Lecture 3 -- R. F. Casten

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

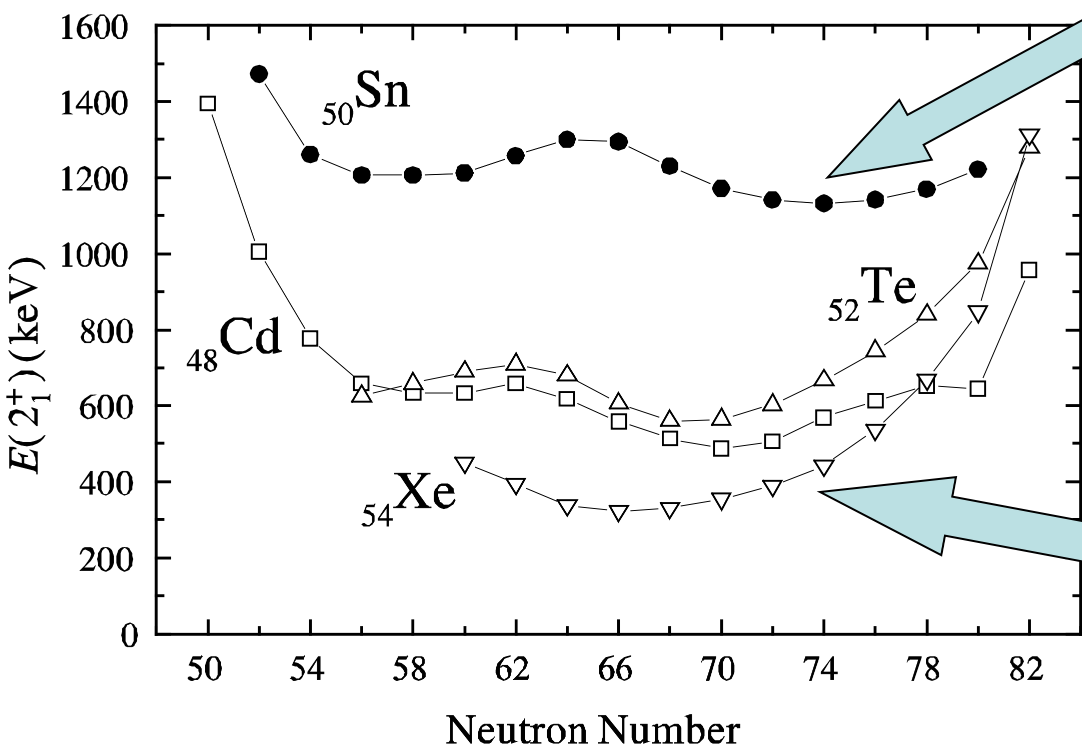
Valence Proton-Neutron Interaction

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

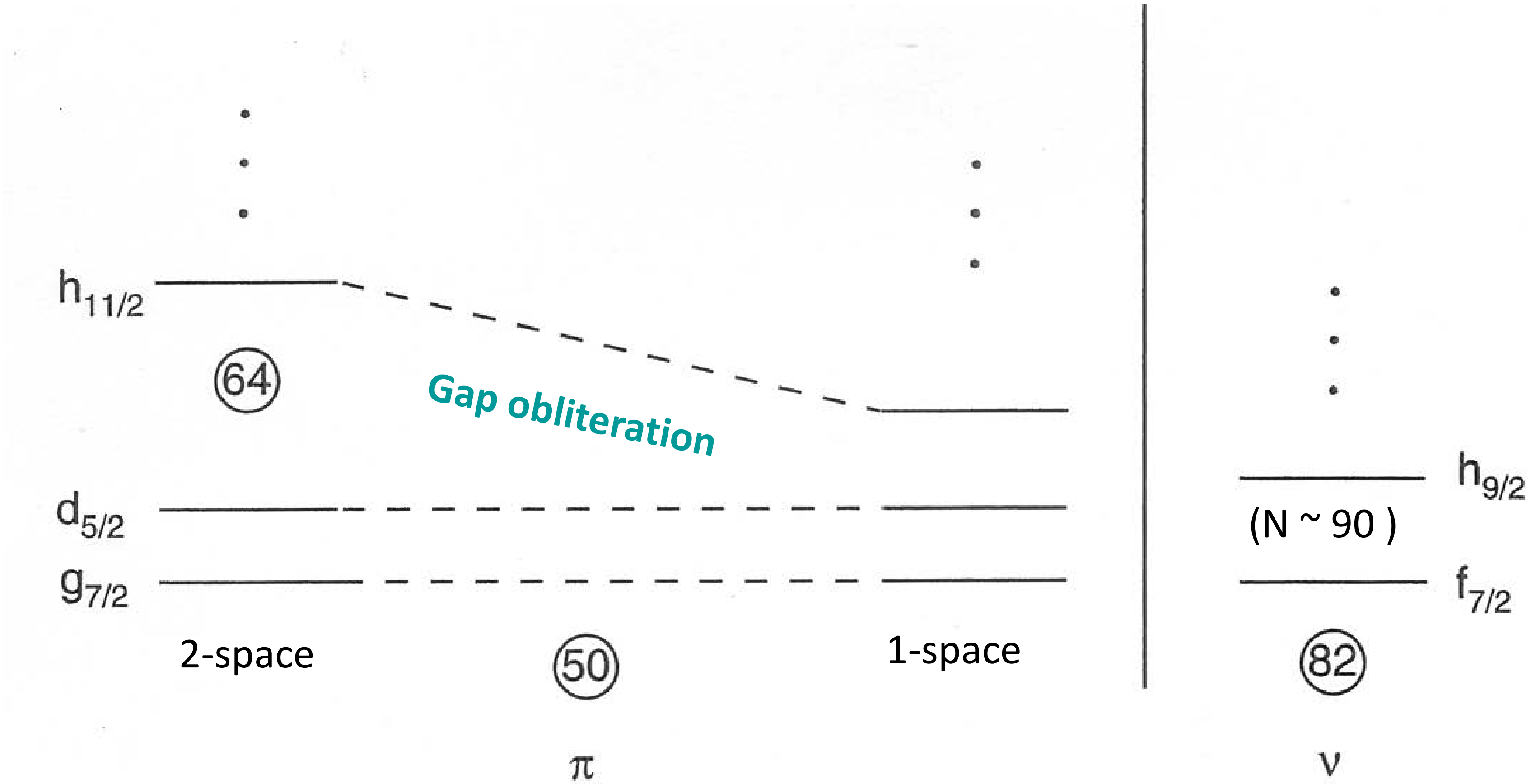


Sn – Magic: no valence p-n interactions

Both valence protons and neutrons

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

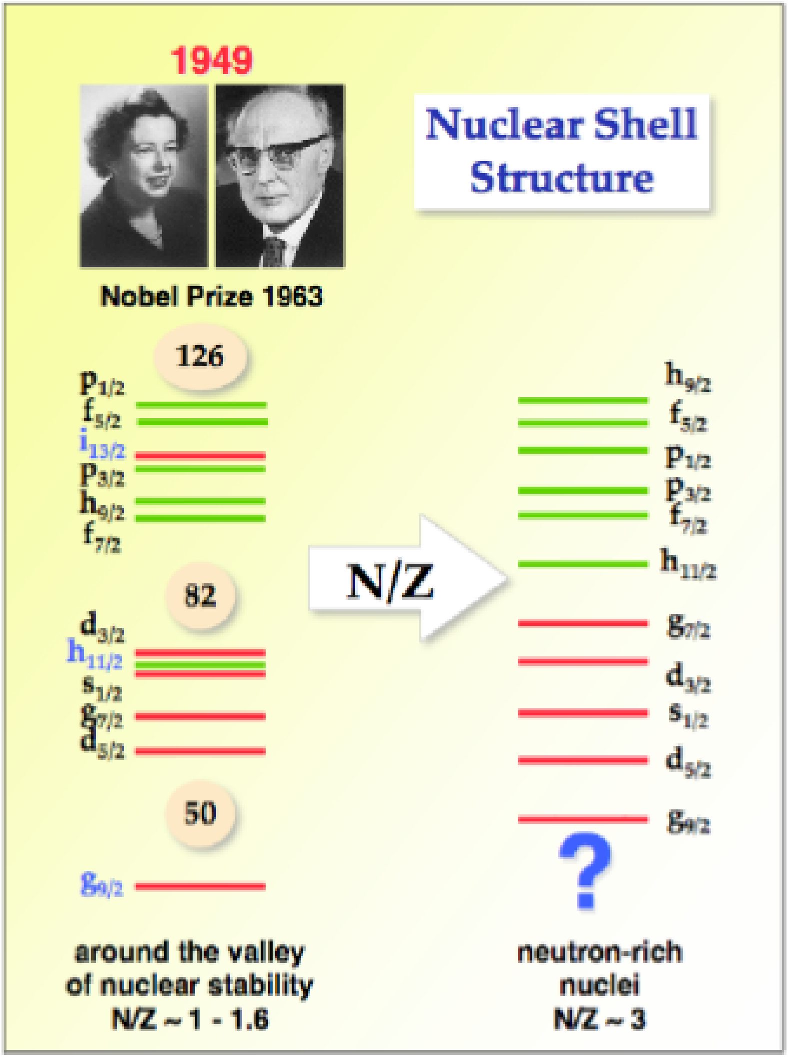
One of the most important effects of the valence p-n interaction is in shifting single particle level energies

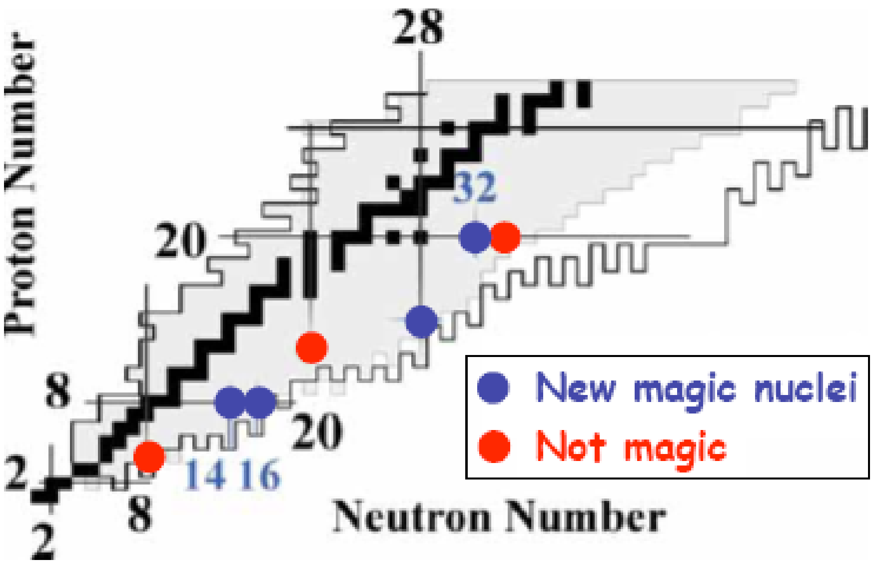


Monopole shift of proton s.p.e. with neutron number. **Tensor interactions.**

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



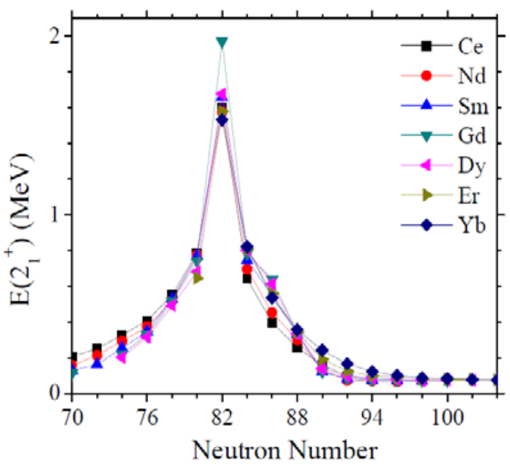


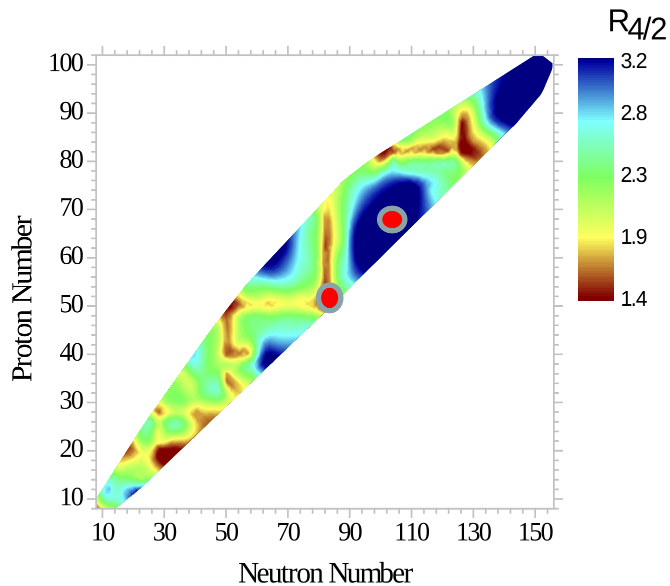
No shell closure for N=8 and 20 for drip-line nuclei; new shells at 14, 16, 32...

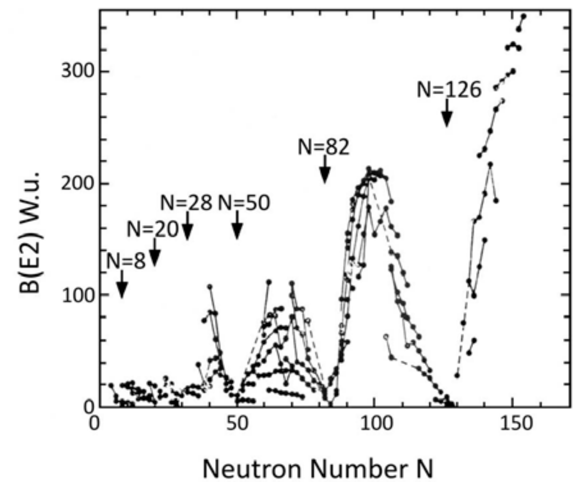
Estimating the properties of nuclei

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 mutliplying two small integers.

