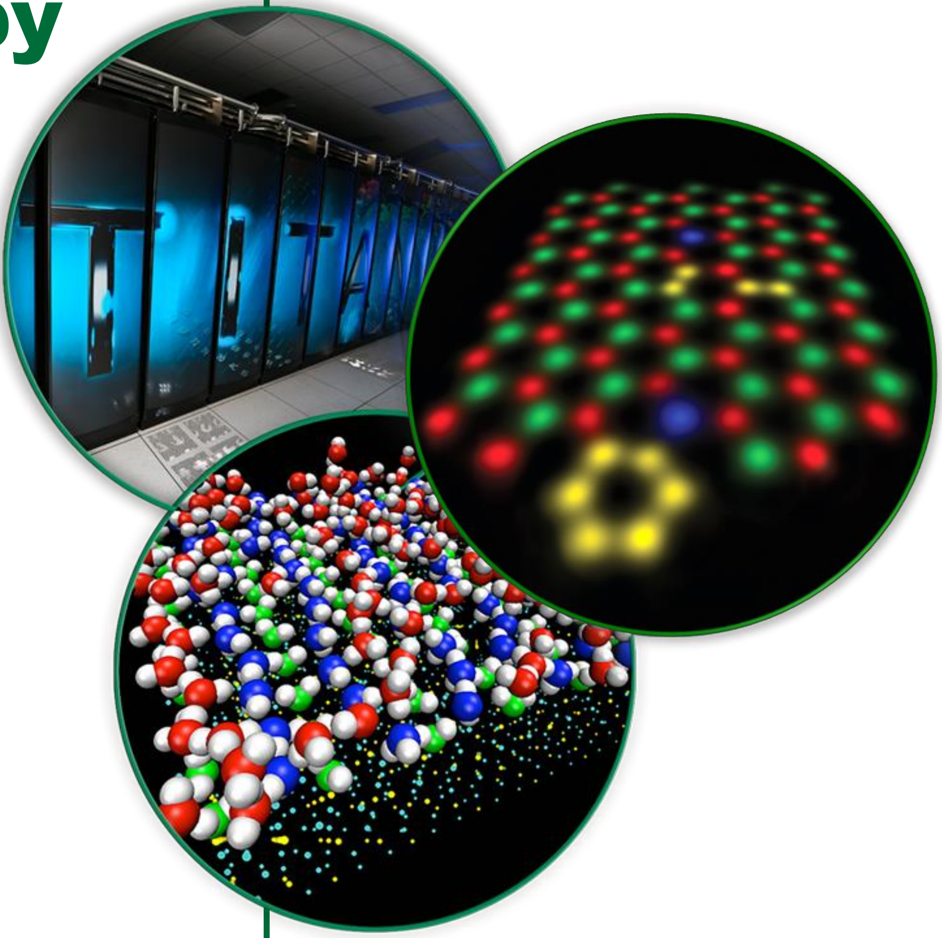
Opportunities with Decay Spectroscopy



Krzysztof Rykaczewski
ORNL Physics Division

Low Energy Community Meeting

College Station, TX, 22nd August 2014

U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

Decay studies focus on major questions in nuclear science

- Decay rates are important for understanding **the origin of atoms and nuclei**
  - β-decays during r-process (half-lives, βxn-emission) beyond ^{78}Ni and ^{132}Sn
  - proton, α, and allowed β decays near ^{100}Sn (defining the termination cycle of rp-process)

- Decay spectroscopy tracks **the evolution of nuclear matter at the limits**
  - single-particle states near doubly magic nuclei, beyond ^{132}Sn, around ^{78}Ni and ^{100}Sn, near ^{48}Ni
  - onset of collectivity (energies of 2^+ states), pp-correlations in 2p emission

- Decays of superheavy nuclei define **the current extent of the grand nuclear landscape**
  - half-lives of new nuclei → emerging "Island of Stability", toward new elements and N=184
  - beyond ground-state properties: alpha-gamma spectroscopy at the "Hot Fusion Island"
  - connecting the Nuclear Mainland and Hot Fusion Island through fission corridor

- **Fundamental interactions/properties of matter**
  - superallowed beta decay (e.g., Z=N=49 ^{98}In)
  - reactor anti-neutrino anomaly

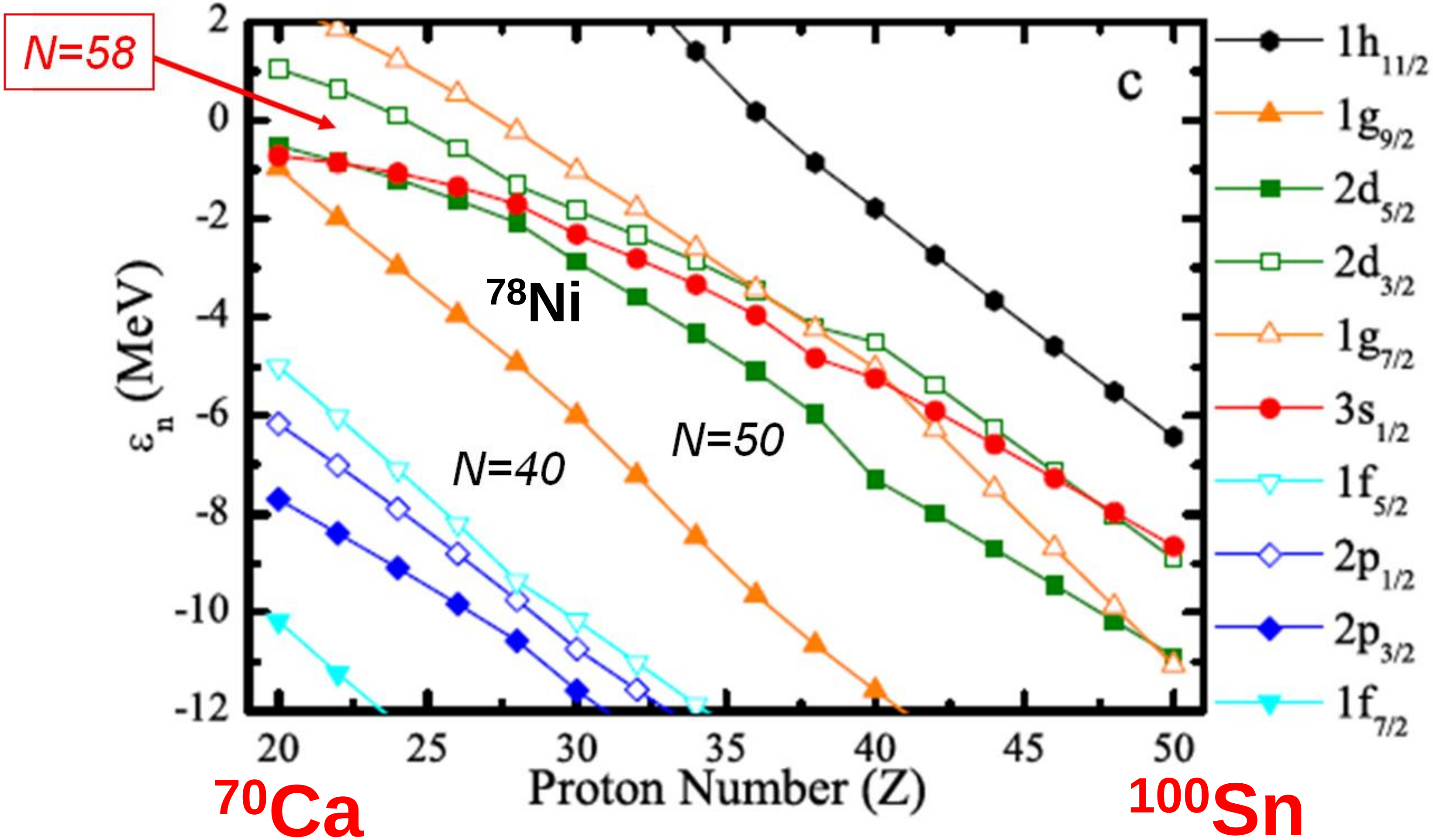
- Decay spectroscopy results **impact our society**
  - larger decay heat release during nuclear fuel cycle, reactor anti-neutrinos → non-proliferation
  - decay studies of medical isotopes (HRIBF measurement with ^{82}Sr radioactive beam)

Decay spectroscopy is sensitive to the most exotic isotopes produced at very low rates, so often provides crucial last data before extrapolation into the unknown.

Important data on the properties of a new nucleus, on the half-life and decay probabilities, on the excited states and isomers.

First studies to be performed when identifying a new nucleus

Properties of single particle states are needed to understand the nuclear structure and processes involving atomic nuclei



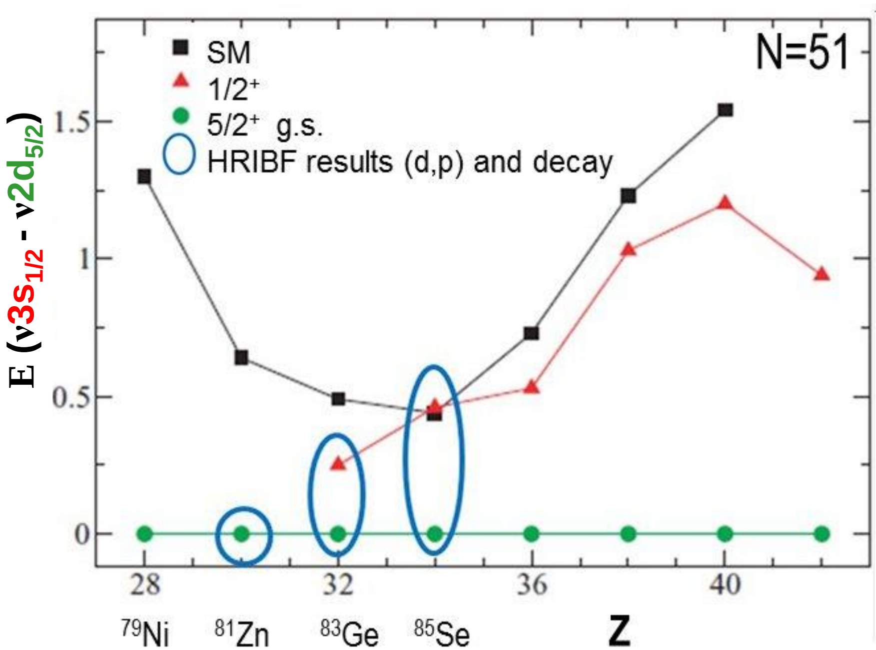
J. Dobaczewski's modeling of proton single particle orbitals in N=50 isotones

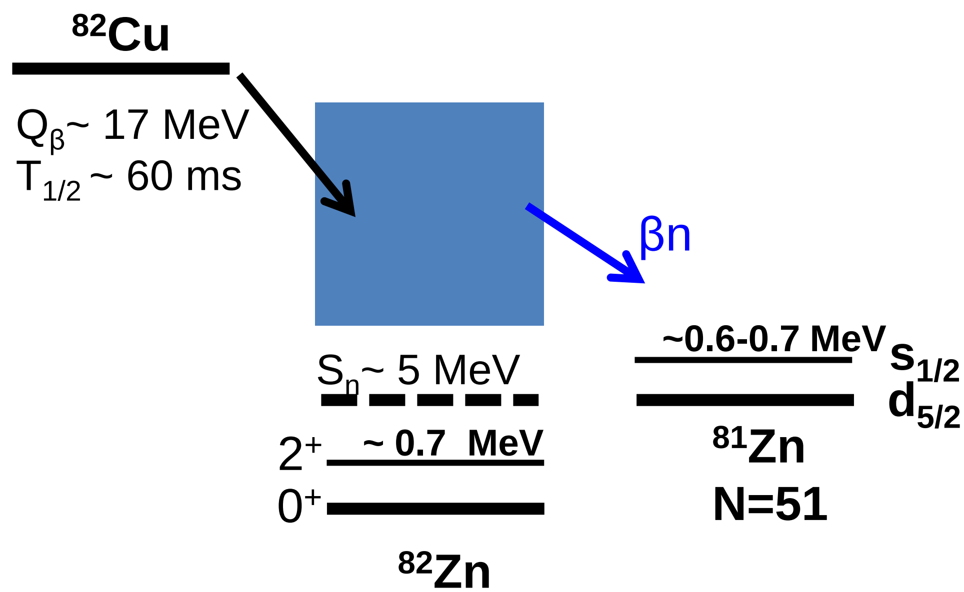
J.A. Winger et al., Phys. Rev. C81, 044303 (2010).

Evolution of neutron single-particle states for N > 50

search for a potential sub-shell closure $\nu 2d_{5/2}$ - $\nu 3s_{1/2}$

Padgett et al., Phys. Rev C **82**, 064314, 2010





- Energy gap at N=56 or at N=58 or no gap beyond ^{78}Ni ?
- Single particle energy of $3s_{1/2}$ vs $2d_{5/2}$ in N=51 ^{79}Ni ?

- **Answer → ^{81,82}Cu β-n-γ exp at RIKEN and ^{79,80}Co β-n-γ exp at FRIB**

Z=29 ^{81}Cu at RIKEN ~ 10^4/week

Z=29 ^{82}Cu at FRIB > $2*10^3$/day

Z=27 ^{79}Co at FRIB > $5*10^3$/week

Beta decay of neutron-rich nuclei and r-process

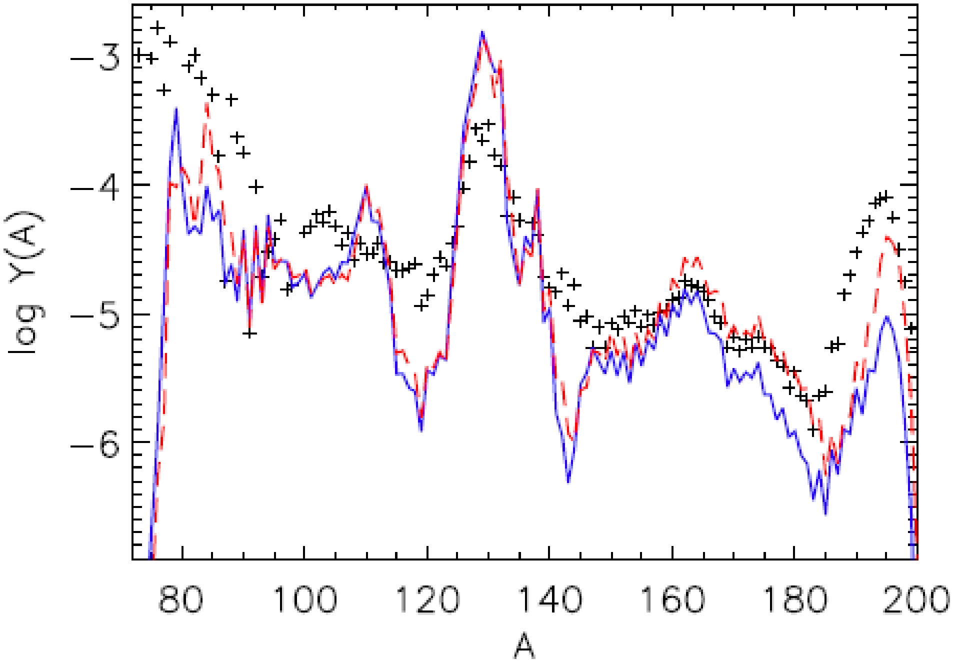
r-process sensitivity studies (R. Surman, M. Mumpower, ...)

