

M. Thoennessen
REB Discussion Meeting
MSU, Feb. 20, 2010
The Reach of FRIB

Rates are available at http://groups.nscl.msu.edu/frib/rates/

4500 isotopes produced at useful rates
Physics with rare isotopes – Physics vs. Intensity

With new technology we can now do experiments with orders of magnitude weaker beams than ever before.

<table>
<thead>
<tr>
<th>Particles/sec</th>
<th>Physics of Nuclei</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-5}$</td>
<td>Existence; perhaps half life, decay modes</td>
</tr>
<tr>
<td>$10^{-4}$ to $10^{-3}$</td>
<td>Half life, mass, min. structural information</td>
</tr>
<tr>
<td>$10^{-2}$ to $10^{-1}$</td>
<td>Some detailed structural information</td>
</tr>
<tr>
<td>$10^3$</td>
<td>Full details of structure</td>
</tr>
<tr>
<td>$&gt;10^5$</td>
<td>Astrophysical reaction rates</td>
</tr>
<tr>
<td>$10^6$</td>
<td>Weak interaction strengths</td>
</tr>
<tr>
<td>$10^8$ to $10^{12}$</td>
<td>Production of superheavy elements</td>
</tr>
</tbody>
</table>
Study of symmetry phases

\[ P = \frac{N_p N_n}{N_p + N_n} \sim \text{deformation pairing} \quad P_{\text{crit}} \sim 5 \]

Possible X(5) transitional nuclei

\( \beta \)-decay

- Known 4\(^+\) states
- 4\(^+\) states, transitions at 10\(^4\) pps
- 4\(^+\) states at 0.1 pps
Explosive Nucleo-Synthesis Paths
\( r \) and \( rp \)-processes

- rp-process in x-ray bursts
- Isotopes with known masses
- A=64-72 waiting point region
- Nickel (28) → Calcium (20) → Tellurium → Tin (50) → Lead (82) → Platinum

Number of protons → Number of neutrons

Mass number 195, Mass number 130, Mass number 82

M. Thoennessen
REB Discussion Meeting
MSU, Feb. 20, 2010
“Back to the Future”

Exotic nuclei

Similar techniques (as in “the old days”): single particle transfer, beta decay, gamma ray spectroscopy, mass measurements, reaction rates

— on new nuclei

New challenges—”10” vs. $10^9$ p/s
Exotic Nuclei Discovery Potential

- Comprehensive nuclear theory
- Reaching the limits of nuclear binding
- Discovery/study of exotic nuclear topologies
- Discovery of new structural symmetries
- Study of phases of nuclei and nuclear matter
- Crucial ingredients for astrophysics
- Tests of fundamental symmetries
- Unforeseen Discoveries

“Spin-offs”

- Applications to medicine, national security,
- Training the next generation of scientists who know and can exploit the atomic nucleus
Thank you

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