Lets 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

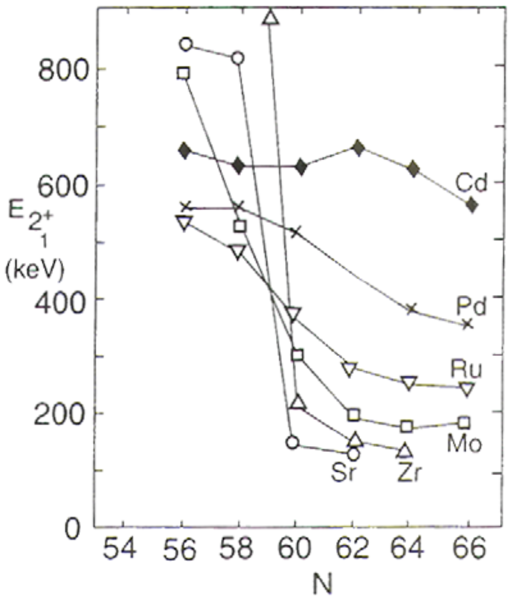
How many valence p-n interactions are there? N_p x N_n. If all are equal then integrated p-n strength should scale with N_pN_n

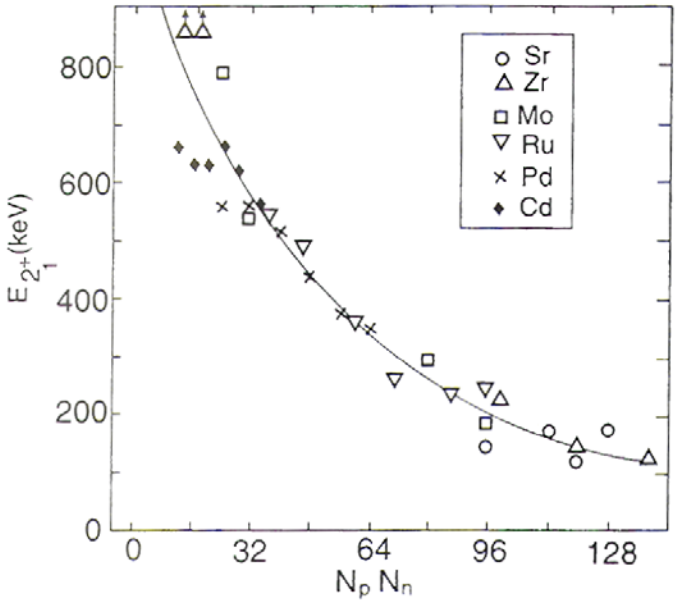
The N_pN_n Scheme

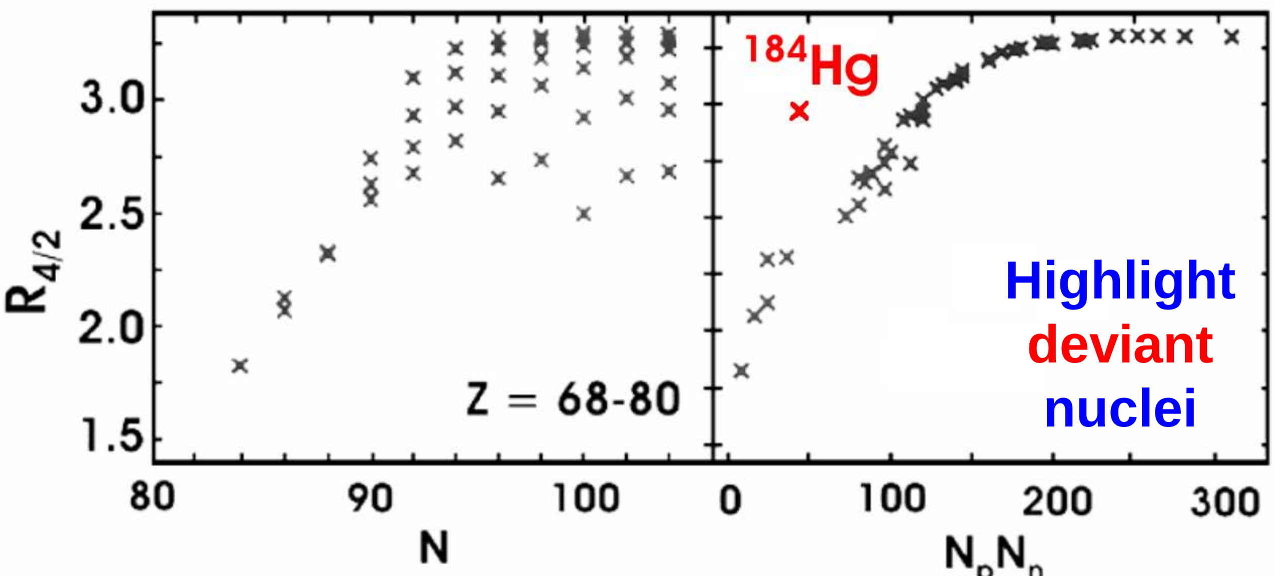
Valence Proton-Neutron Interactions

Correlations, collectivity, deformation. Sensitive to magic numbers.

N_pN_n Scheme

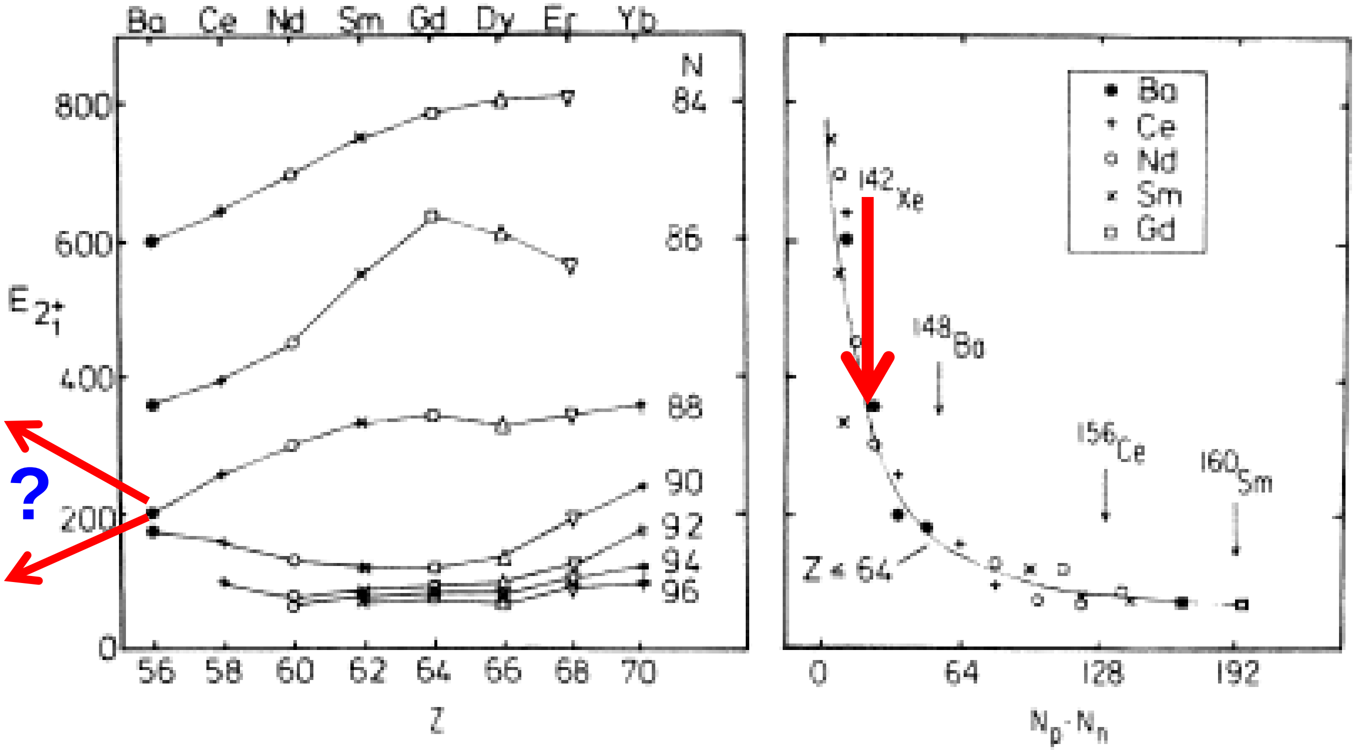






Highlight
deviant
nuclei

The N_pN_n scheme: Interpolation vs. Extrapolation



^{142}Xe (54,88) ?

$N_p N_p = 4 \times 6 = 24$

- ^{156}Te (52, 104) ^{156}Gd (64, 92) ^{184}Pt (78, 106).
- N_pN_n : 2x22 = 44 14x10 = 140 4x20 = 80

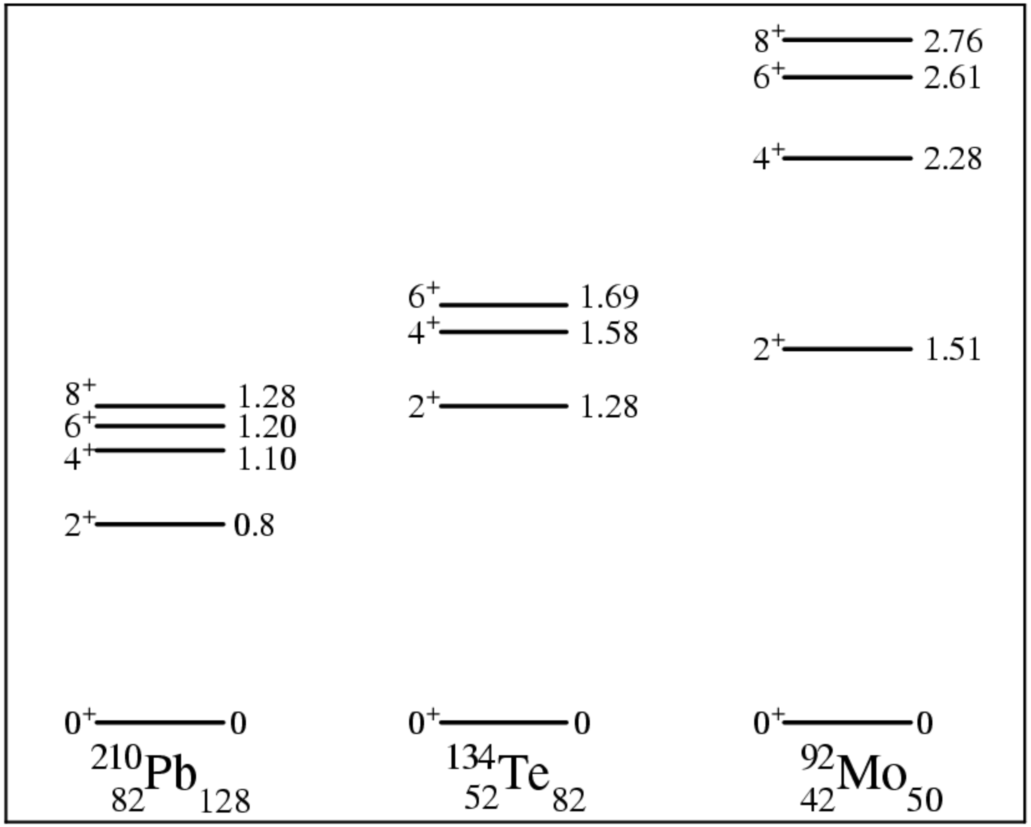
Competition of p-n interaction with pairing: simple estimate of evolution of structure with N and Z

p-n / pairing

$$P = \frac{N_p N_n}{N_p + N_n} \sim \frac{p-n}{pairing}$$

p-n interactions per pairing interaction

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



Competition of p-n interaction with pairing: simple estimate of evolution of structure with N and Z

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p-n interactions per pairing interaction

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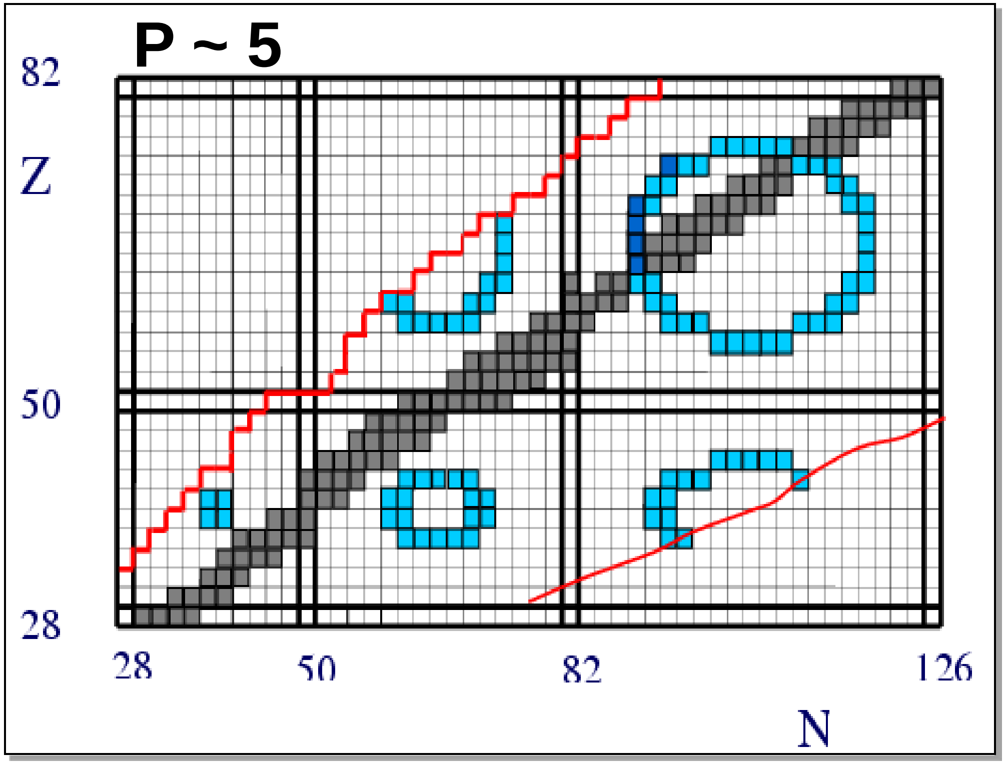
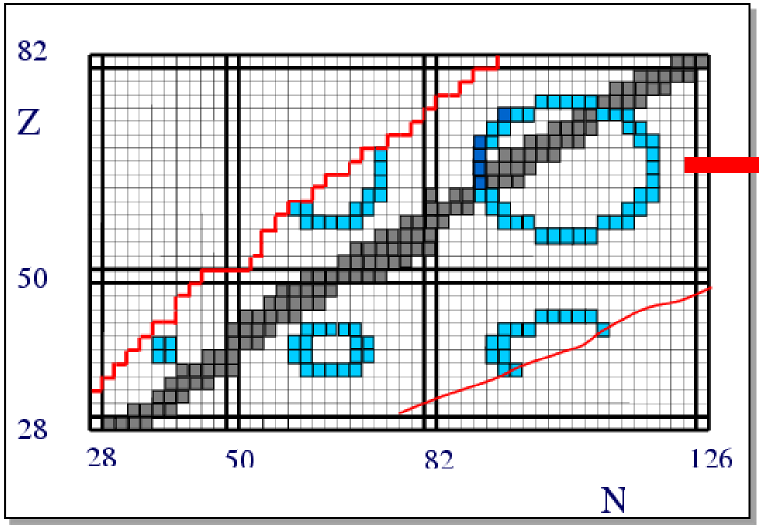
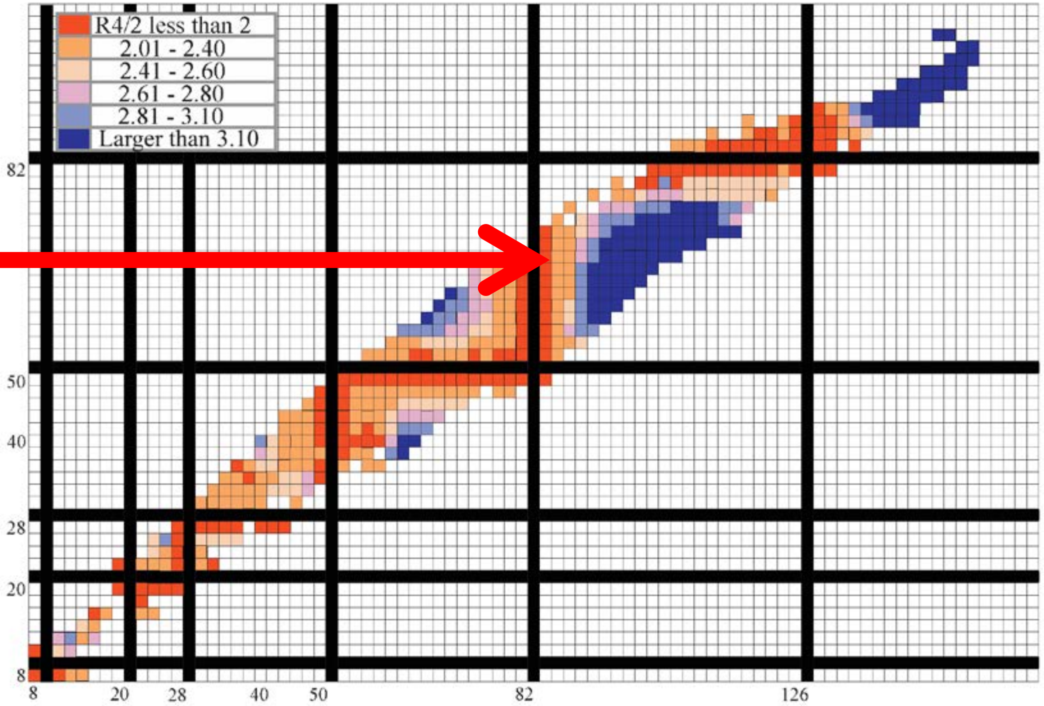
Hence takes ~ 5 p-n int. to compete with one pairing int.