$T_{1/2}$

\+ post r-process abundances

simulations with $T_{1/2}$'s from the global model (Moeller 2003)

simulations with new exp data near ^{78}Ni and CQRPA's **$T_{1/2}$'s**



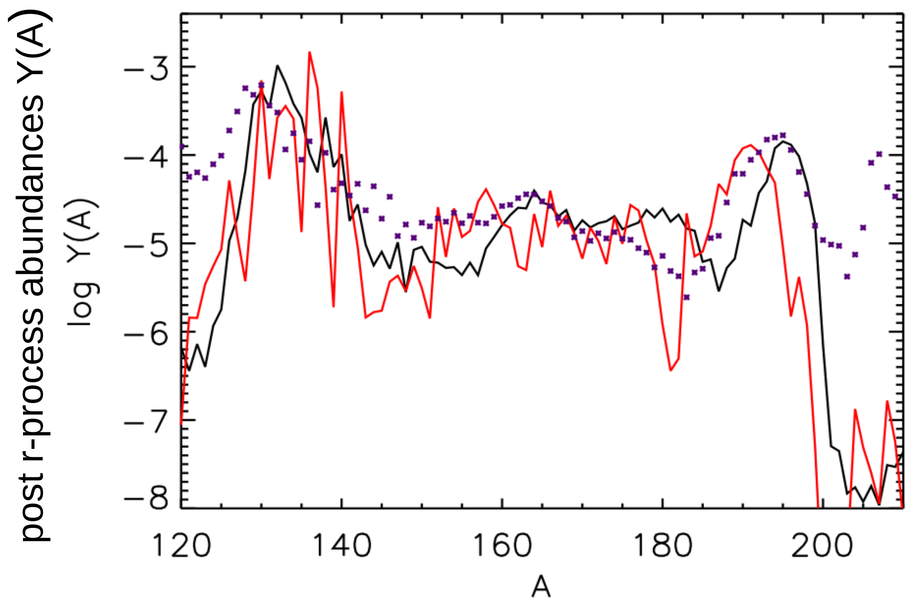
- Fast β-decays near ^{78}Ni make faster flow towards A > 140 nuclei

$P_{\beta n}$

\+ post r-process abundances

simulations **with $P_{\beta n}$'s** from the global model

simulations **without** β-delayed neutron emission

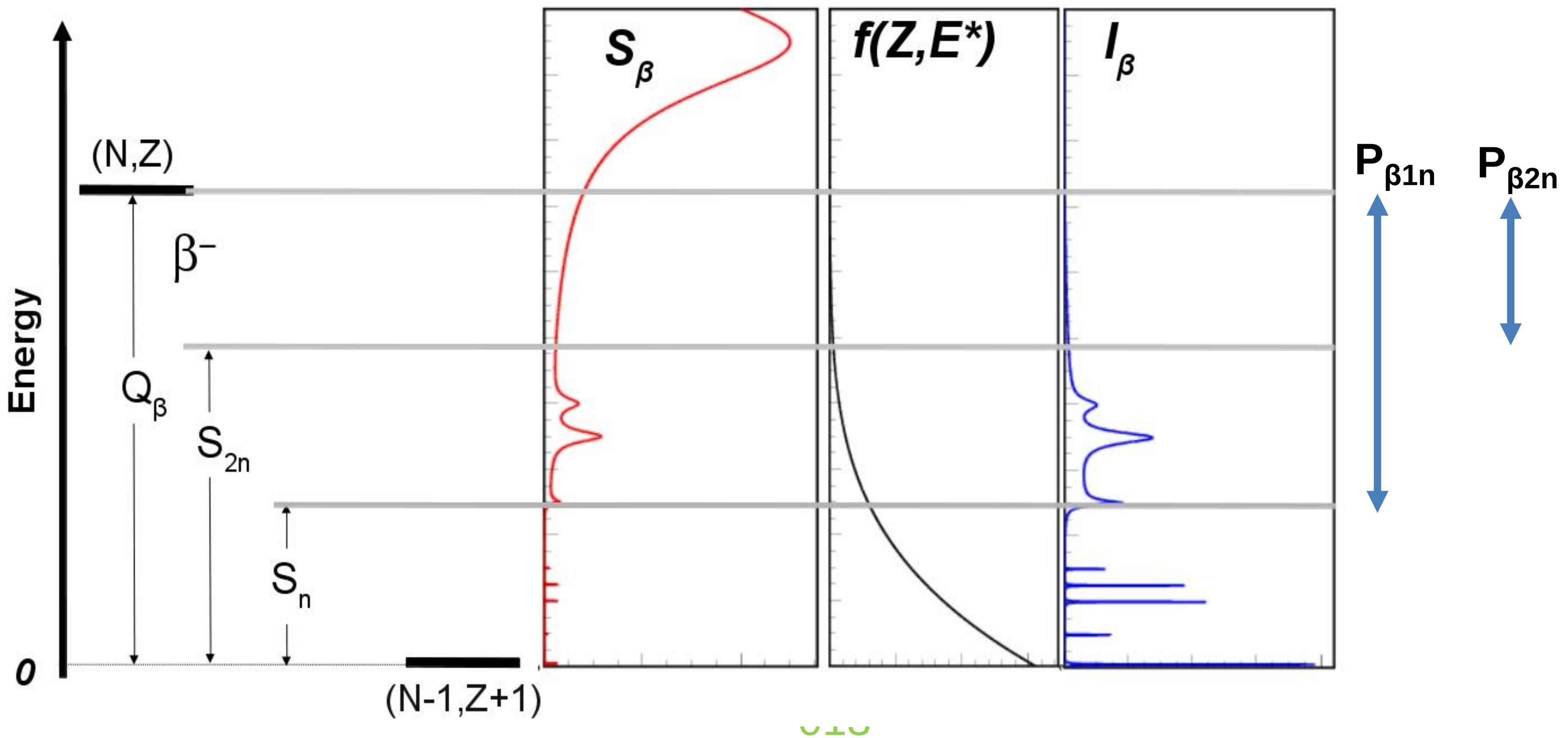


- βn-emission provides additional neutrons for capture
- βn-emission defines the fine details of final isotope abundance pattern

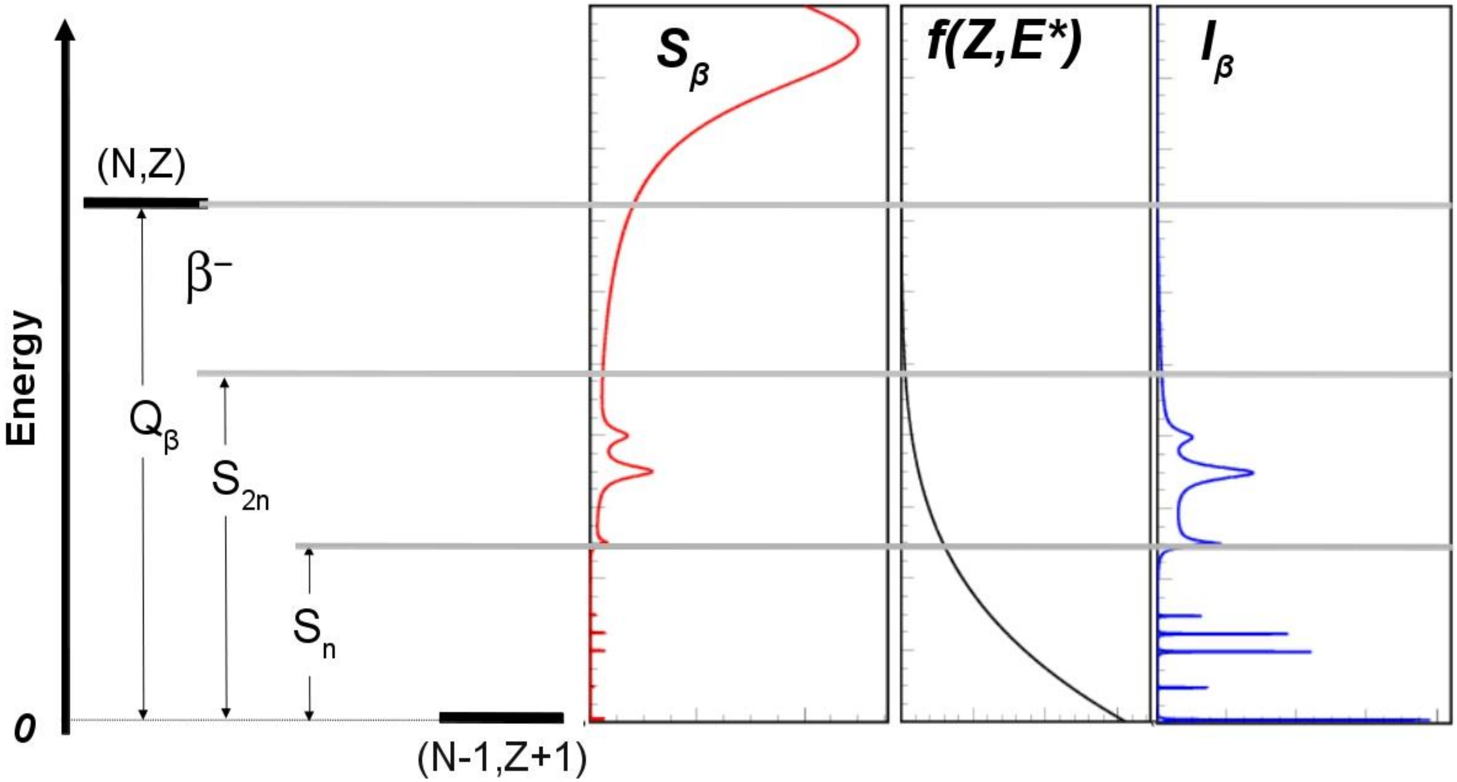
Physics case:

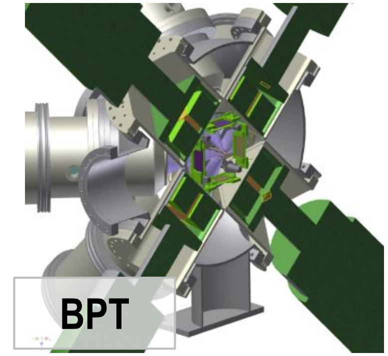
β-strength function → β-half-life and β1n - β2n competition (βxn)

$T_{1/2}$, $P_{\beta 1n}$ and $P_{\beta 2n}$ as input values for the r-process path analysis



Studies of β-strength in neutron-rich nuclei require advance detectors



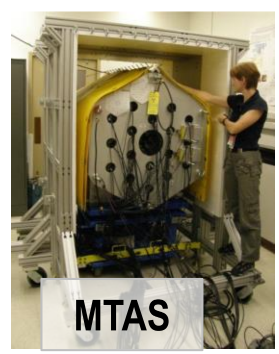


neutron (energy) detection

3Hen, VANDLE, BPT

βγ and MTAS

Beta-strength "around S_n" can be studied and compared to models when suitable devices like **Modular Total Absorption Spectrometer (MTAS), 3Hen, VANDLE , BPT** are available.



★ $^{78}Ni/^{79}Ni/^{81}Cu$ ★ $^{82}Cu/^{84}Zn/^{86}Ga$ ★ $^{85}Zn/^{87}Ga/^{89}Ge$

Experimental $P_{\beta 1n}$ values in black.

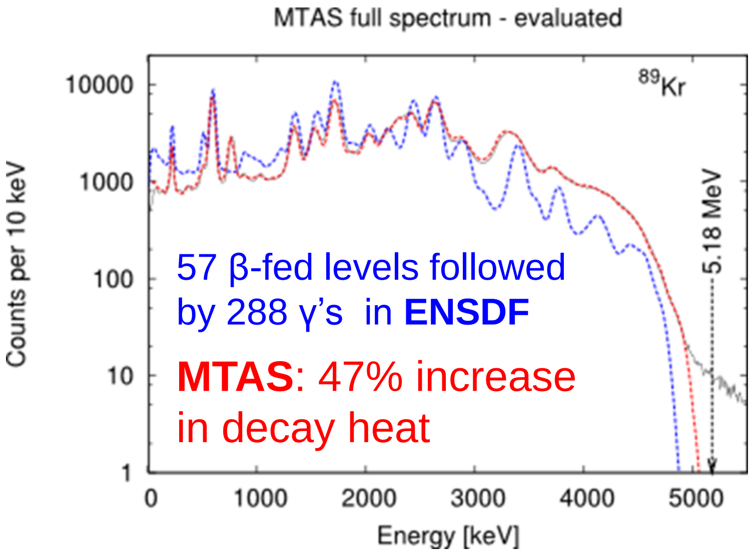
Note only one β1n/β2n emitter ^{86}Ga known so far