McCutchan and Zamfir

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

Macro

Micro

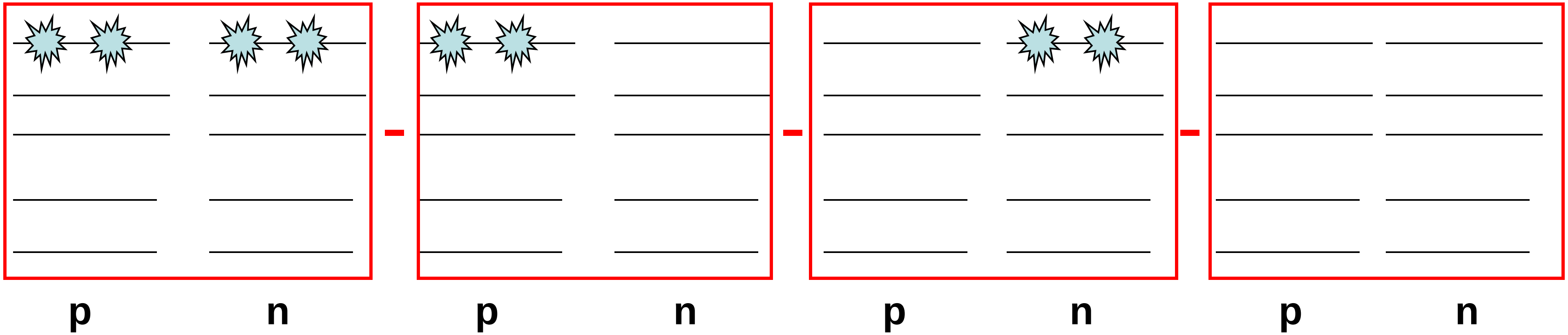
- Shell structure: ~ 1 MeV
- Quantum phase transitions: ~ 100s keV
- Collective effects: ~ 100s keV
- Interaction filters (e.g., p-n) ~ 10-15 keV
- Fundamental Interactions < 1 keV

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

$$\delta V_{pn}(Z,N) =$$

$$-\tfrac{1}{4}\,[\,\{B(Z,N) \;-\; B(Z,N-2)\} \;-\; \{B(Z-2,N) \;-\; B(Z-2,N-2)\}\,]$$



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

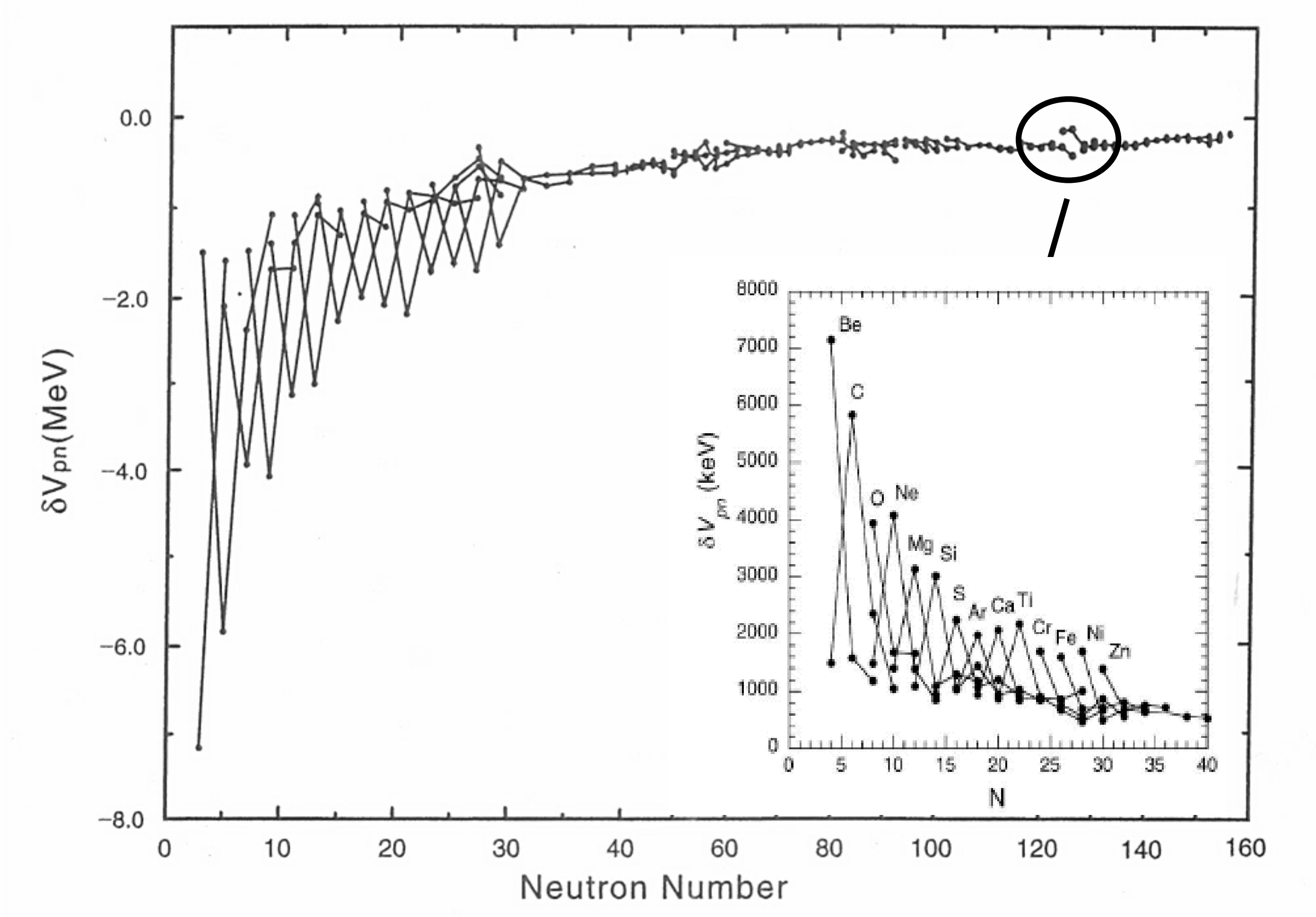
–

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

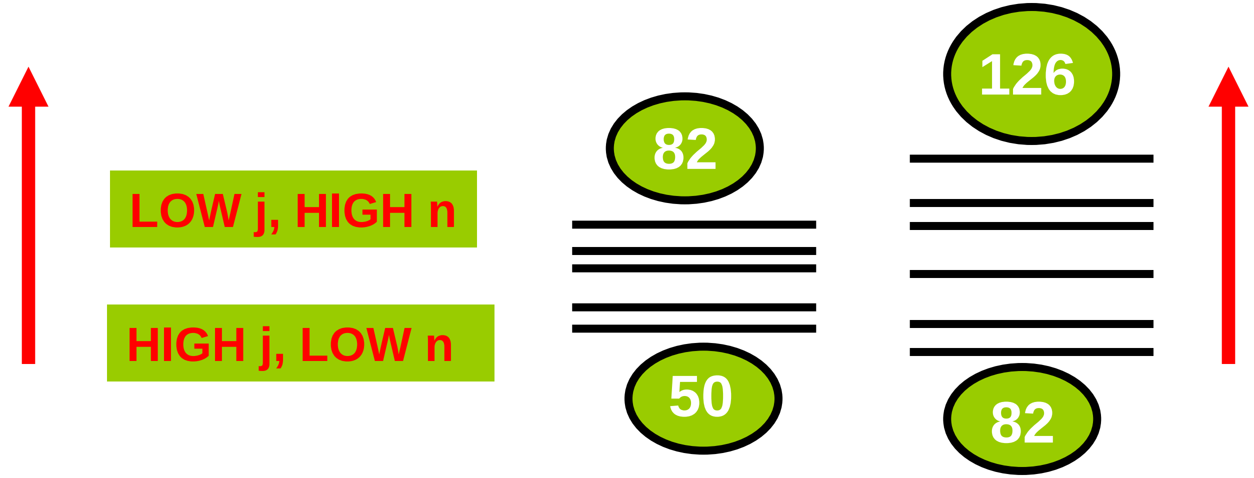
Empirical interactions of the last proton with the last neutron