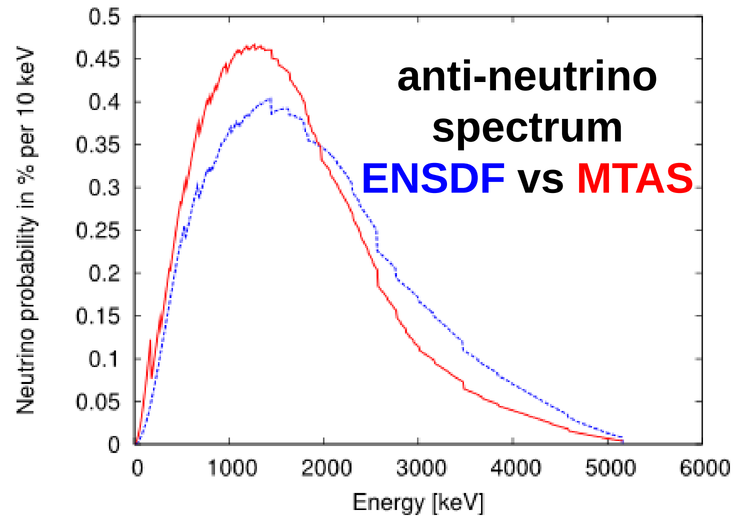
Se						1%	8%	0.8%	~21% 0.01%	3.2%	10% 0%
As				63%	36%	15%	32% 2.2%	76% 1.3%	28% 2.6%	89% 3.2%	45% 39%
Ge		β0n	β0n	10%	17%	45%	31% 4.6%	49% 0.5%	9.9% 1.2%	74% 3.2%	43% 19%
Ga	0.9%	12%	20%	63%	74% 15%	61% 10%	60% 20%	31% 4.6%	35% 41%	70% 19% 9%	20% 47% 10%
Zn	1.3%	1.0%	12%	58%	29% 21%	49% 13%	28% 9%	64% 5%	46% 27% 5%	65% 10% 8%	
Cu	66%	72%	44% 13%	62% 21%	29% 57%	46% 31% 18%	13% 64% 18%	24% 43% 31%			
Ni Z=28	~30%	39% 0%	62% 5%	64% 14%	20% 57% 6%	37% 22% 29%	35% 22% 29%				
Co	26% 6%	69% 7%	41% 25%	67% 16% 15%	1% 73% 25%						
		N=50		52		54		56		58	

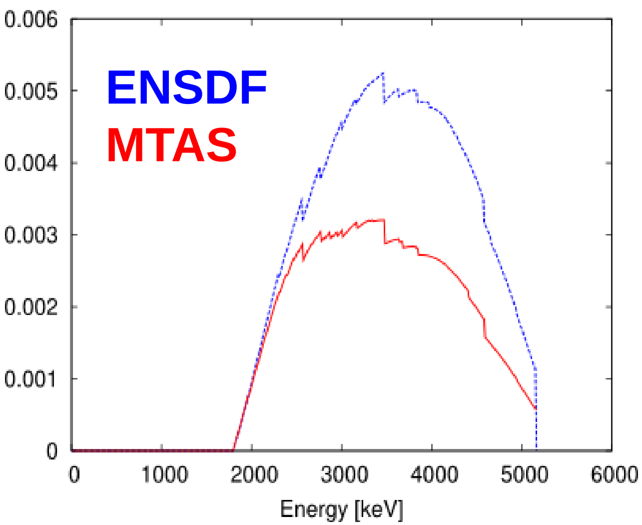
Present reach of 3 days exp at RIKEN with ^{238}U 25 pnA/345 MeV/u and BRIKEN βn-array

Predicted $P_{\beta 1n}$, $P_{\beta 2n}$ and $P_{\beta 3n}$ values listed according to Moeller 2003

Total Absorption Spectroscopy (MTAS) of ^{89}Kr decay relevant for "reactor anti-neutrino anomaly"







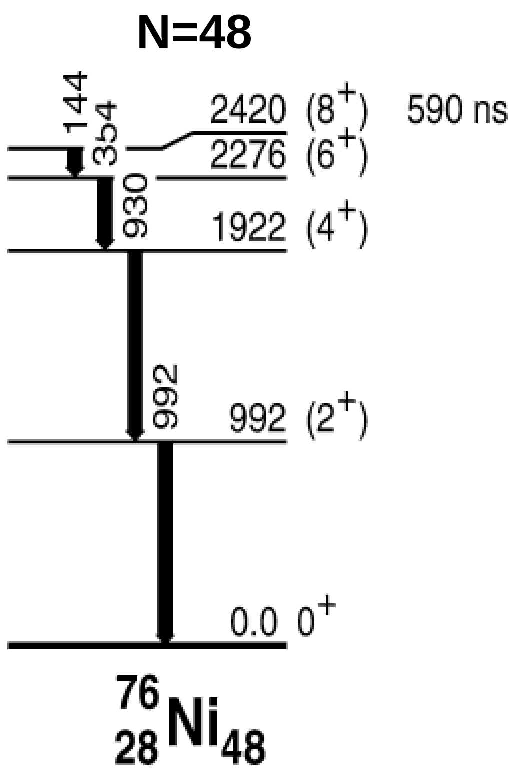
MTAS: number of ^{89}Kr anti-neutrino interactions with matter (protons) is reduced by **41%.**

With ^{235}U, ^{239}Pu, ^{241}Pu and ^{238}U nuclear fuel components taken into account, the overall number of reactor anti-neutrino interactions is reduced by **1% to 2%,** depending on the fuel burn-up phase.

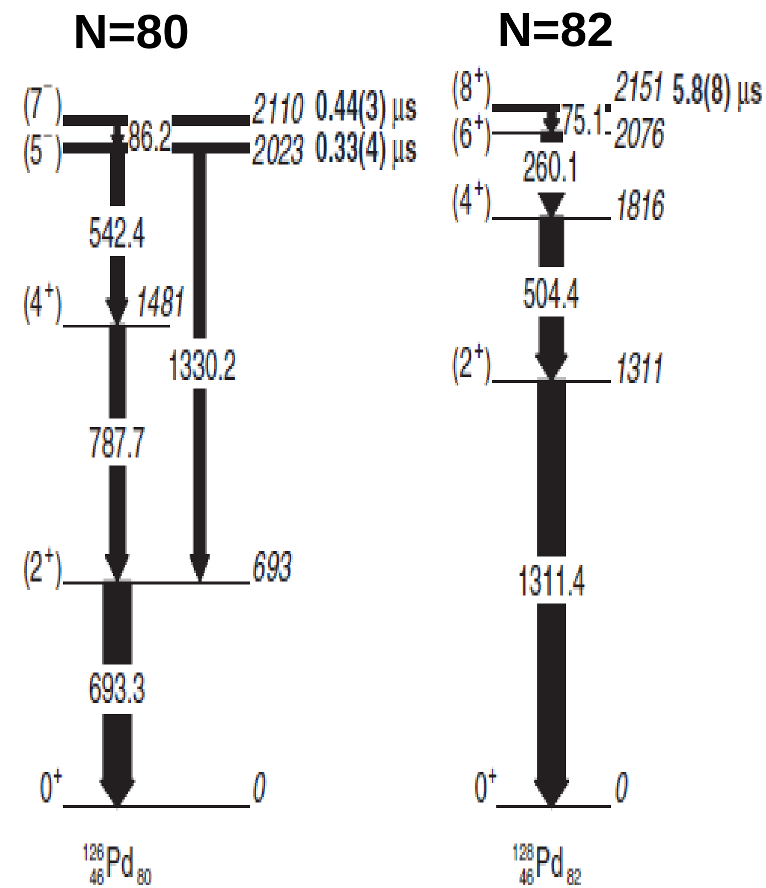
"reactor anti-neutrino anomaly" ~ 94.3(23) % [Mention et al., PR D83, 2011]

→ CARIBU, low energy beams at NSCL/FRIB

Microsecond Isomers in Exotic Nuclei



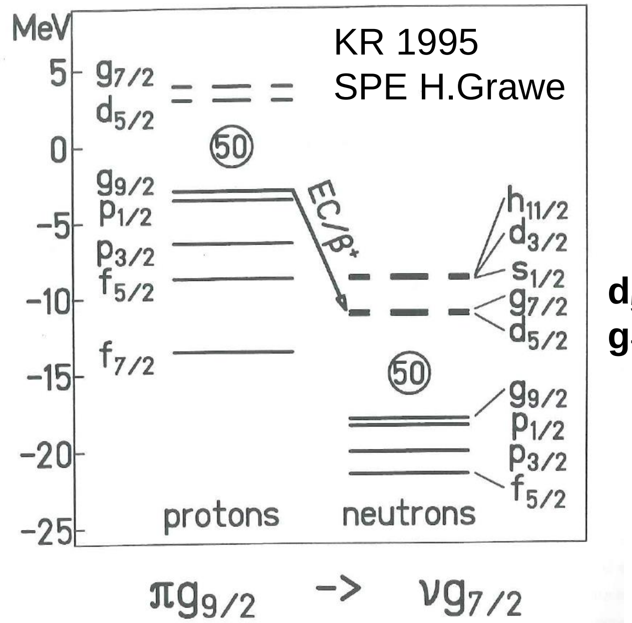
GANIL - NSCL
Mazzocchi et al.,
Phys.Lett. B622, 2005



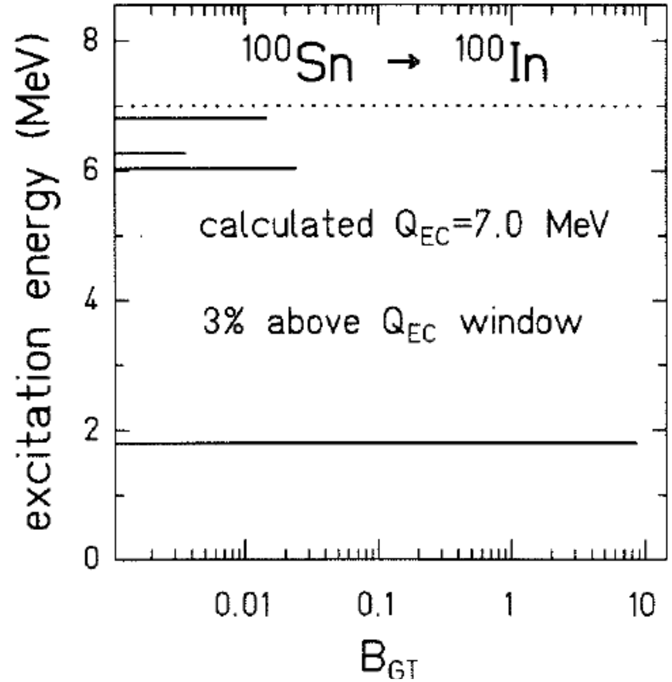
EURICA at RIKEN:
Watanabe et al.,
PRL 111, 152501, 2013

Exotic Isomeric Decays in Nuclei →next talk by Sean Liddick

“Super” allowed Gamow-Teller β-decay of ^{100}Sn

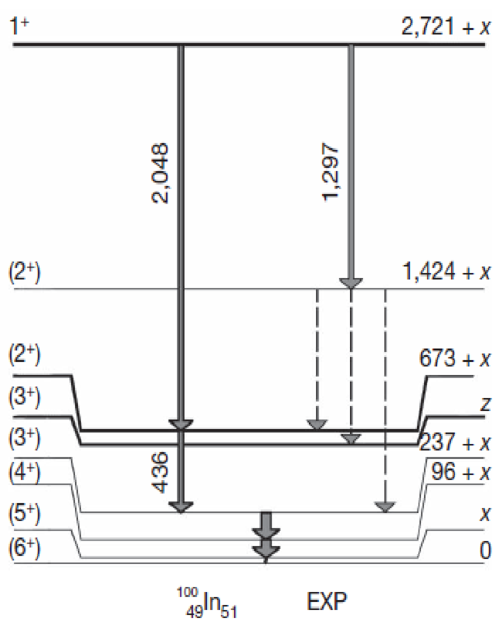


$d_{5/2}$
$g_{7/2}$



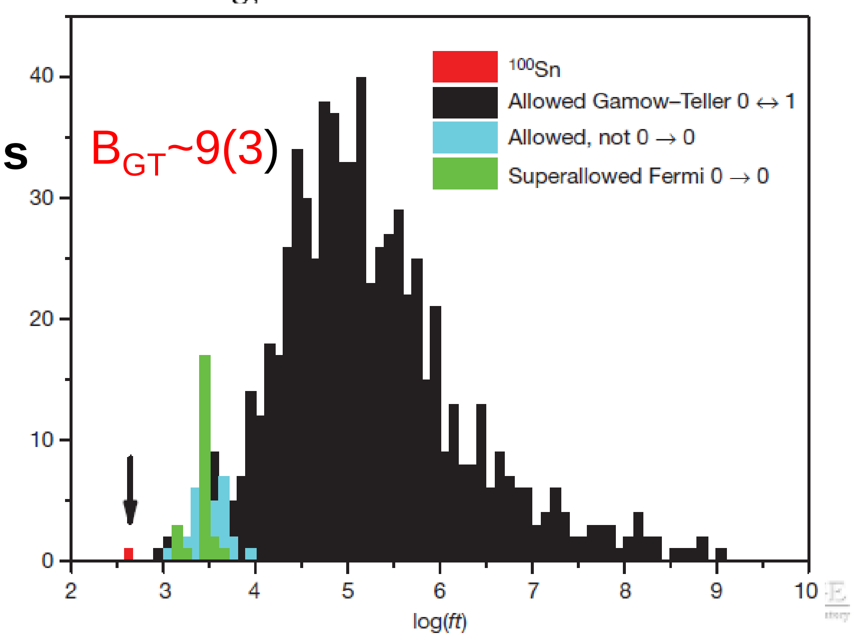
ESSPSM:
B_{GT}=160/9=17.8

B. A. Brown & KR
PR C50, R2270
1994

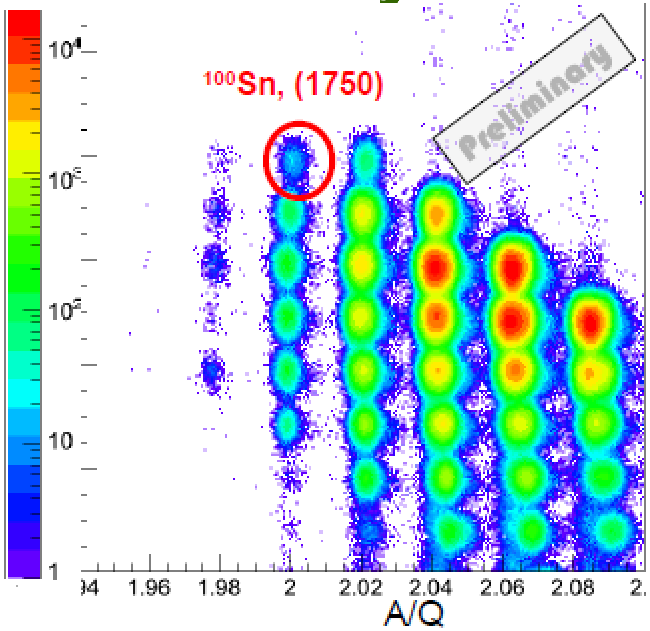


~ 260 ^{100}Sn ions
FRS-GSI

Hinke *et al.*, Nature 486, 341, 2012



^{100}Sn decay with EURICA at RIKEN

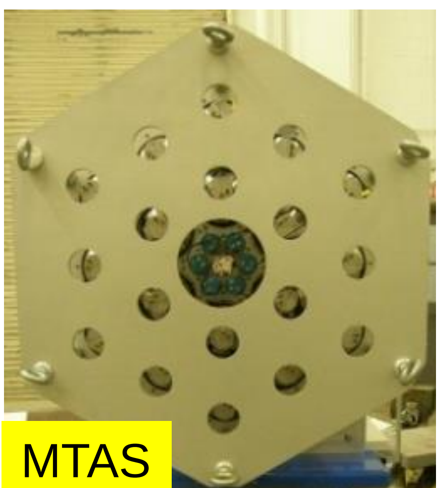


R. Gernhauser, ARIS 2014

We should increase the sensitivity for low energy γ-transitions and achieve much better sensitivity limit for β-strength detection at higher excitation energies.