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

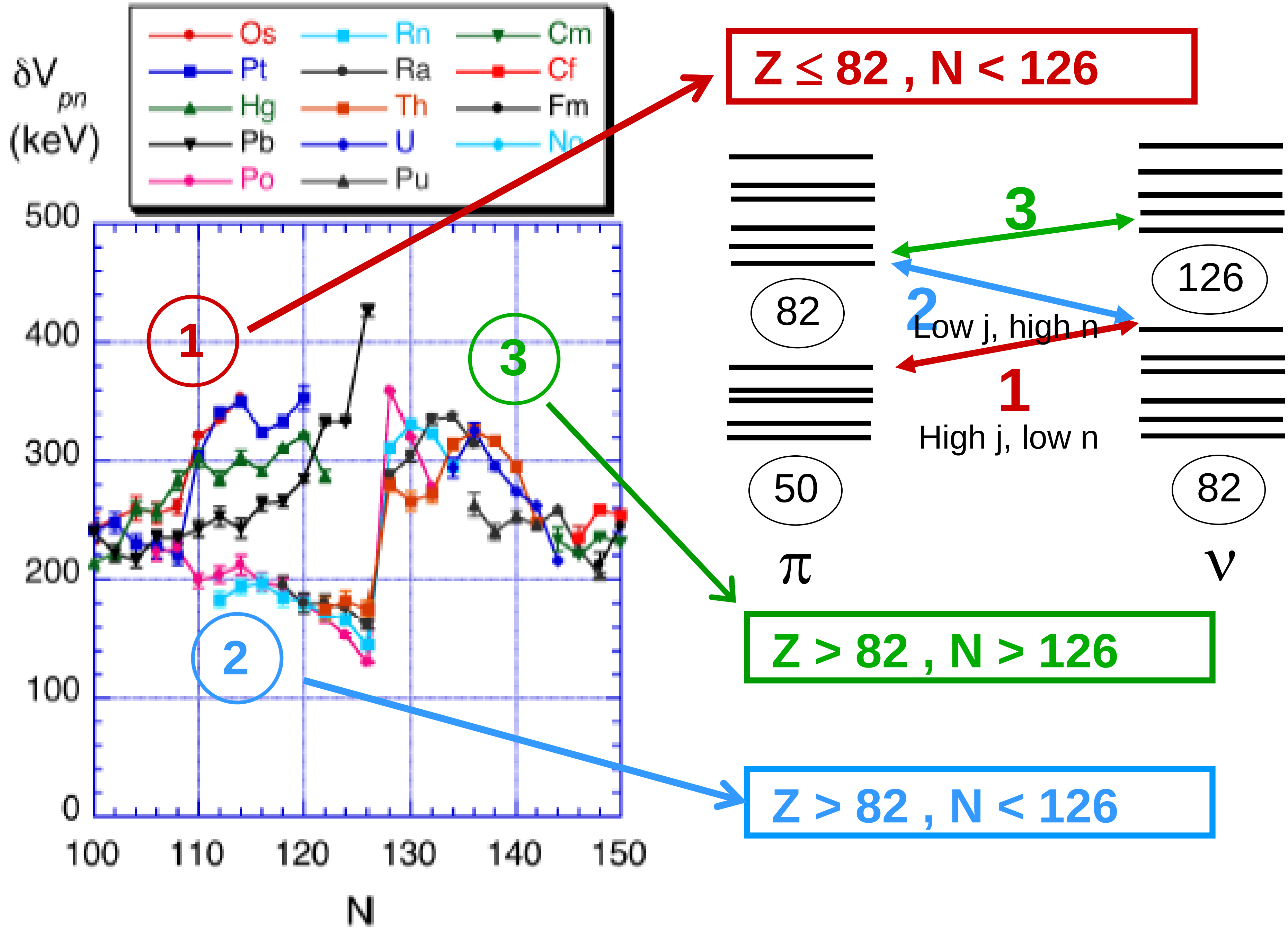


In terms of proton and neutron orbit filling, p-n interaction

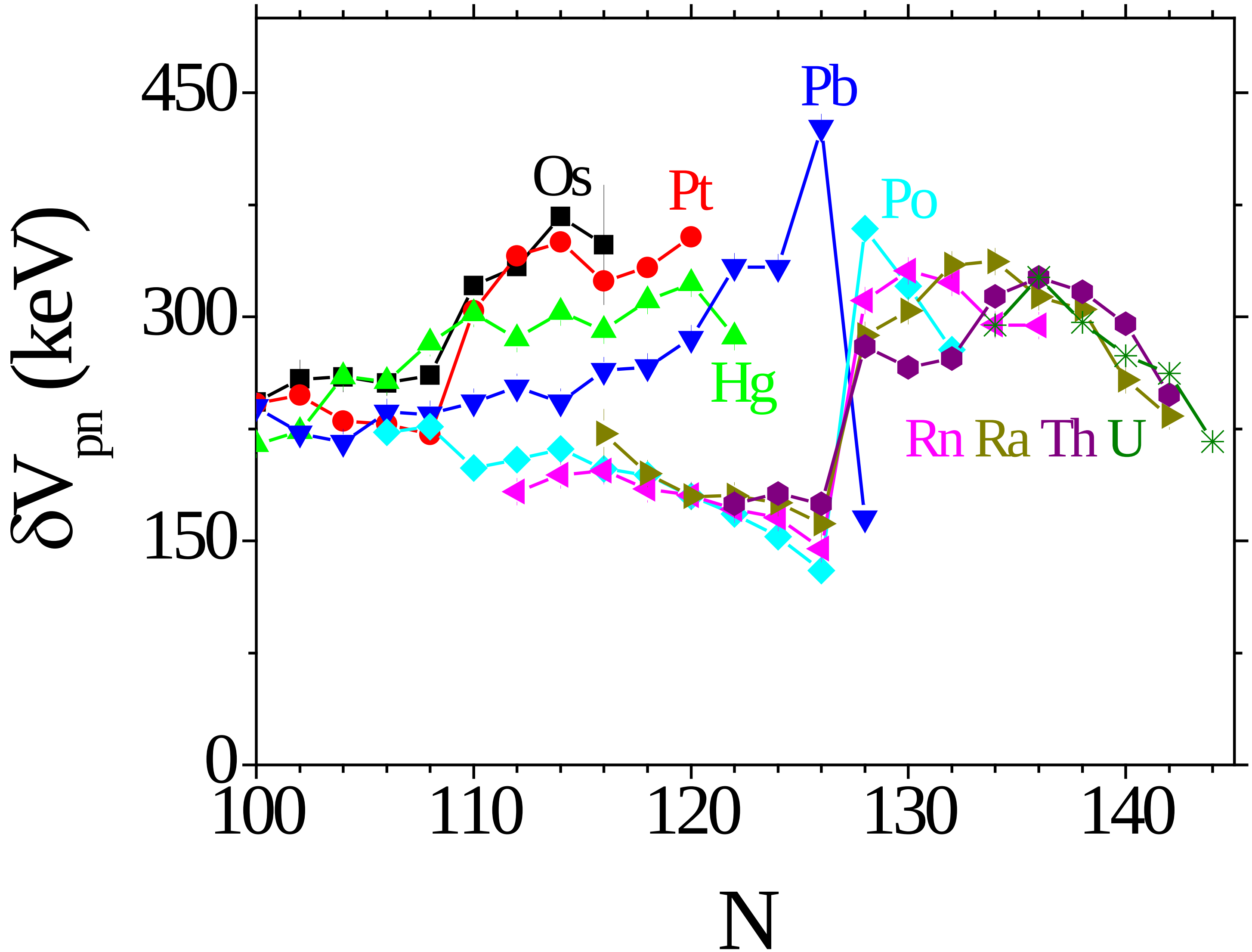
p-n interaction is short range
similar orbits give largest p-n interaction



Largest p-n interactions if proton and neutron shells are filling similar orbits



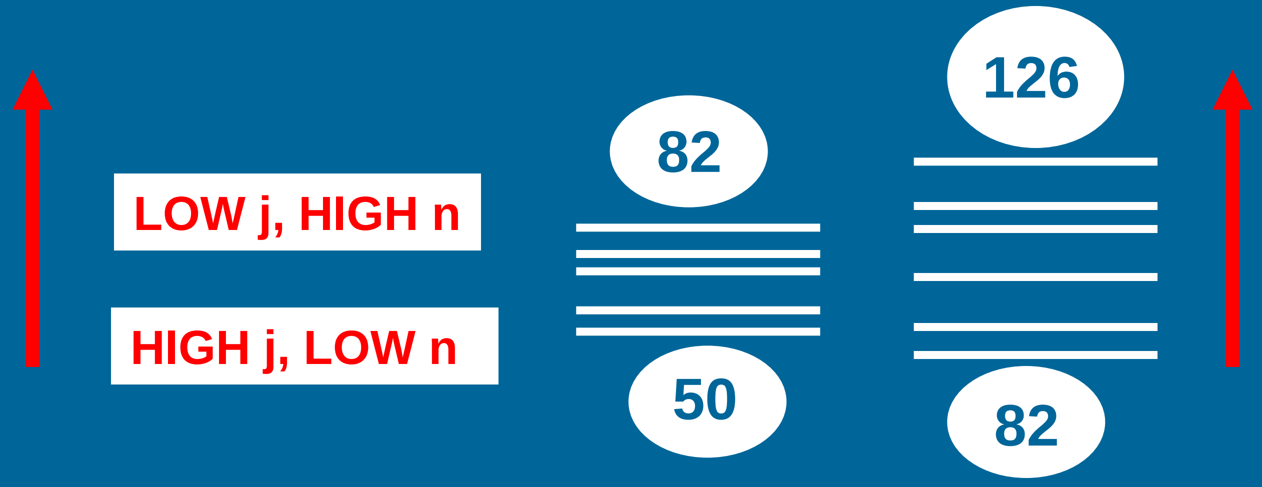
δV_pn (keV)
Os
Pt
Hg
Pb
Po
Rn
Ra
Th
U
Pu
Cm
Cf
Fm
No
500
400
300
200
100
0
100
110
120
130
140
150
N
1
2
3
Z ≤ 82 , N < 126
Z > 82 , N > 126
Z > 82 , N < 126
82
50
126
82
π
ν
3
2
Low j, high n
1
High j, low n



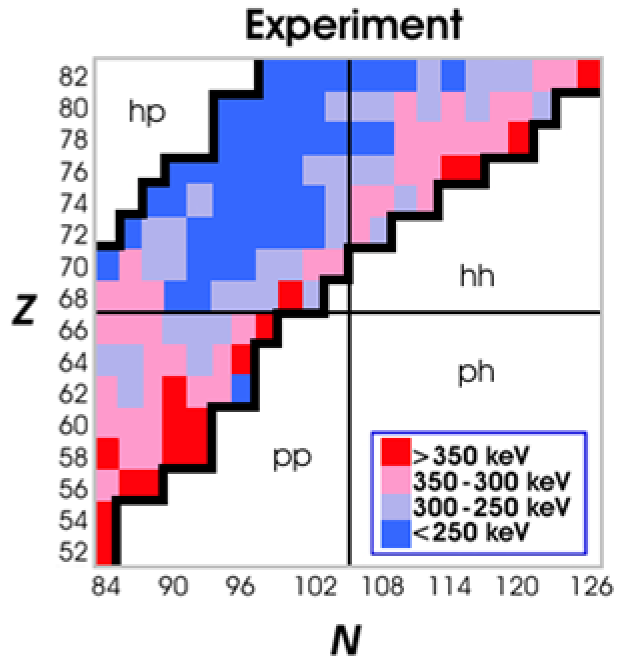
δV_pn (keV)
450
300
150
0
100
110
120
130
140
N
Os
Pt
Hg
Pb
Po
Rn
Ra
Th
U

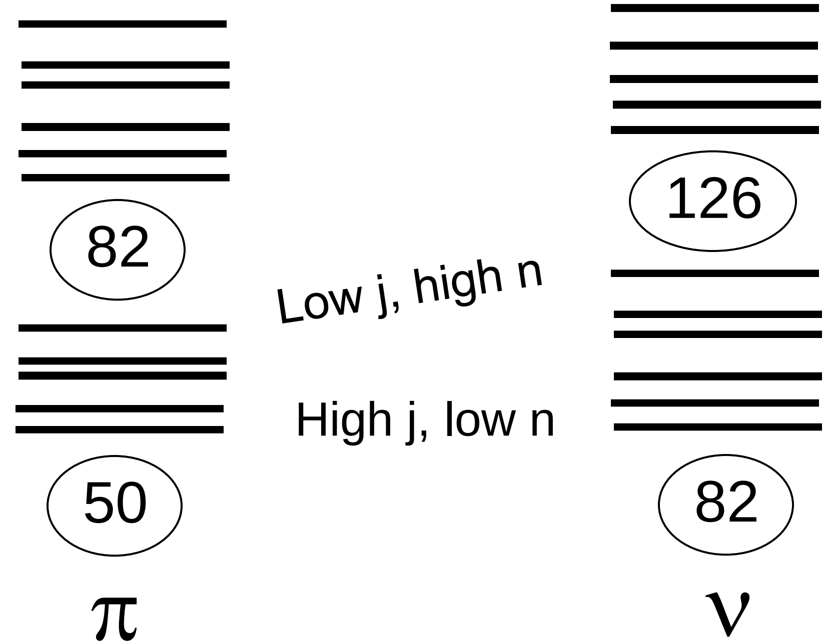
Away from closed shells, these simple arguments are too crude. But some general predictions can be made

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



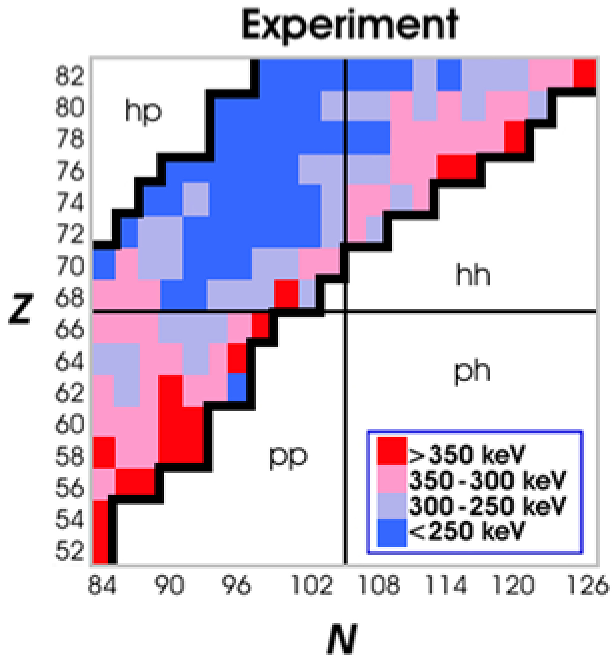
Largest p-n interactions if proton and neutron shells are filling similar orbits

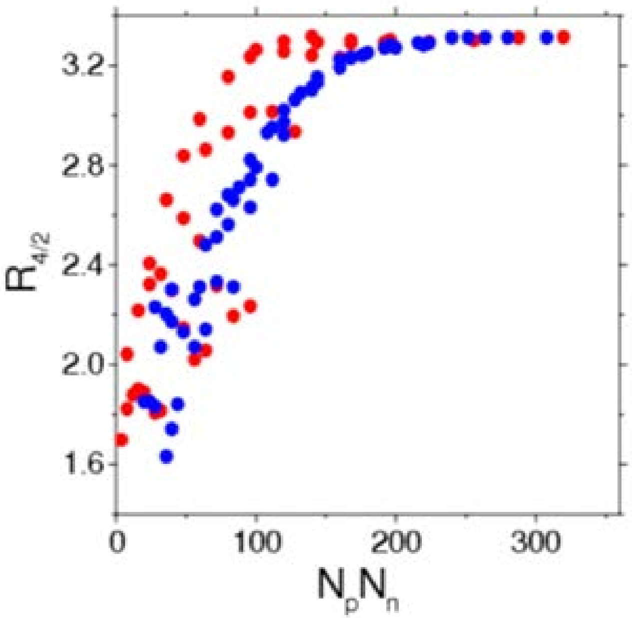




Empirical p-n interaction strengths stronger in like regions than unlike regions.

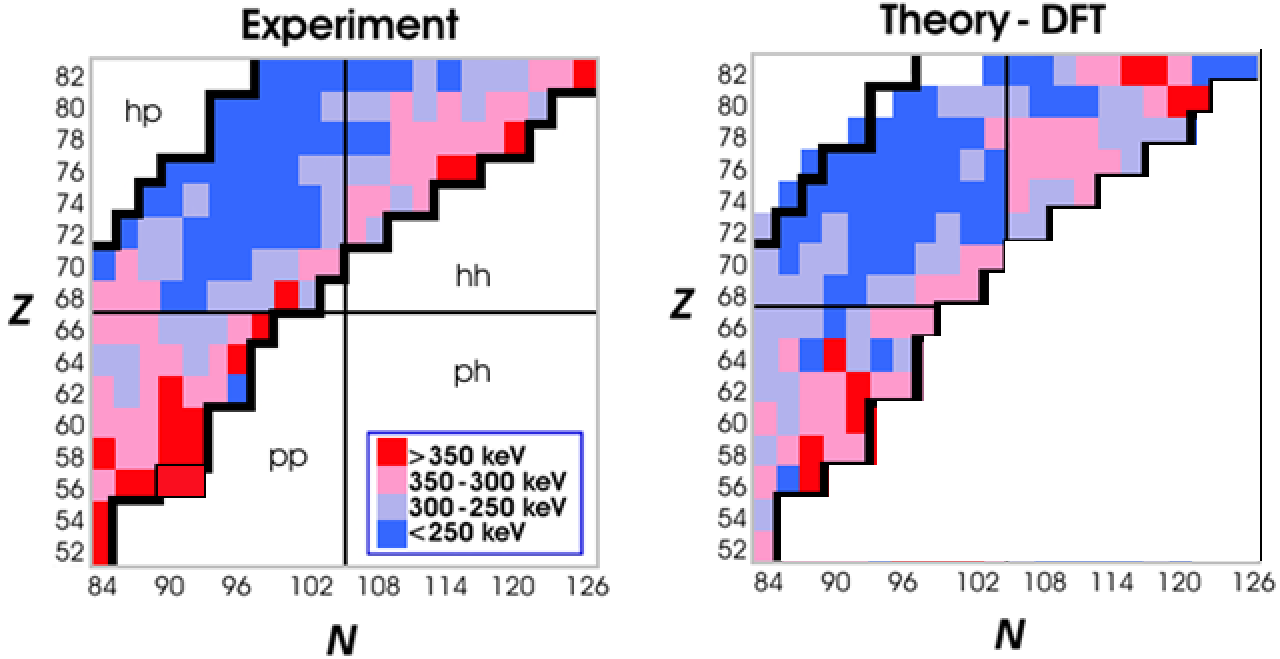
Empirical p-n interaction strengths indeed strongest along diagonal.





p-n interactions and the evolution of structure

Direct correlation of observed growth rates of collectivity with empirical p-n interaction strengths

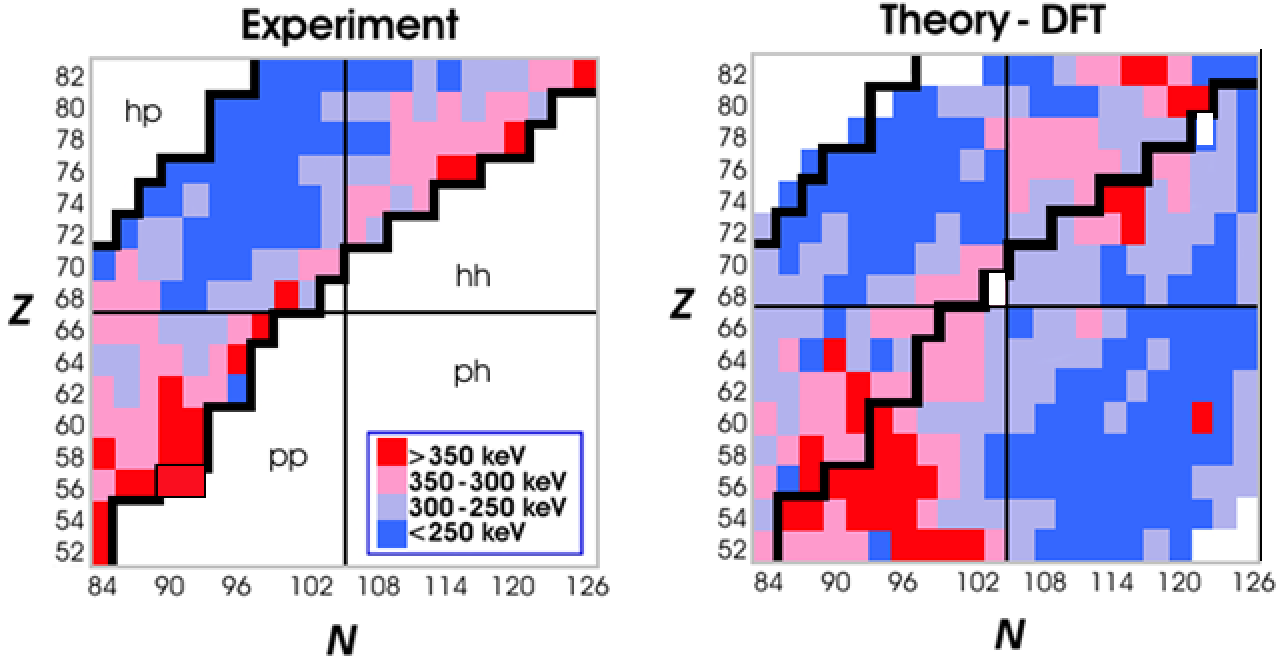


Comparison of empirical p-n interactions with the DFT

These DFT calculations accurate only to ~ 1 MeV.
δVpn allows one to focus on specific correlations.