At FRIB, the expected rate of ^{100}Sn is 1 pps.

→ MTAS with GeDSSD at FRIB



+

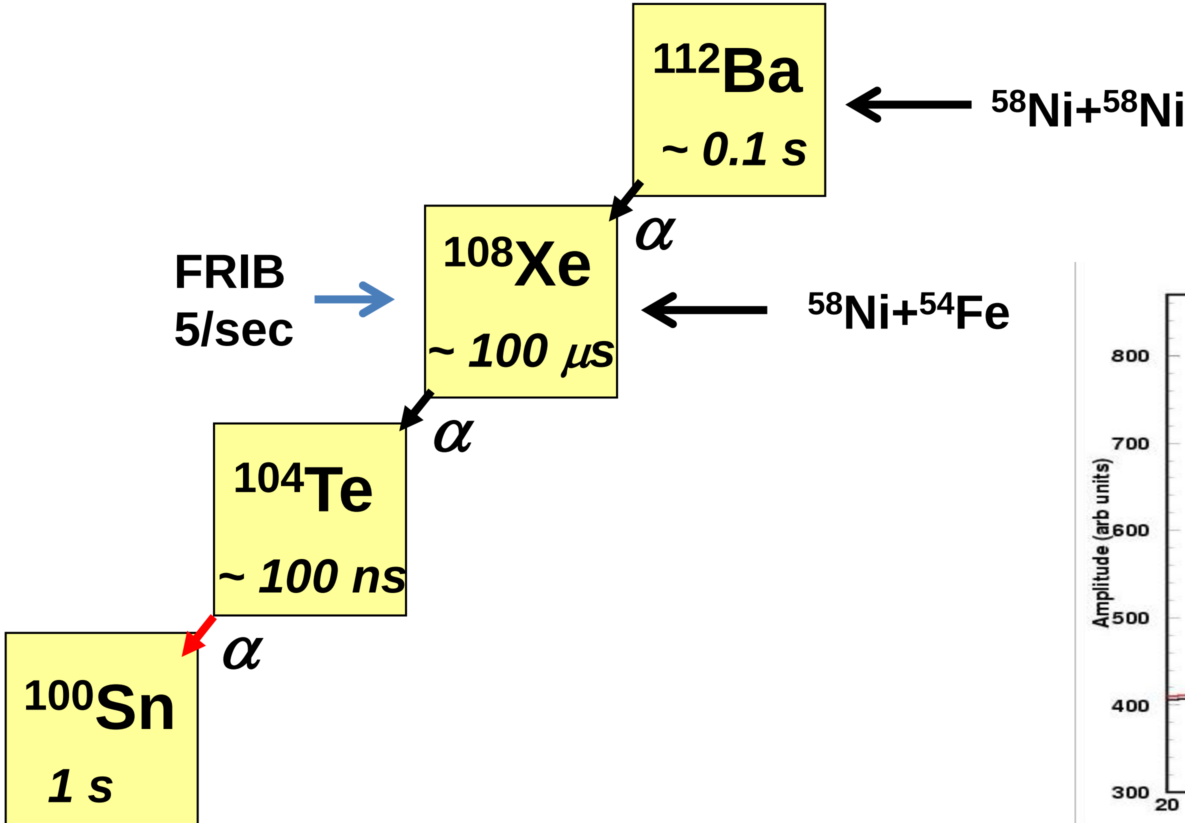
+

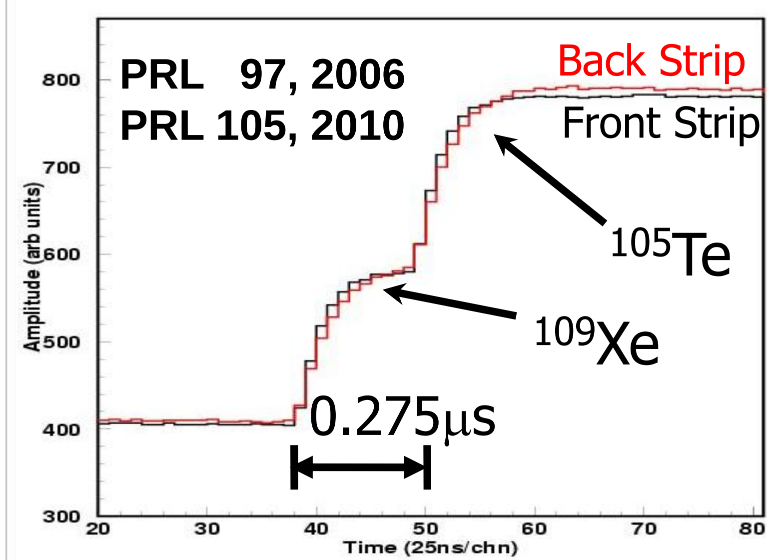
1 pps of ^{100}Sn

GT-strength quenching (non-nucleonic degrees of freedom ?)

α-decay along N=Z nuclei $^{112}Ba \rightarrow ^{108}Xe \rightarrow ^{104}Te \rightarrow ^{100}Sn$

Opportunities at the recoil (FMA, AGFA) and fragment separators (RIKEN, FRIB)



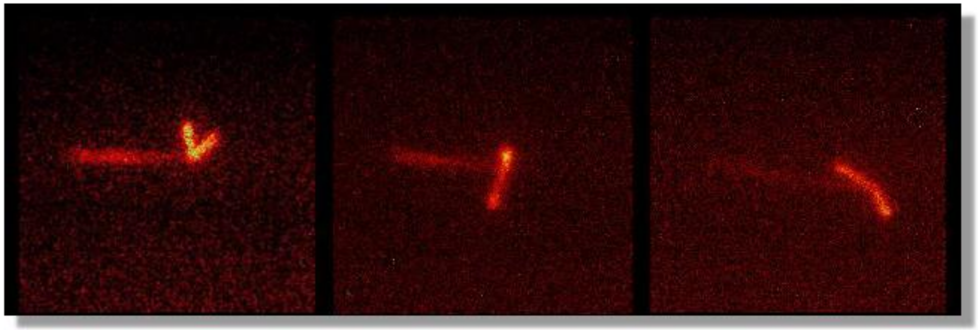


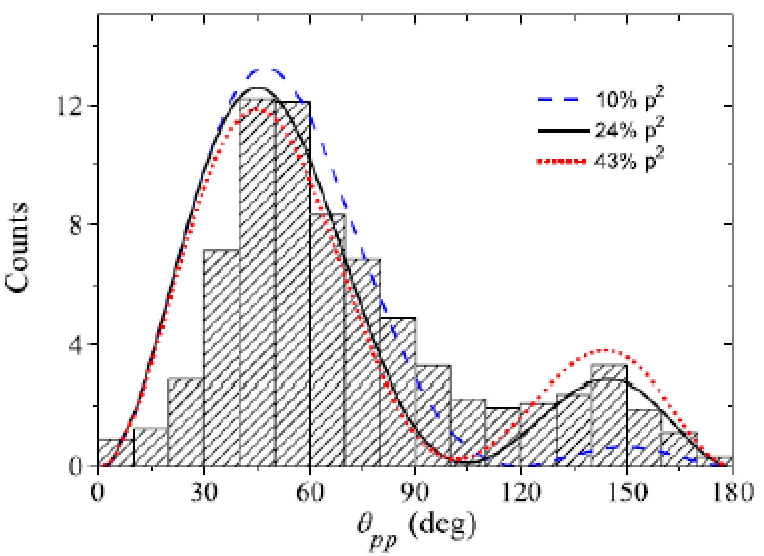
Reference strength for α-decay

$^{104}Te \rightarrow ^{100}Sn$

Two-proton radioactivity

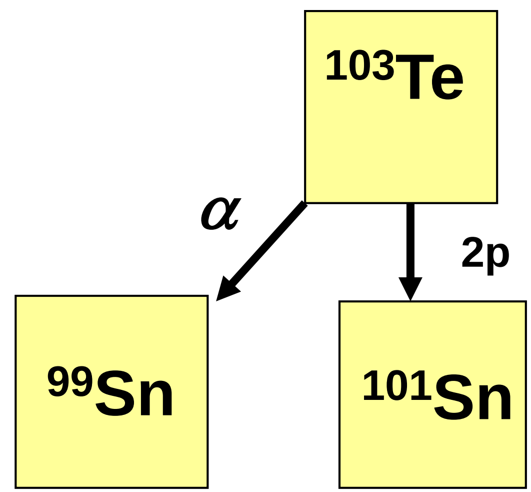
2p





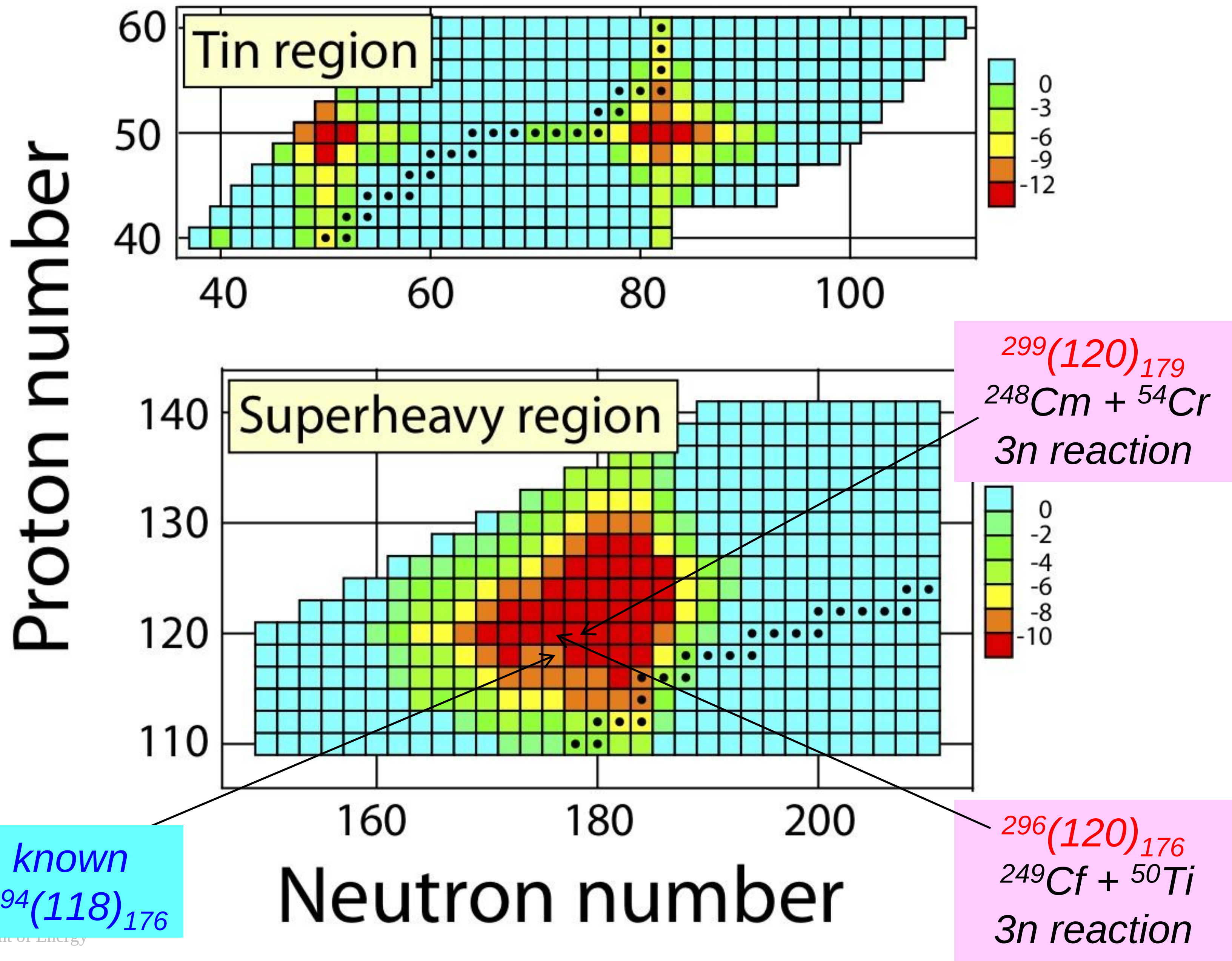
2p decays of ^{45}Fe studied at the NSCL with Optical Time Projection Chamber.

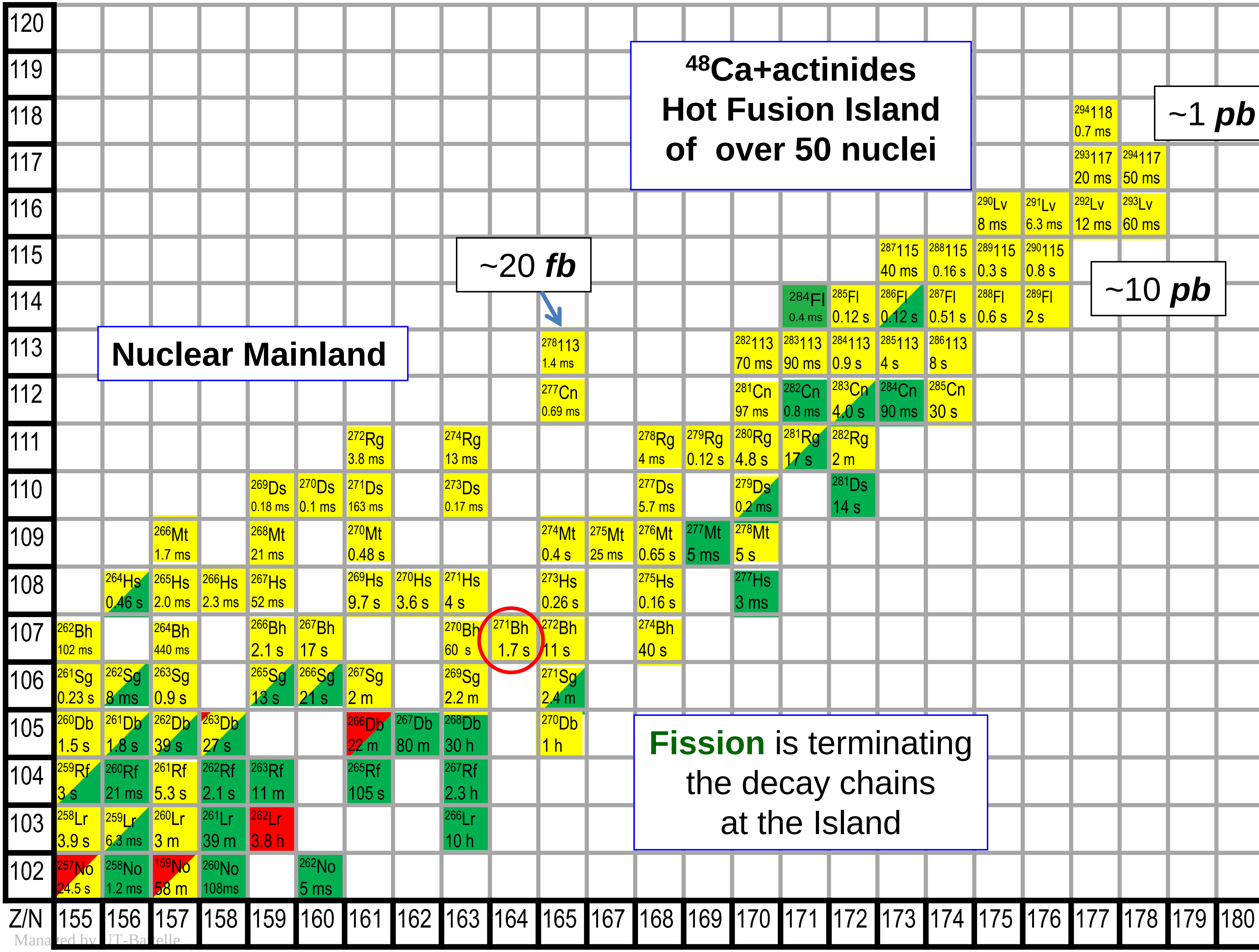
So far ^{45}Fe is the only 2p-radioactivity in a heavy nucleus with well measured p-p angular correlations pointing to large p-p correlation energy. New emitters in Ge-Kr region and above ^{100}Sn can be reached at RIKEN and studied at FRIB.



FRIB ~5/min

M. Bender, W. Nazarewicz, P.-G. Reinhard , Phys. Lett. B 515, 42, 2001
"Shell stabilization of super- and hyper-heavy nuclei without magic gaps"



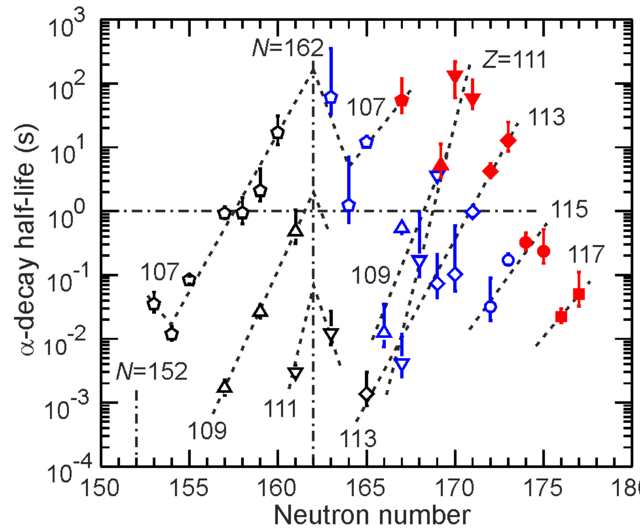


48Ca+actinides
Hot Fusion Island
of over 50 nuclei
~1 pb
~20 fb
~10 pb
Nuclear Mainland
Fission is terminating the decay chains at the Island
120
119
118
117
116
115
114
113
112
111
110
109
108
107
106
105
104
103
102
294118 0.7 ms
293117 20 ms
294117 50 ms
290Lv 8 ms
291Lv 6.3 ms
292Lv 12 ms
293Lv 60 ms
287115 40 ms
288115 0.16 s
289115 0.3 s
290115 0.8 s
284Fl 0.4 ms
285Fl 0.12 s
286Fl 0.12 s
287Fl 0.51 s
288Fl 0.6 s
289Fl 2 s
278113 1.4 ms
282113 70 ms
283113 90 ms
284113 0.9 s
285113 4 s
286113 8 s
277Cn 0.69 ms
281Cn 97 ms
282Cn 0.8 ms
283Cn 4.0 s
284Cn 90 ms
285Cn 30 s
272Rg 3.8 ms
274Rg 13 ms
278Rg 4 ms
279Rg 0.12 s
280Rg 4.8 s
281Rg 17 s
282Rg 2 m
269Ds 0.18 ms
270Ds 0.1 ms
271Ds 163 ms
273Ds 0.17 ms
277Ds 5.7 ms
279Ds 0.2 ms
281Ds 14 s
266Mt 1.7 ms
268Mt 21 ms
270Mt 0.48 s
274Mt 0.4 s
275Mt 25 ms
276Mt 0.65 s
277Mt 5 ms
278Mt 5 s
264Hs 0.46 s
265Hs 2.0 ms
266Hs 2.3 ms
267Hs 52 ms
269Hs 9.7 s
270Hs 3.6 s
271Hs 4 s
273Hs 0.26 s
275Hs 0.16 s
277Hs 3 ms
262Bh 102 ms
264Bh 440 ms
266Bh 2.1 s
267Bh 17 s
270Bh 60 s
271Bh 1.7 s
272Bh 11 s
274Bh 40 s
261Sg 0.23 s
262Sg 8 ms
263Sg 0.9 s
265Sg 13 s
266Sg 21 s
267Sg 2 m
269Sg 2.2 m
271Sg 2.4 m
260Db 1.5 s
261Db 1.8 s
262Db 39 s
263Db 27 s
266Db 22 m
267Db 80 m
268Db 30 h
270Db 1 h
259Rf 3 s
260Rf 21 ms
261Rf 5.3 s
262Rf 2.1 s
263Rf 11 m
265Rf 105 s
267Rf 2.3 h
258Lr 3.9 s
259Lr 6.3 ms
260Lr 3 m
261Lr 39 m
262Lr 3.8 h
266Lr 10 h
257No 24.5 s
258No 1.2 ms
159No 58 m
260No 108ms
262No 5 ms
Z/N
155 156 157 158 159 160 161 162 163 164 165 167 168 169 170 171 172 173 174 175 176 177 178 179 180

Superheavy Nuclei at Hot Fusion Island

- **Decay rates show an emerging Island of Stability**
- New element 117 identified at Dubna (now 20 decay chains)
- Elements 117, 115 and 113 confirmed at Darmstadt
- α-γ studies of ^{288}115 decay chain at Darmstadt and Berkeley
- ~ 100 decay chains of 115 isotopes
- Search for new elements 119 and 120 at Darmstadt

Emerging “Island of Stability”



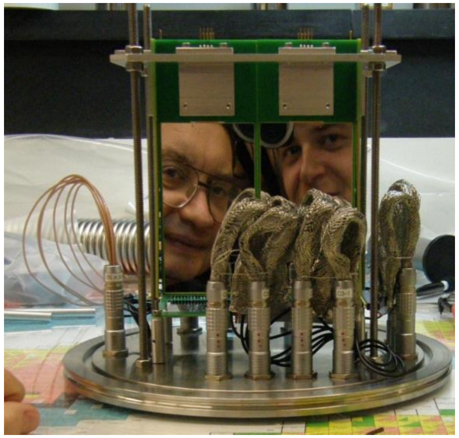
Oganessian *et al.*, PR C87, 054621, 2013

During 2014-2019

- Anchoring Hot Fusion Island to the Nuclear Mainland (e.g., ^{239,240}Pu, ^{245}Cm+^{48}Ca reaction, ^{248}Cm+^{40,44}Ca)
- New data on “fission corridor” nuclei like ^{284}Fl
- **Search for the heaviest atomic nuclei ^{295,296}(118) with Cf-target**
- Reaction mechanism and further α-γ spectroscopy studies

After 2019

- Search for new elements Z > 118 at Dubna SHE Factory and RIKEN with beams heavier than ^{48}Ca
- Structure of superheavy nuclei (α-γ-X ray-electron spectroscopy) at the Hot Fusion Island
- Spectroscopy after a gas-cell with mass-separated SHE’s



- Reduced random events
- Observation of sub-μs activities

Toward new elements and N~184 nuclei

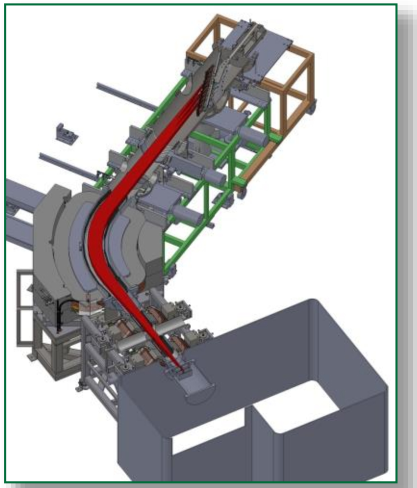
- Most neutron-rich actinide target materials ^{248}Cm,^{249}Bk, and preferably ^{251}Cf in 15 mg quantities
- Intense 1 part*μA - 10 part*μA heavy-ion beams above ^{48}Ca (^{50}Ti, ^{51}V, ^{54}Cr, ^{58}Fe, ^{64}Ni)
- **Accelerator time of many months to years (beam dose above 10^{20})**
- Efficient separator and detection system sensitive to short half-lives

From mixed-Cf to electromagnetically enriched ^{251}Cf target

^{251}Cf ($T_{1/2}$=898 years) is the most neutron-rich, long-lived and non radio-toxic target material, *available* the synthesis of new super heavy elements and nuclei.
Most likely, it can be used at LBNL and ANL for SHE studies,
and it is an interesting opportunity for FRIB/ReA6.

Electromagnetic Isotope Separator at ORNL

- Versatile and proven to separate nearly all stable isotopes and some radioisotopes (enrichment to >98%)
- Throughput at the level of milligrams per hour
- Prototype for proposed actinide separator



OAK RIDGE National Laboratory

Impact of decay studies

Understanding the structure and decay rates in nuclei at the limits

- **β-strength function within full decay energy window:**

  - measured β half-lives and TAS spectra help modeling of β-decay and analysis of post r-process abundances.

  - β-delayed multi-neutron emission and fine structure in βn-emission affect the energy spectrum of emitted neutrons in environments like r-process and nuclear fuel (IAEA CRP 2013-2017)

  - quenching of GT strength (non-nucleonic degrees of freedom affecting decay processes ?)

  - superallowed β-transitions in large-Z emitters (radiative corrections ^{98}In)

- **Evolution of single-particle states and collectivity**.

  - $\nu s_{1/2}$ and $\nu d_{5/2}$ next to ^{78}Ni, $\nu d_{5/2}$ and $\nu g_{7/2}$ next to ^{100}Sn, $\pi p_{1/2}$ and $\pi g_{9/2}$ below ^{100}Sn,

  - 2+ , 4+ and higher energy states, isomers helping to establish shell model interactions parameters

  - 2p and α-radioactivity (pp correlation energy, α-preformation probability, ^{103}Te, ^{104}Te decays)

- **Island of (increased) Stability**

  - new elements and new superheavy nuclei

  - excited states in nuclei at the Hot Fusion Island

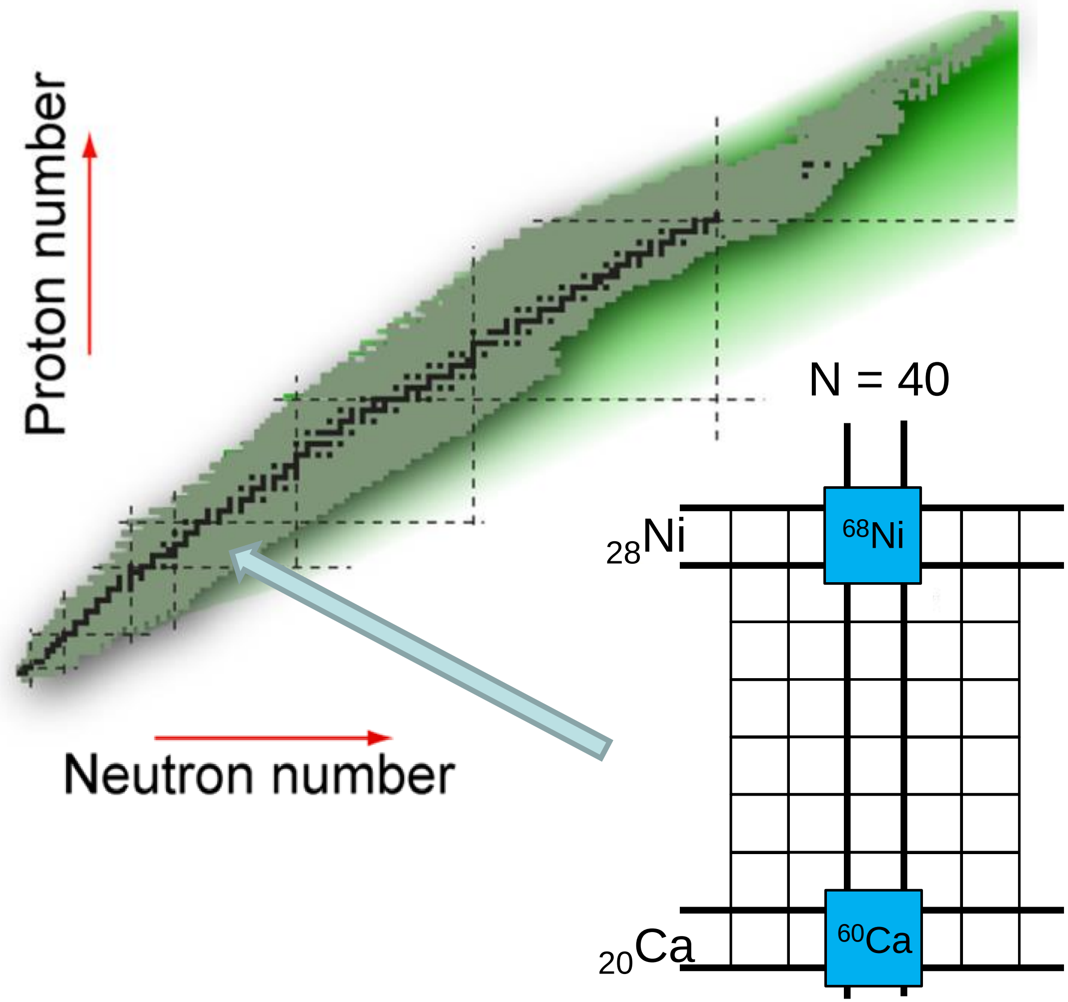
  - origin of "fission corridor" between the Mainland and Hot Fusion Island, fission mechanism