New measurements at ISOLTRAP/ISOLDE test DFT

M. Stoitsov, R. B. Cakirli, R. F. Casten, W. Nazarewicz, and W. Satula PRL 98, 132502 (2007);
D. Neidherr et al, Phys. Rev. **C 80**, 044323 (2009)



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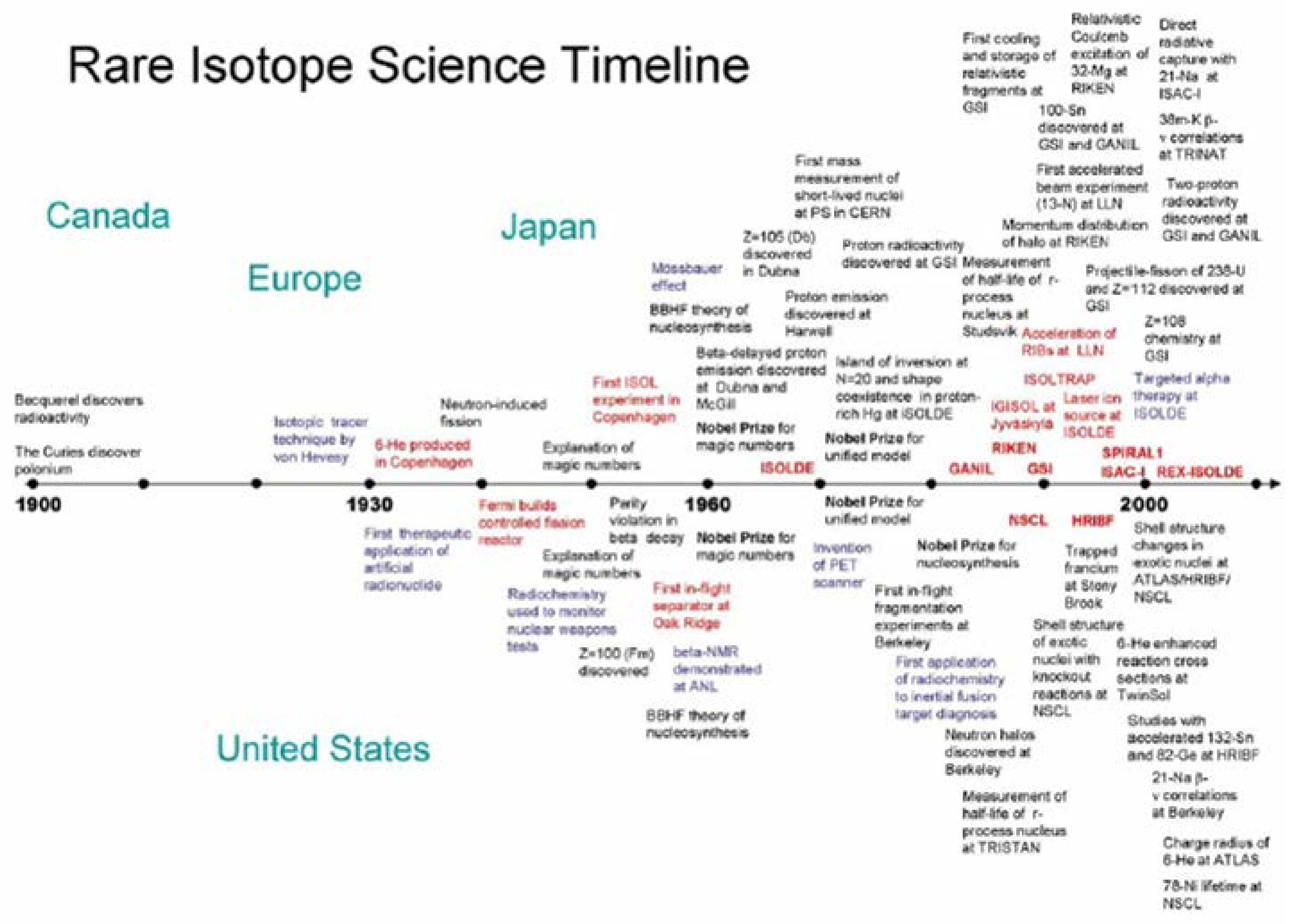
Exotic Nuclei

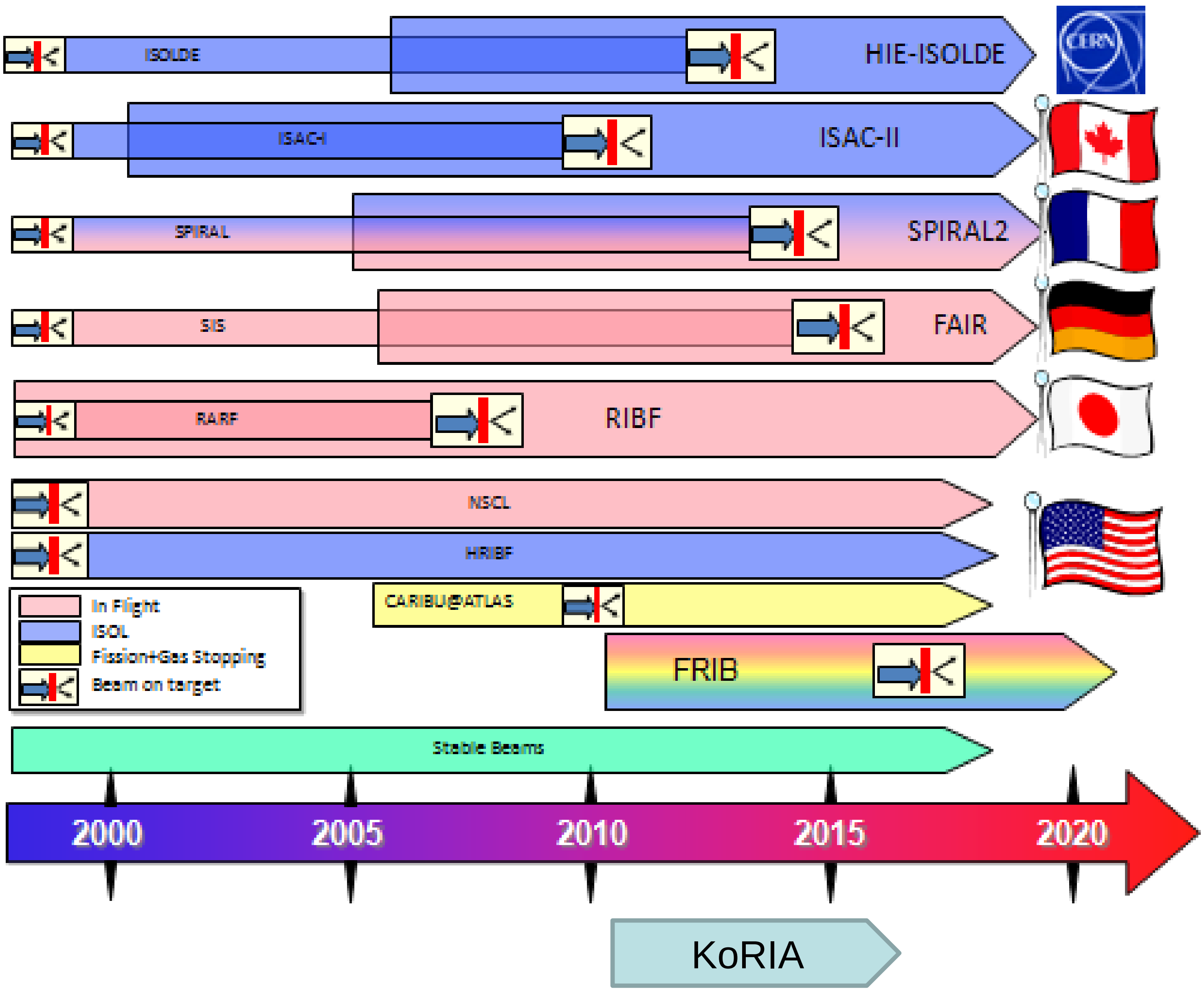
A new era in nuclear structure, reaction, and astrophysics

Science, Production, Recent results, and Facilities


Rare Isotope Science Timeline
Canada
Europe
Japan
United States
1900
1930
1960
2000
Becquerel discovers radioactivity
The Curies discover polonium
Isotopic tracer technique by von Hevesy
6-He produced in Copenhagen
Neutron-induced fission
Explanation of magic numbers
First ISOL experiment in Copenhagen
Mössbauer effect
BBHF theory of nucleosynthesis
Beta-delayed proton emission discovered at Dubna and McGill
Nobel Prize for magic numbers
Z=105 (Db) discovered in Dubna
Proton emission discovered at Harwell
ISOLDE
First mass measurement of short-lived nuclei at PS in CERN
Proton radioactivity discovered at GSI
Island of inversion at N=20 and shape coexistence in proton-rich Hg at ISOLDE
Nobel Prize for unified model
GANIL
Measurement of half-life of r-process nucleus at Studsvik
Acceleration of RIBs at LLN
IGISOL at Jyväskylä
RIKEN
ISOLTRAP
Laser ion source at ISOLDE
GSI
First cooling and storage of relativistic fragments at GSI
Relativistic Coulomb excitation of 32-Mg at RIKEN
100-Sn discovered at GSI and GANIL
First accelerated beam experiment (13-N) at LLN
Momentum distribution of halo at RIKEN
Projectile-fission of 238-U and Z=112 discovered at GSI
Z=108 chemistry at GSI
Targeted alpha therapy at ISOLDE
SPIRAL 1
ISAC-I
REX-ISOLDE
Direct radiative capture with 21-Na at ISAC-I
38m-K β-ν correlations at TRINAT
Two-proton radioactivity discovered at GSI and GANIL
First therapeutic application of artificial radionuclide
Fermi builds controlled fission reactor
Parity violation in beta decay
Explanation of magic numbers
Radiochemistry used to monitor nuclear weapons tests
Z=100 (Fm) discovered
First in-flight separator at Oak Ridge
beta-NMR demonstrated at ANL
BBHF theory of nucleosynthesis
Nobel Prize for magic numbers
Nobel Prize for unified model
Invention of PET scanner
Nobel Prize for nucleosynthesis
First in-flight fragmentation experiments at Berkeley
First application of radiochemistry to inertial fusion target diagnosis
Neutron halos discovered at Berkeley
Measurement of half-life of r-process nucleus at TRISTAN
NSCL
HRIBF
Trapped francium at Stony Brook
Shell structure of exotic nuclei with knockout reactions at NSCL
6-He enhanced reaction cross sections at TwinSol
Shell structure changes in exotic nuclei at ATLAS/HRIBF/NSCL
Studies with accelerated 132-Sn and 82-Ge at HRIBF
21-Na β-ν correlations at Berkeley
Charge radius of 6-He at ATLAS
78-Ni lifetime at NSCL

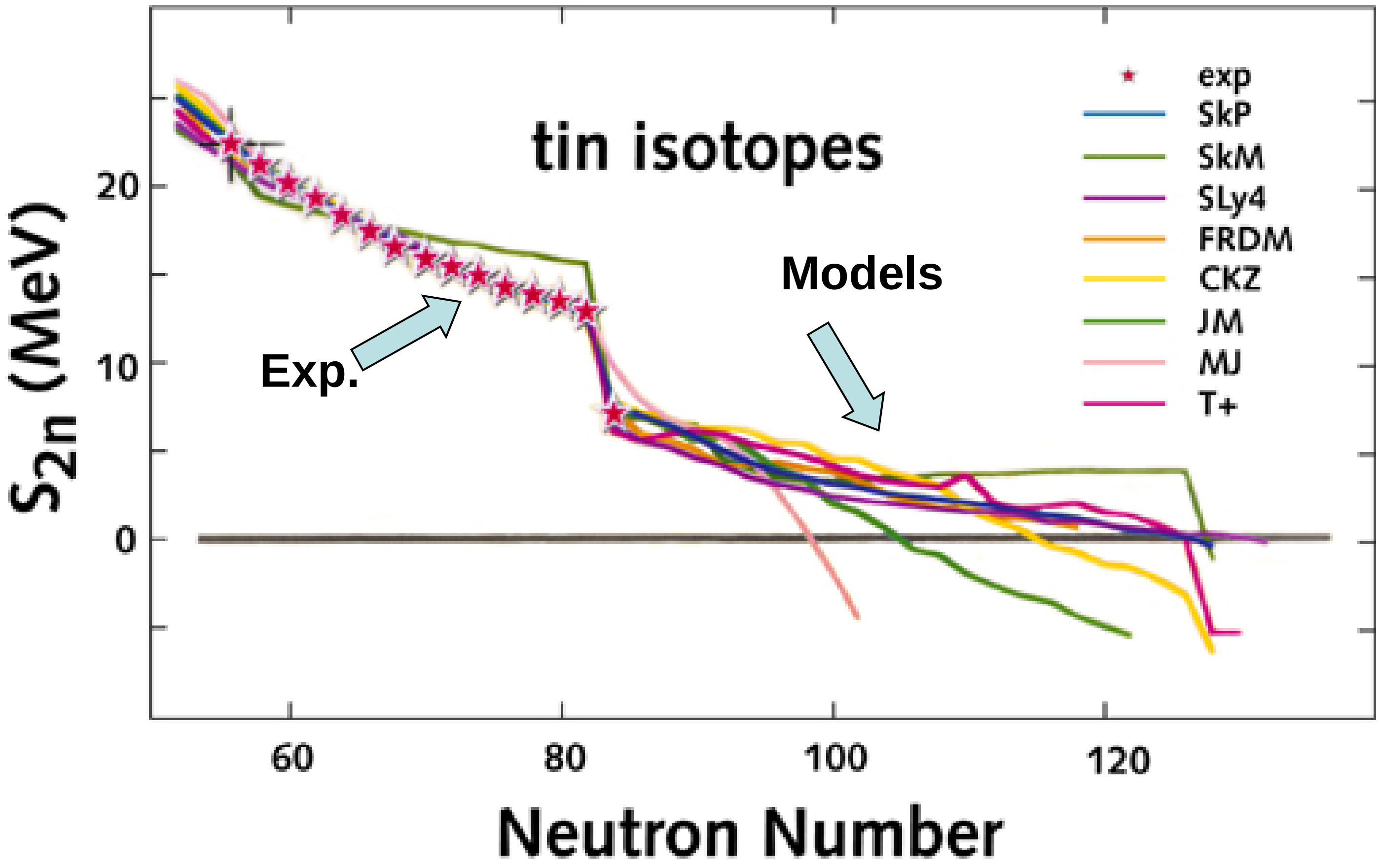
Major Exotic Beam Facilities Worldwide

A field that is energized worldwide



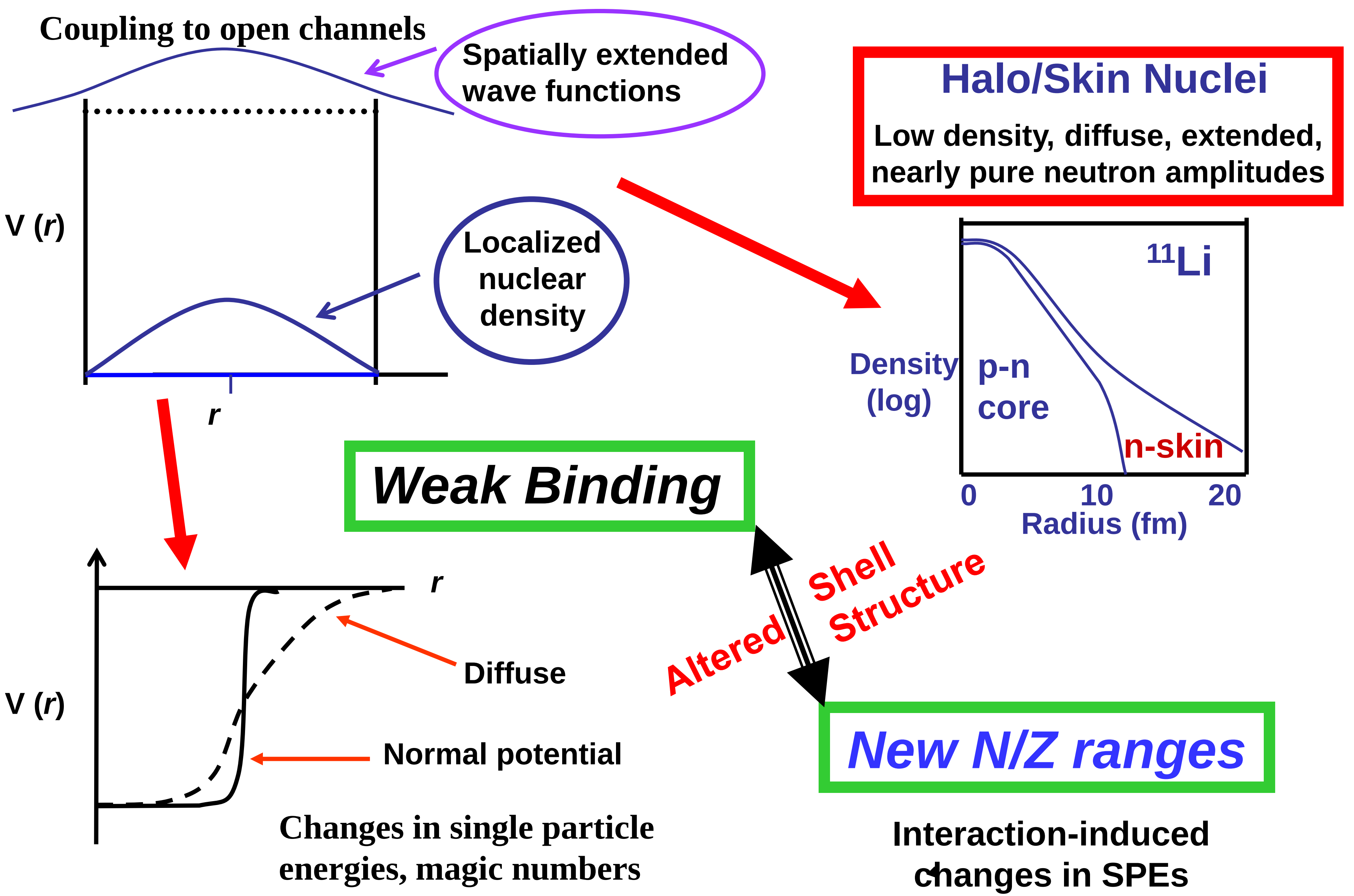
Some themes in the science of exotic nuclei

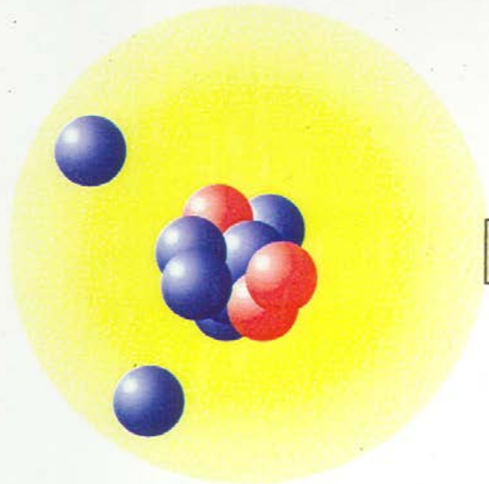
Physics of exotic, weakly bound nuclei



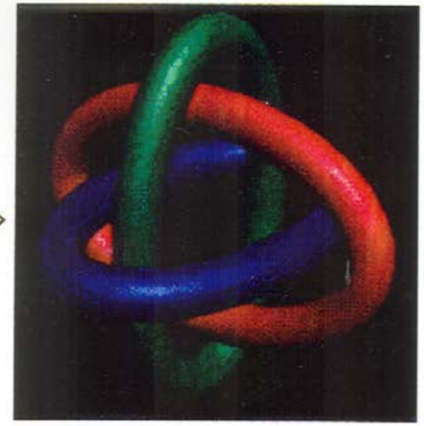
The ultimate goal of the physics of nuclei is to develop a unified, predictive theory of nucleonic matter

New Features in Exotic Nuclei



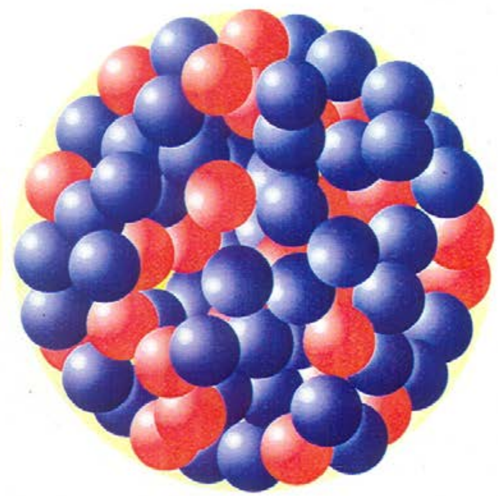


^{11}Li: Borromean Halo Nucleus



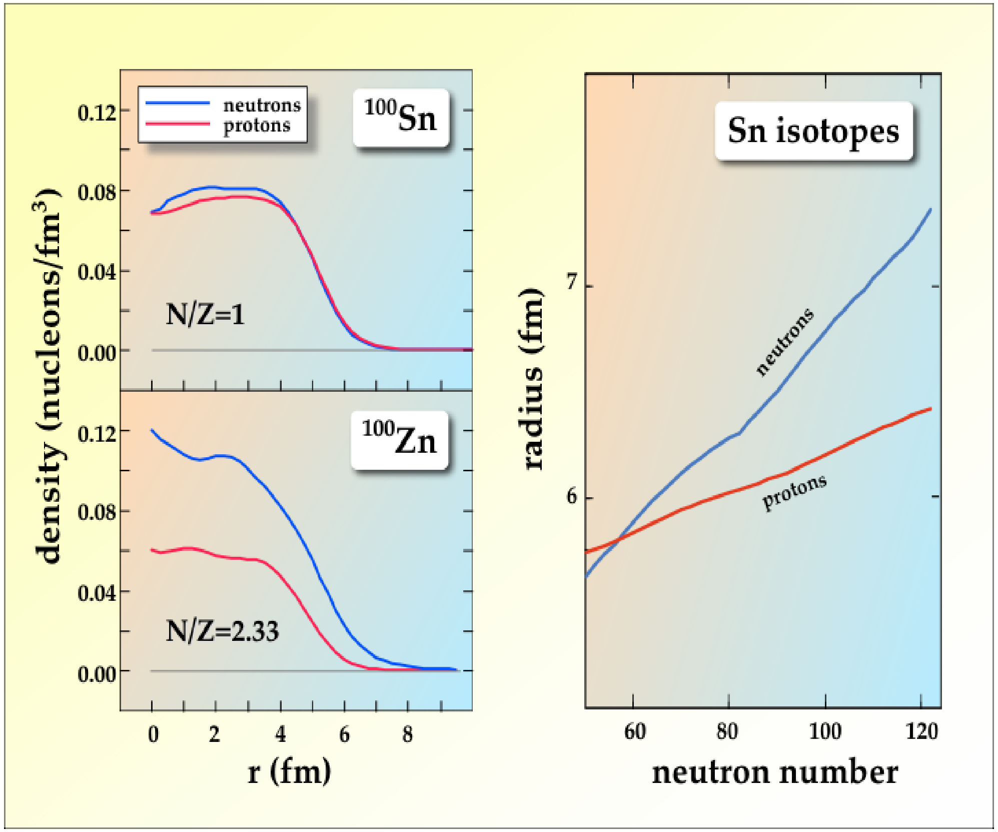
The Borromean Rings

^{19}C: The Heaviest Known Halo Nucleus

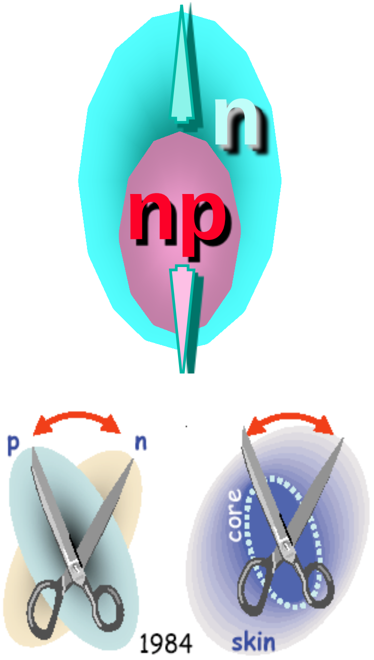


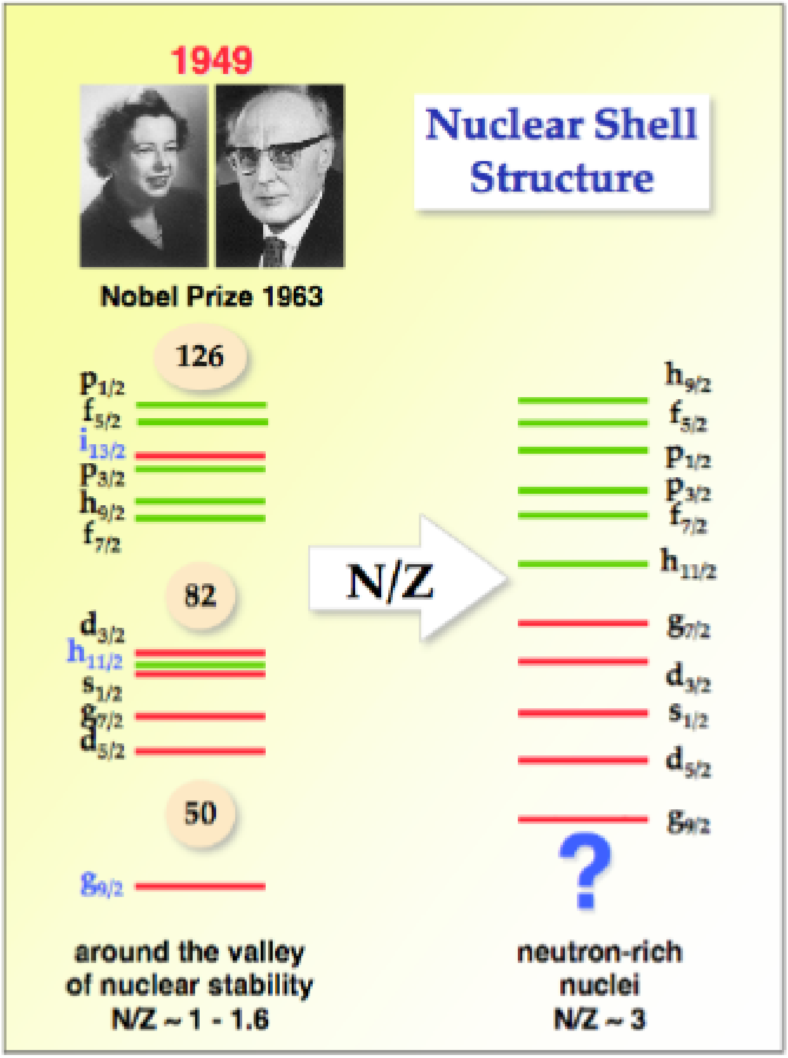
^{208}Pb: Well Bound Heavy Nucleus

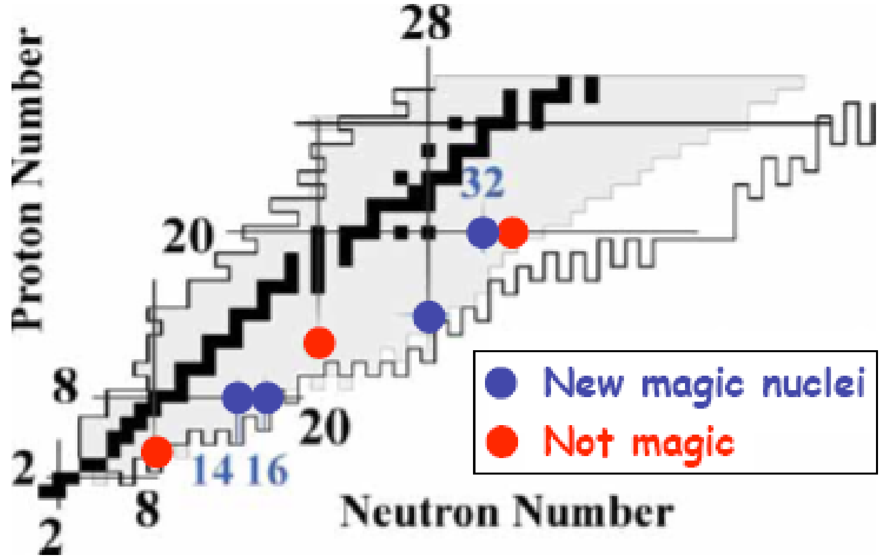
Neutron "skins" near the neutron drip line