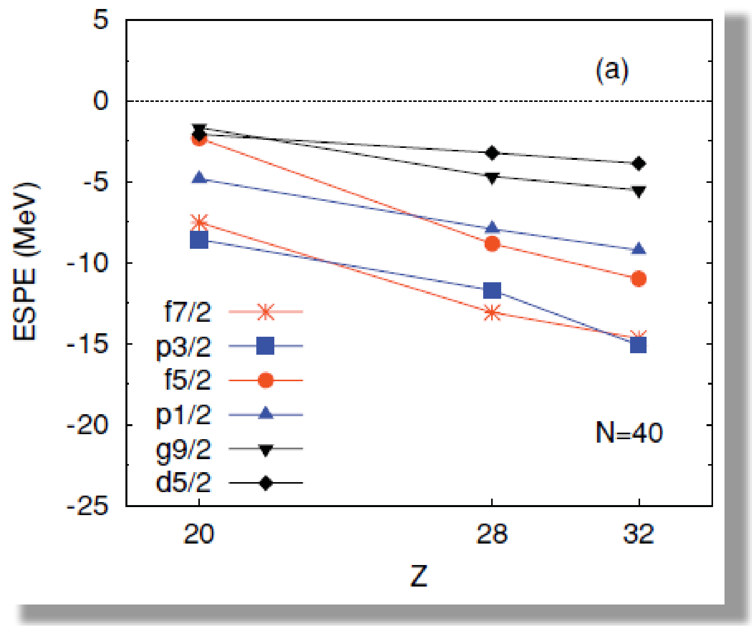
- **Reactor science**

  - total absorption spectroscopy and decay heat

  - reactor anti-neutrino spectra for non-proliferation applications (and "anti-neutrino anomaly")

Neutron-rich beta decay spectroscopy



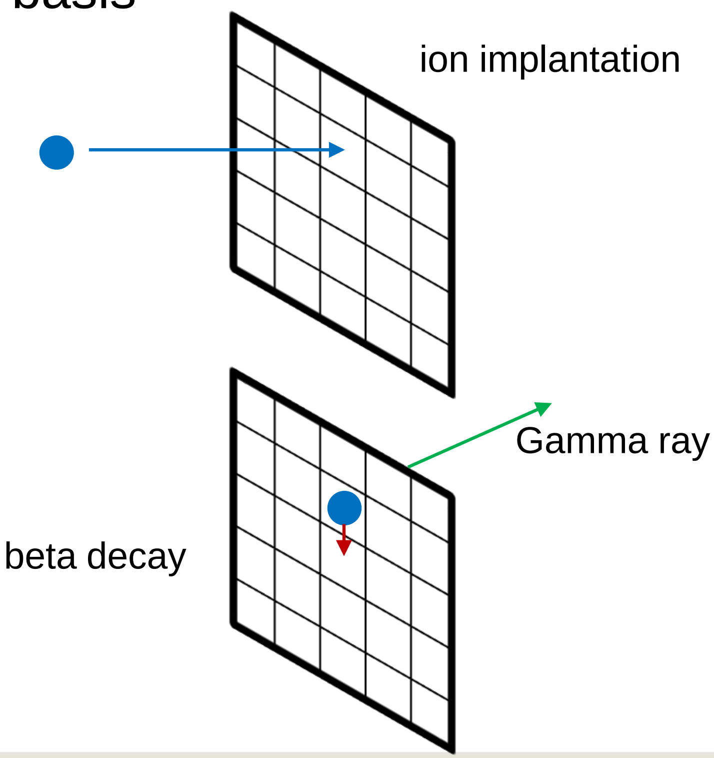


Nucleus	$\nu g_{9/2}$	$\nu d_{5/2}$	0p0h	2p2h	4p4h	6p6h
^{68}Ni	0.98	0.10	55.5	35.5	8.5	0.5
^{66}Fe	3.17	0.46	1	19	72	8
^{64}Cr	3.41	0.76	0	9	73	18
^{62}Ti	3.17	1.09	1	14	63	22
^{60}Ca	2.55	1.52	1	18	59	22

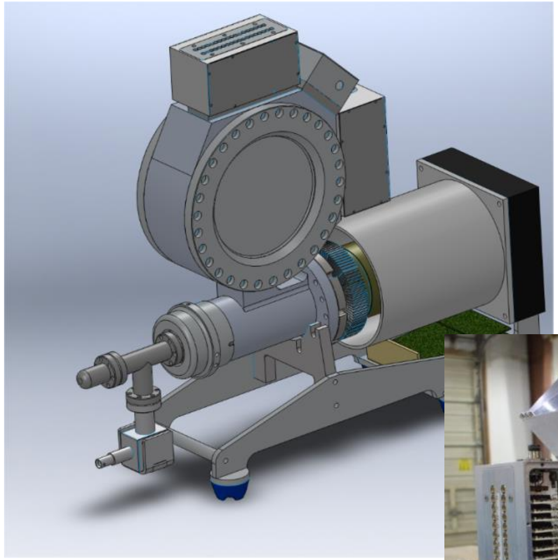
S. Lenzi *et al*., Phys. Rev. C, 82, 054301 (2010)

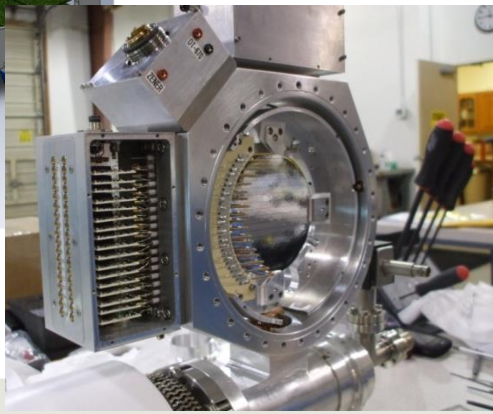
GeDSSD

- Beta-decay apparatus allows the correlation of exotic ion implants with their subsequent decays on an event-by-event basis



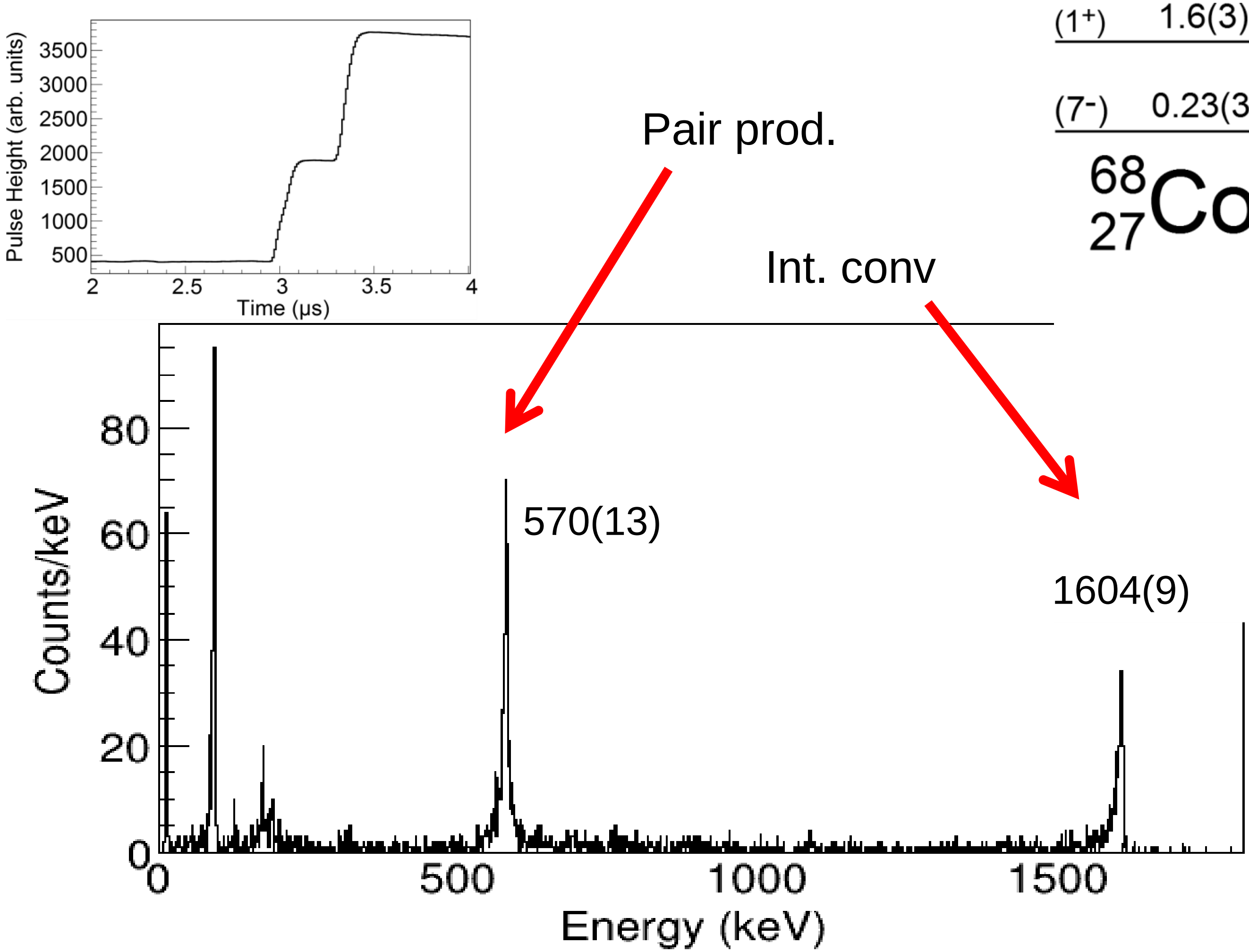
- GeDSSD
- ~mm pitch on strips
- Mechanically cooled
- Electrically segmented
- Dual gain