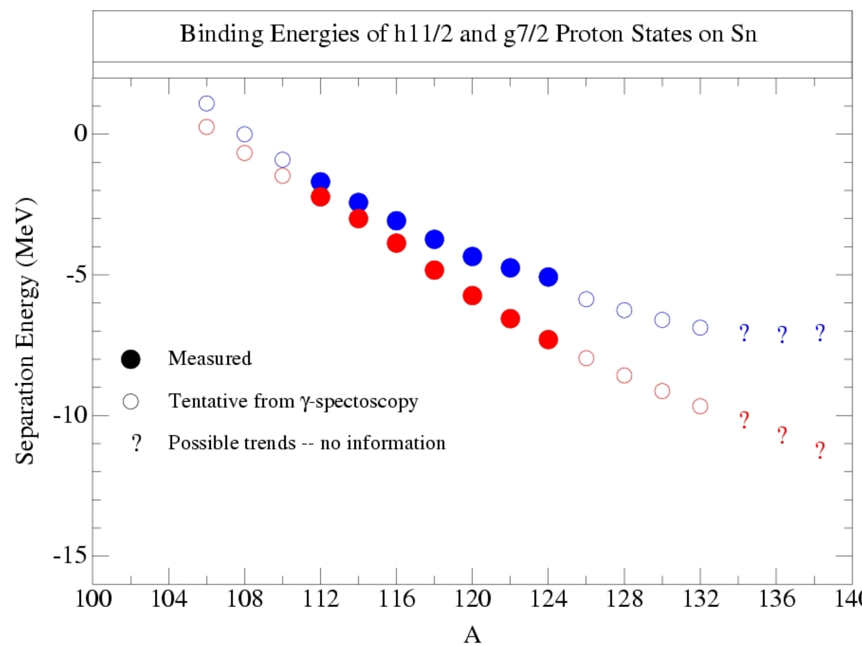


Skins and Skin Modes




1949
Nuclear Shell Structure
Nobel Prize 1963
126
p1/2
f5/2
i13/2
p3/2
h9/2
f7/2
82
d3/2
h11/2
s1/2
g7/2
d5/2
50
g9/2
N/Z
h9/2
f5/2
p1/2
p3/2
f7/2
h11/2
g7/2
d3/2
s1/2
d5/2
g9/2
?
around the valley
of nuclear stability
N/Z ~ 1 - 1.6
neutron-rich
nuclei
N/Z ~ 3

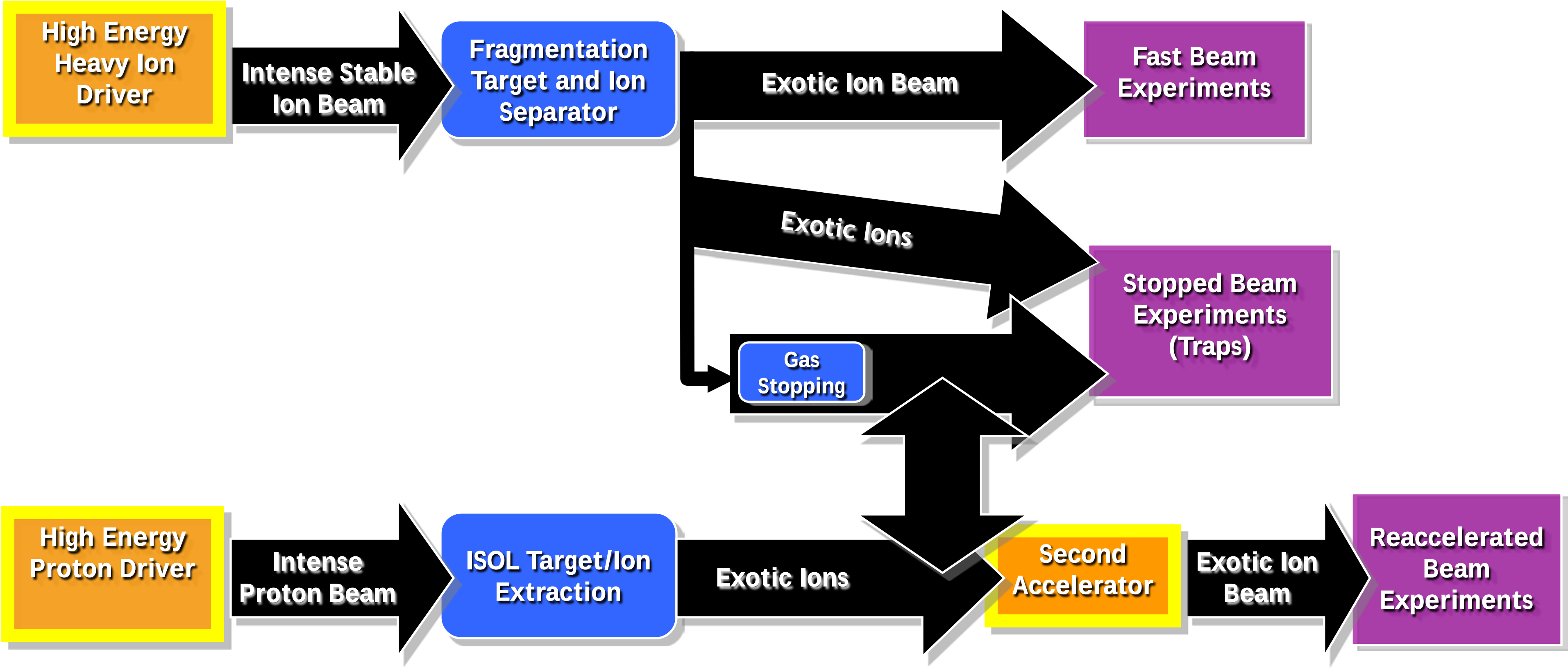

Proton Number
Neutron Number
28
32
20
8
2
2
8
14 16
20
New magic nuclei
Not magic


Binding Energies of h11/2 and g7/2 Proton States on Sn
Separation Energy (MeV)
A
0
-5
-10
-15
100
104
108
112
116
120
124
128
132
136
140
Measured
Tentative from γ-spectoscopy
? Possible trends -- no information

Themes in the new era of Nuclear Structure

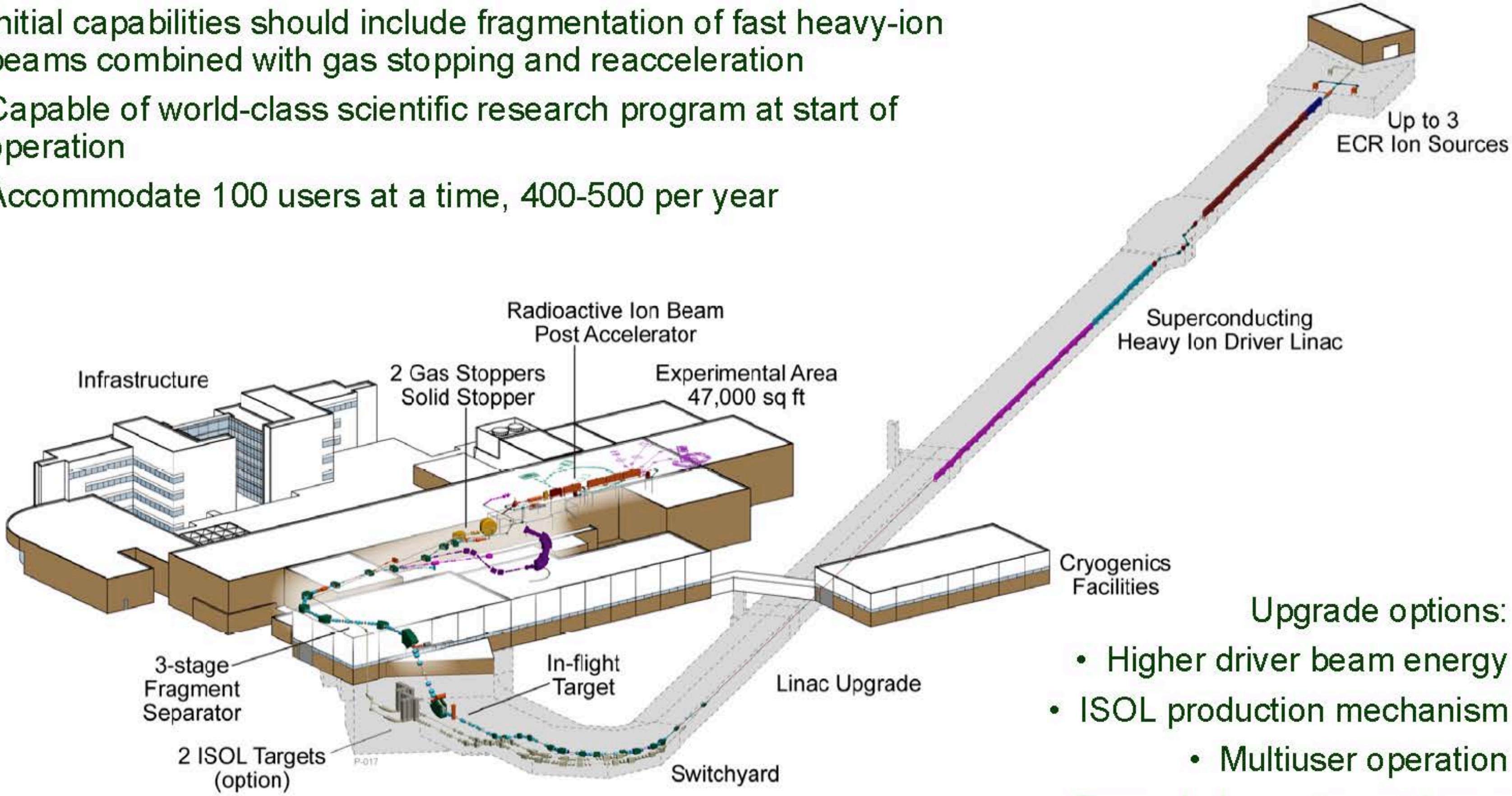
- Changing Shell Structure – The nucleonic foundation of nuclear behavior – changing paradigms after half a century
- Nucleonic interactions – Pairing and p-n: new density regimes and the effects of the continuum.
- The evolution of structure – Symmetries, phase transitions, and critical points in complex 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