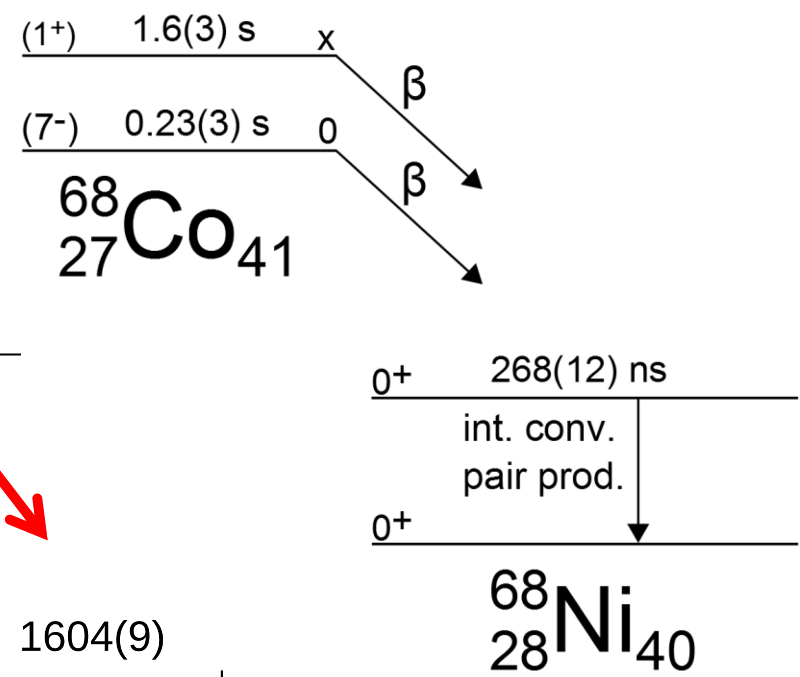




N. Larson *et al.*, Nucl. Instrum. Methods Phys. Res., 727, 59 (2013)

Conversion electron detection





S. Suchyta et al., Phys. Rev. C, 89, 021301 (2014)

Beta-delayed neutron studies with VANDLE

CENTER OF EXCELLENCE FOR RADIOACTIVE ION BEAM STUDIES FOR STEWARDSHIP SCIENCE

K. Kolos

Department of Physics and Astronomy
University of Tennessee, Knoxville

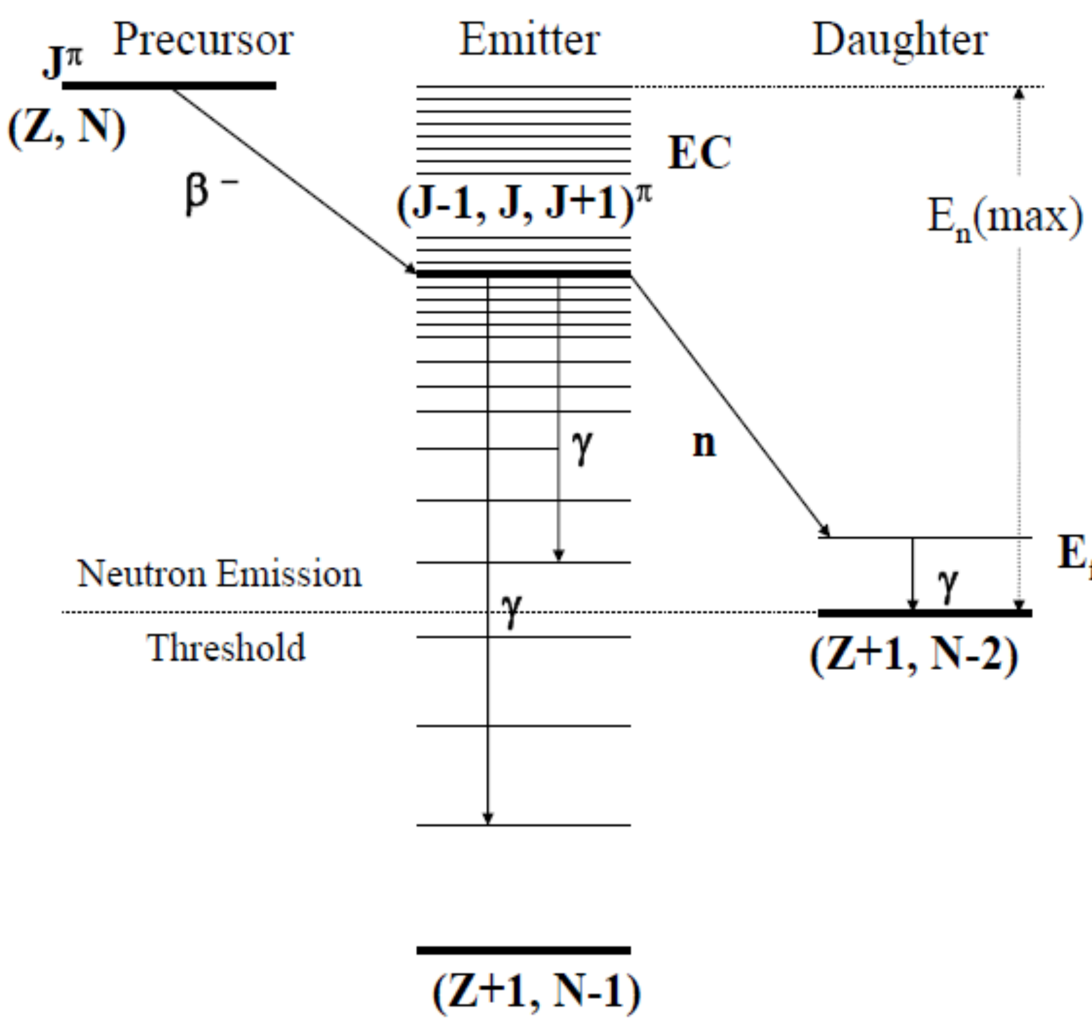
for VANDLE collaboration

R. Grzywacz, K. Kolos, M. Al-Shudifat, L. Cartegni,
M. Madurga, D. Miller, S. Padgett, **S. Paulauskas**, S. Taylor **UTK**
K. Rykaczewski, C. Gross, A.J. Mendes II, D. Stracener, C. Jost, Y. Liu, D. W. Bardayan,
K. Miernik, M. Wolinska-Cichocka, **ORNL**
J.C. Batchelder, S. Liu, C. Matei, **W. Peters** and I. Spassova, **ORAU**
N. Brewer, J.K. Hwang, **Vanderbilt**
P.D. O'Malley, M. Howard, B. Manning, E. Merino, A. Ratkiewicz, and J. Cizewski, **Rutgers U.**
C. Brune and T. Massey, **Ohio U.**
S. Ilyushkin, F. Raiola, D. Walter and F. Sarazin, **Colorado School of Mines**
J. Blackmon, E. Zganjar, **Louisiana State U.**
P.A. Copp, **WUL**
*Theory: I. Borzov (**Obninsk**), M. Bertolli (**LANL, ORNL**)*

Beta-delayed neutron decay (βn)

→ **far from stability**
βn-decay becomes
dominating decay channel

→ **only small fraction of P_n values are known**



Schematic energy-level diagram for β-delayed neutron emission.

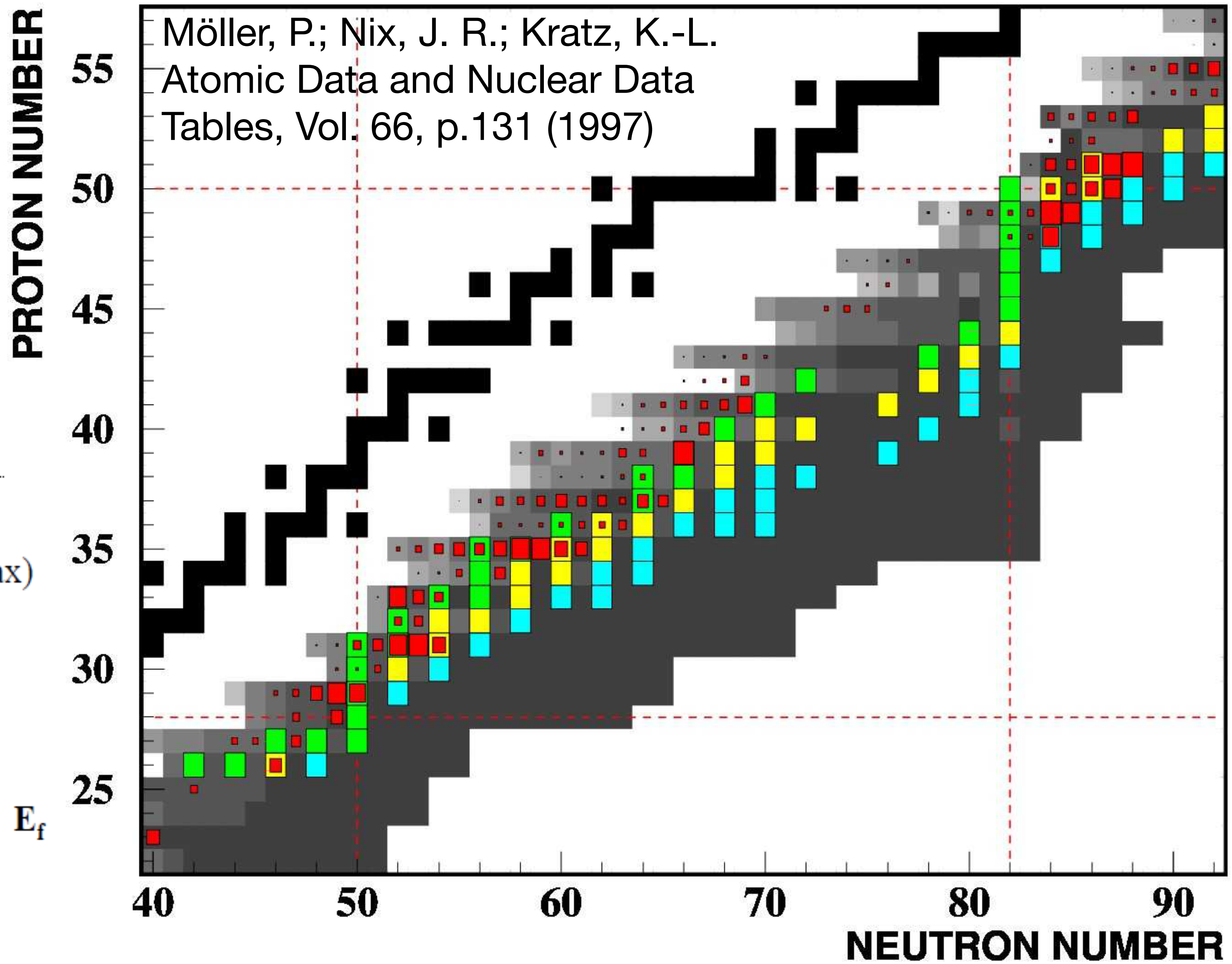
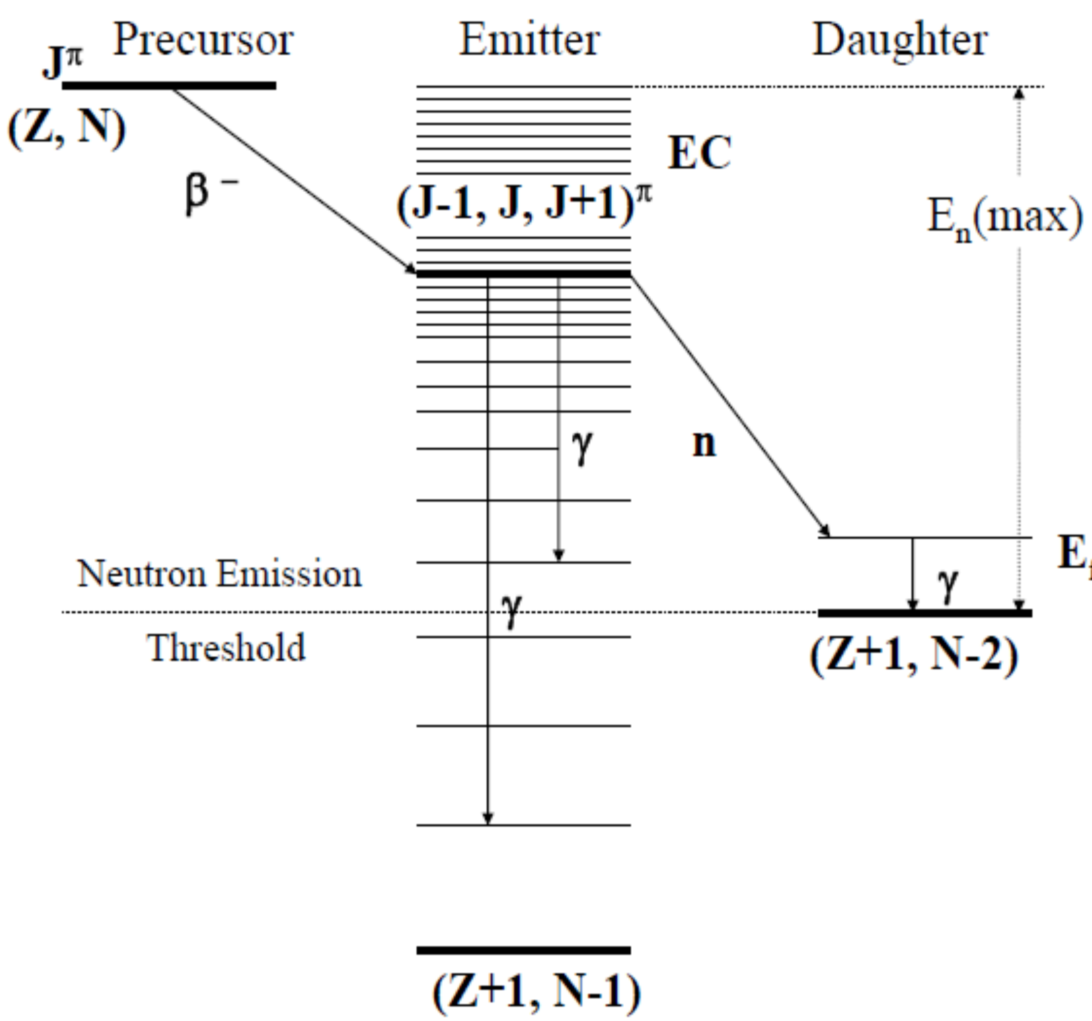


Fig. Predicted r-process paths for different neutron densities.

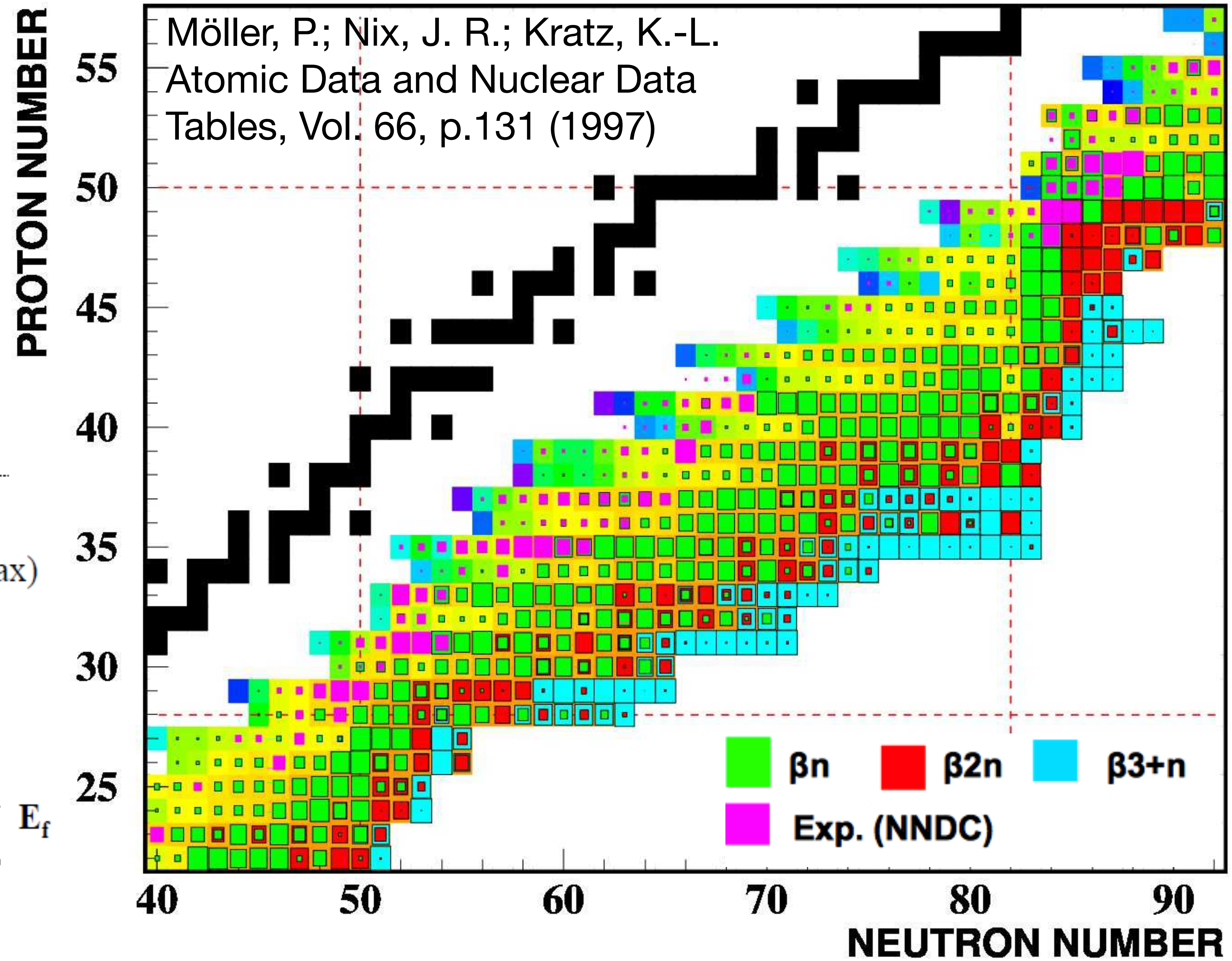
Beta-delayed neutron decay (βxn)