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

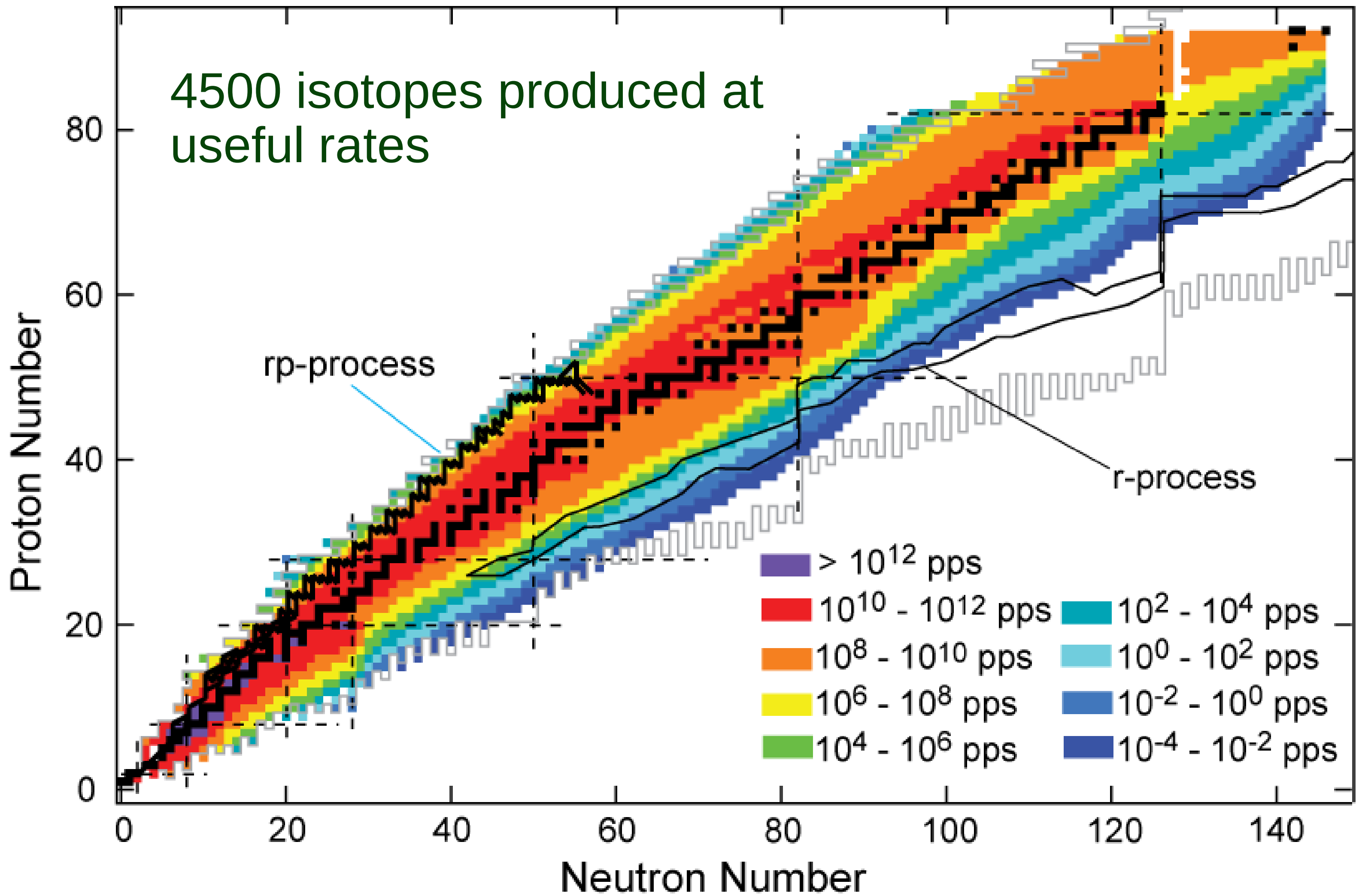


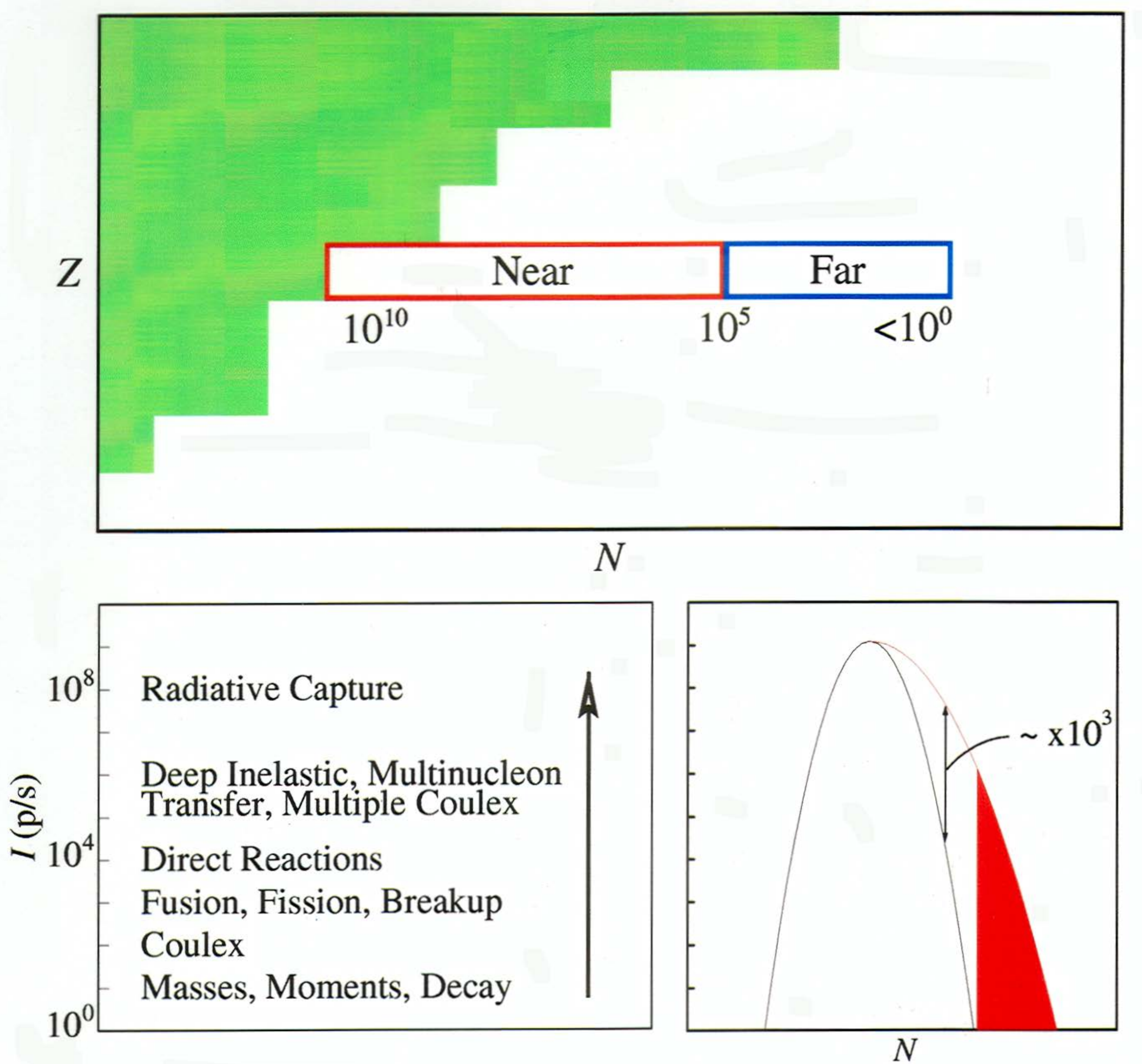
Upgrade options:

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

The Reach of FRIB

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

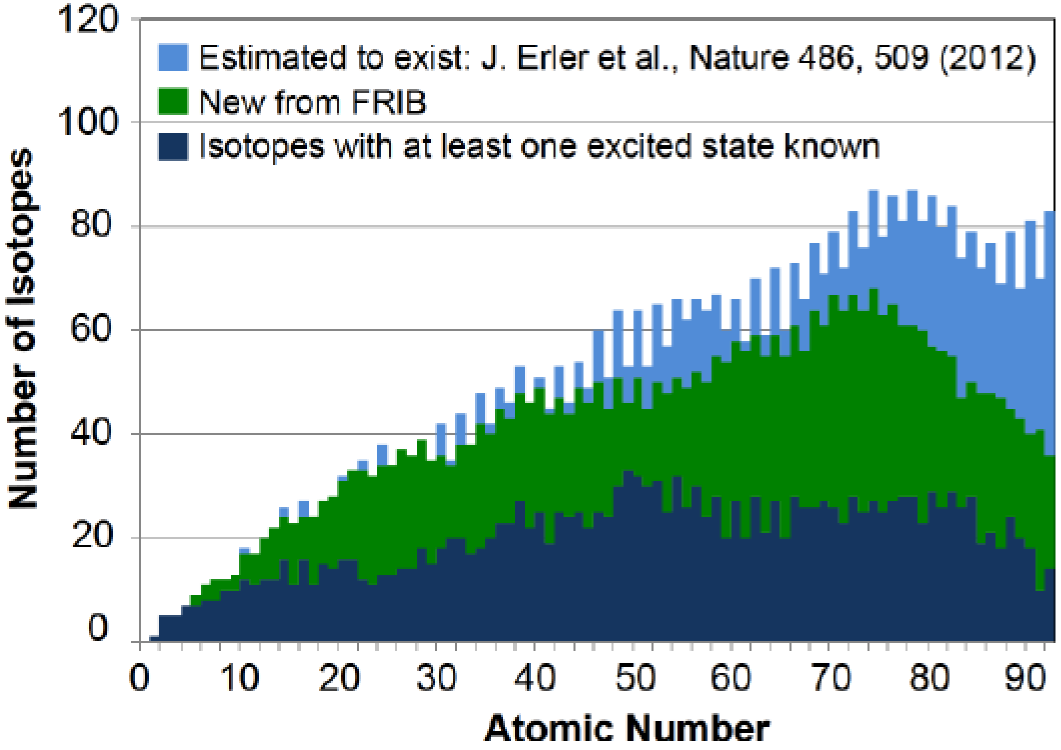



Z
Near
Far
10^10
10^5
<10^0
N
10^8
10^4
10^0
I (p/s)
Radiative Capture
Deep Inelastic, Multinucleon
Transfer, Multiple Coulex
Direct Reactions
Fusion, Fission, Breakup
Coulex
Masses, Moments, Decay
~ x10^3
N

Physics with rare isotopes – Physics vs. Intensity

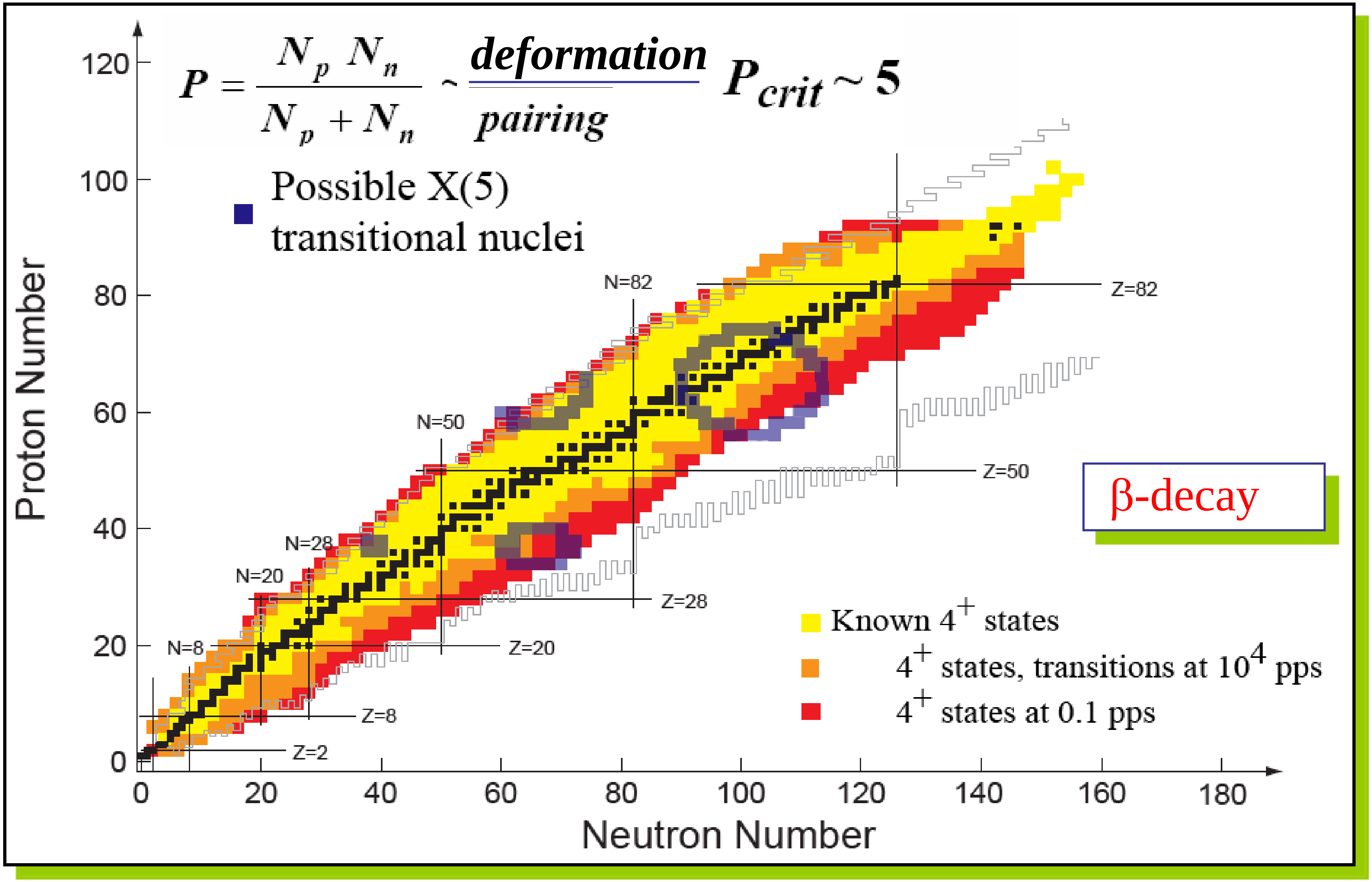
With new technology we can now do experiments with orders of magnitude weaker beams than ever before.

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



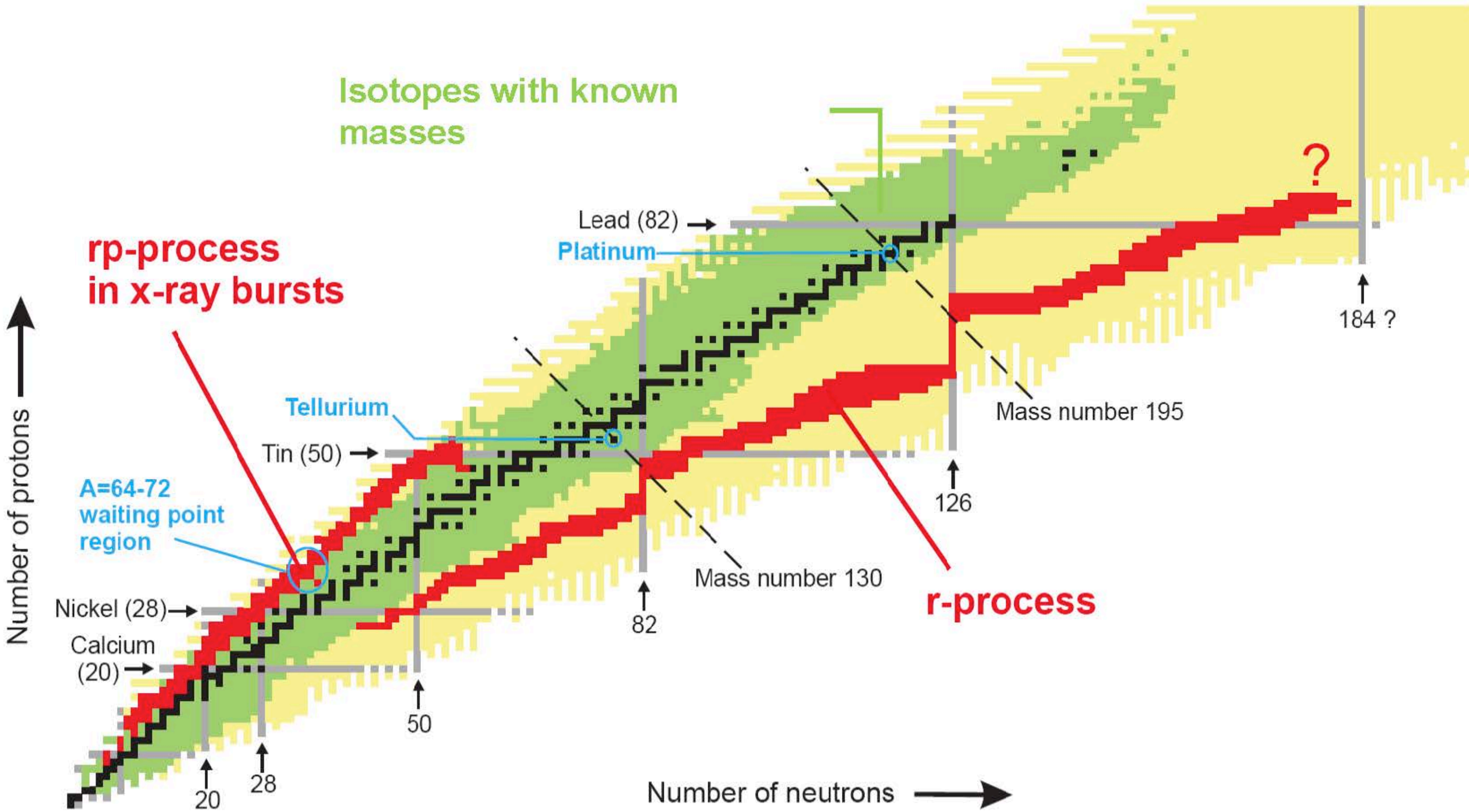
Estimated to exist: J. Erler et al., Nature 486, 509 (2012)
New from FRIB
Isotopes with at least one excited state known
Number of Isotopes
0
20
40
60
80
100
120
Atomic Number
0
10
20
30
40
50
60
70
80
90

Study of symmetry phases



Explosive Nucleo-Synthesis Paths

r and rp-processes



U.S. Department of Energy Office of Science
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Michigan State University

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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