→ **far from stability**
βn-decay becomes
dominating decay channel

→ **only small fraction of P_{xn} values are known**



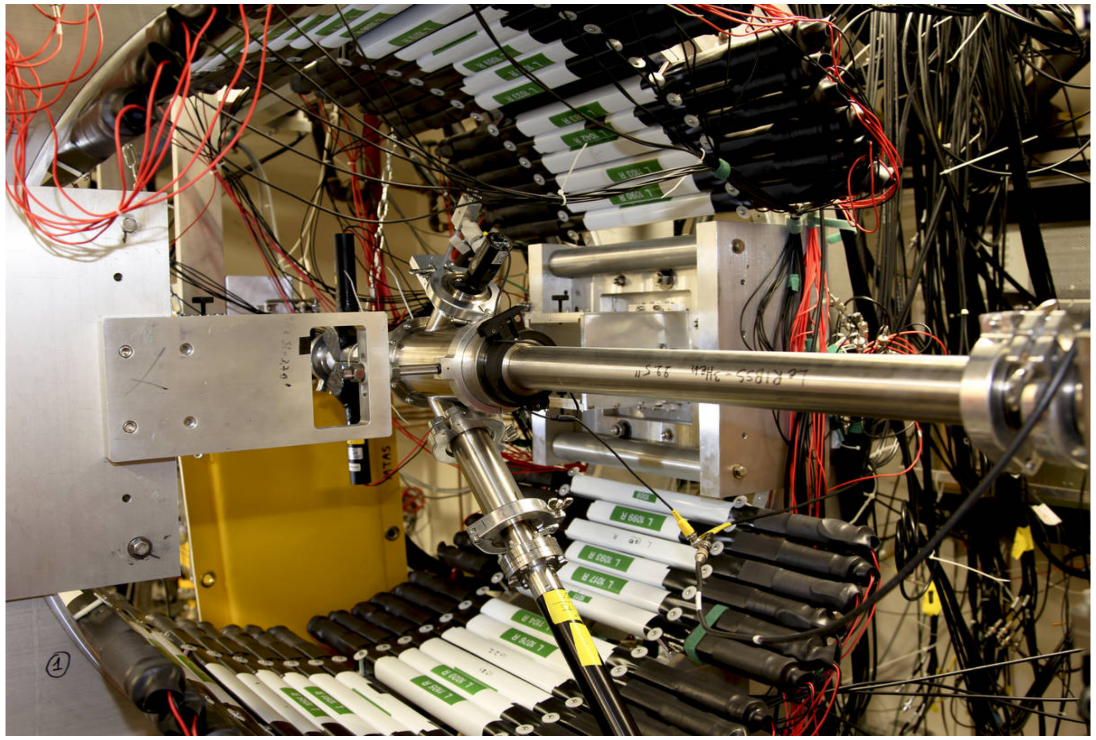
Schematic energy-level diagram for β-delayed neutron emission.



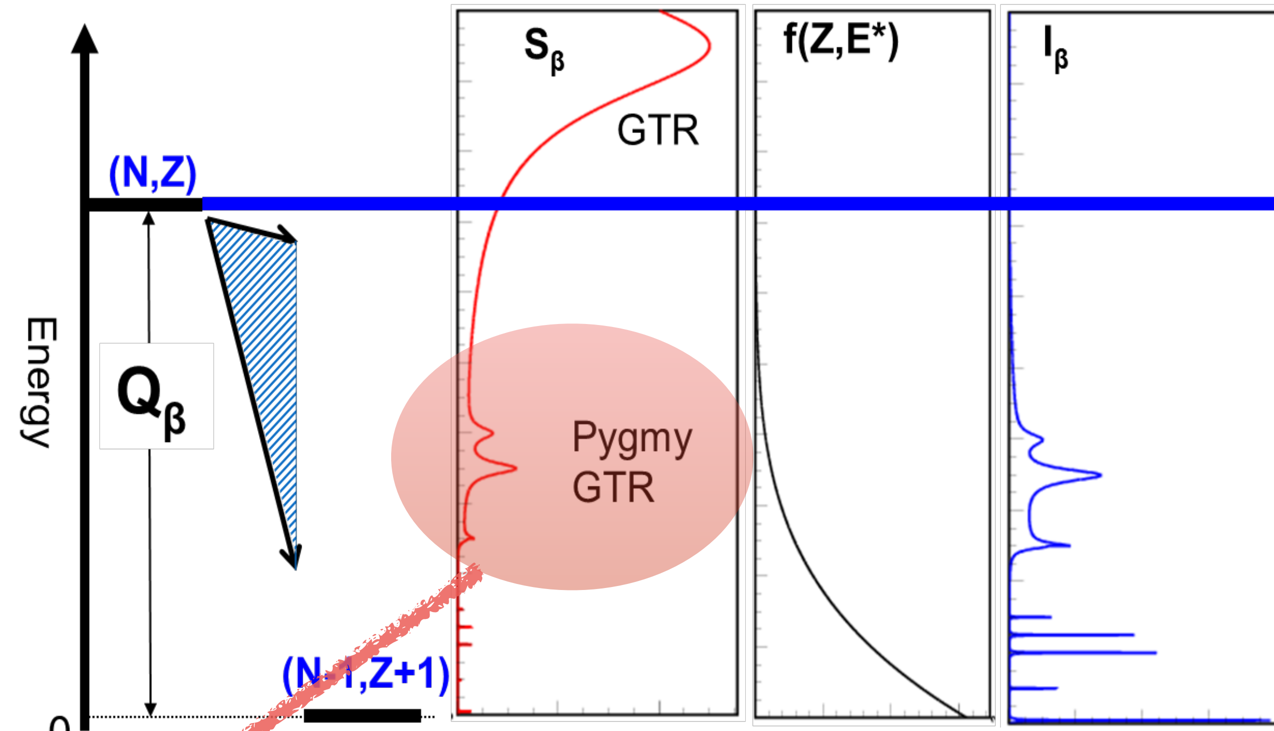
→ **all r-process nuclei are beta-n emitters**

→ **multi-neutron emission becomes important**

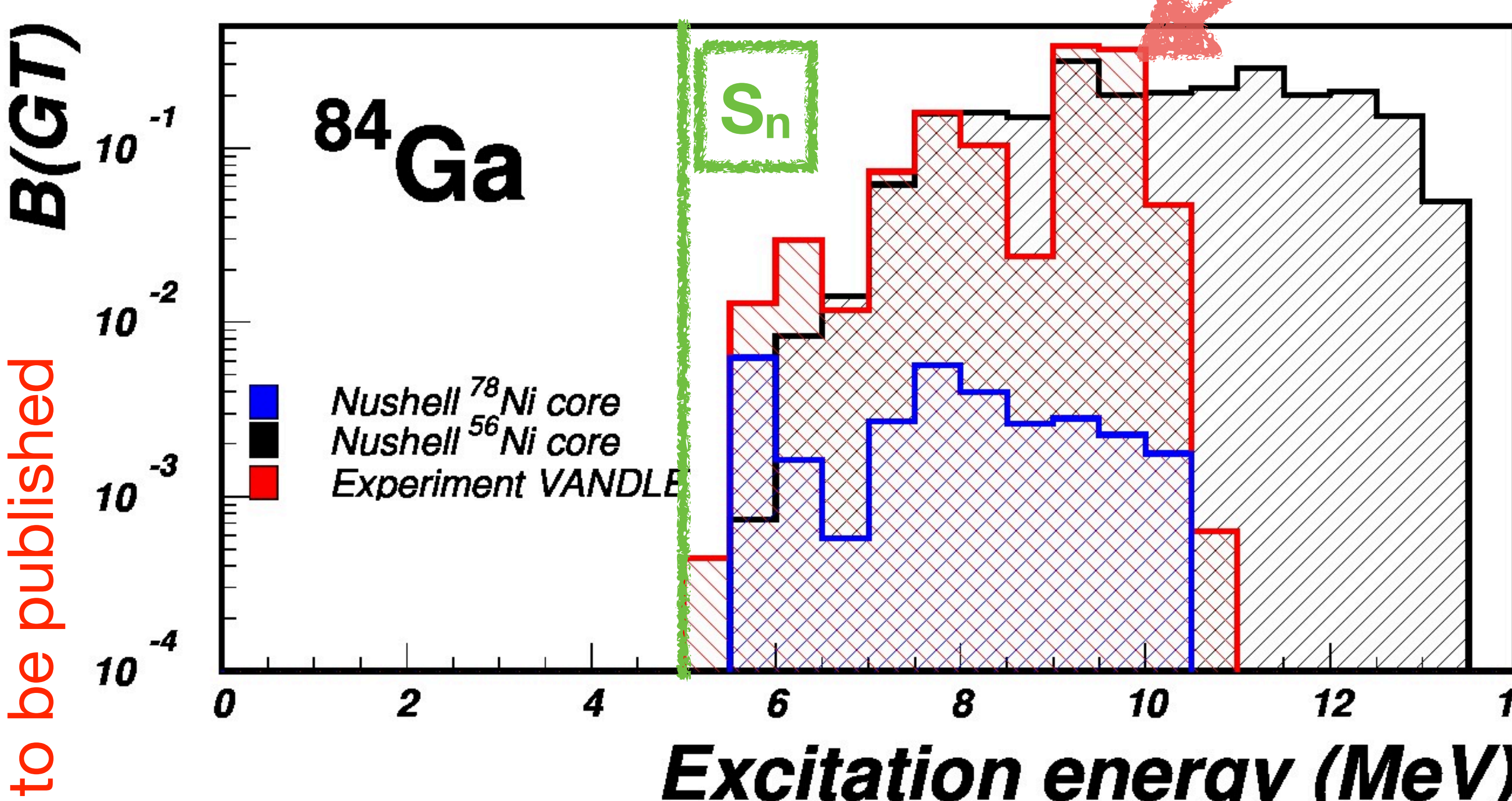
Beta-delayed neutron studies with VANDLE



Versatile Array of Neutron Detectors at Low Energy (VANDLE)



$$\frac{1}{T_{1/2}} = \sum_{E_i \geq 0}^{E_i \leq Q_\beta} S_\beta(E_i) \times f\left(Z, Q_\beta - E_i\right)$$



results: M. Madurga et al. to be published

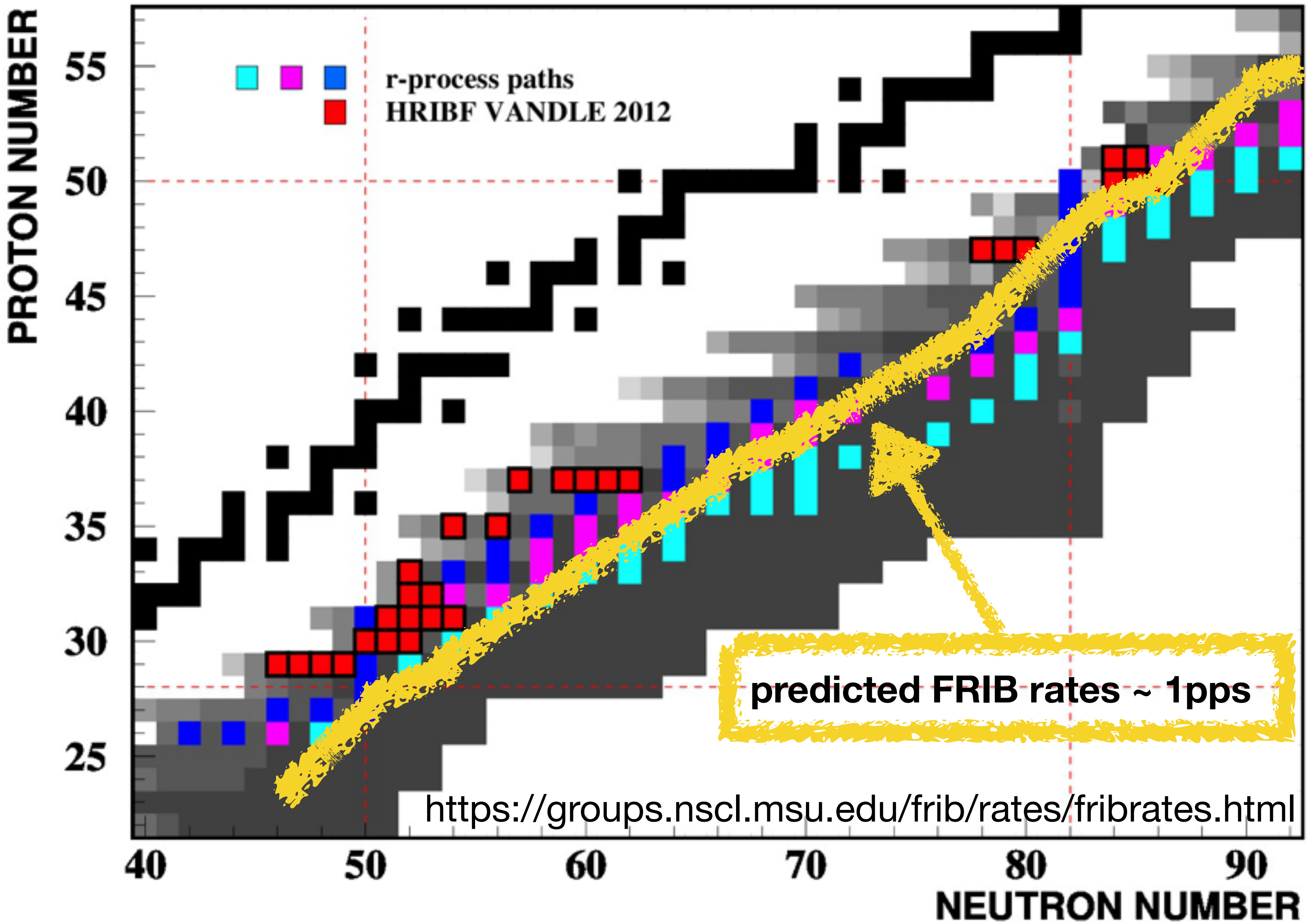
- **Large beta decay strength above S_n (neutron separation energy)**
- **Gamow-Teller (GT) transition dominates beta-neutron emission**

Beta-delayed neutron decay studies @ FRIB

Large number of very neutron-rich nuclei expected to be produced @ FRIB

Predicted properties of neutron rich nuclei:
70% of all neutron rich nuclei have P_{1n} > 10%
about half are beta delayed multi-neutron emitters

Experimental information needed to model theoretical predictions especially for heavier nuclei

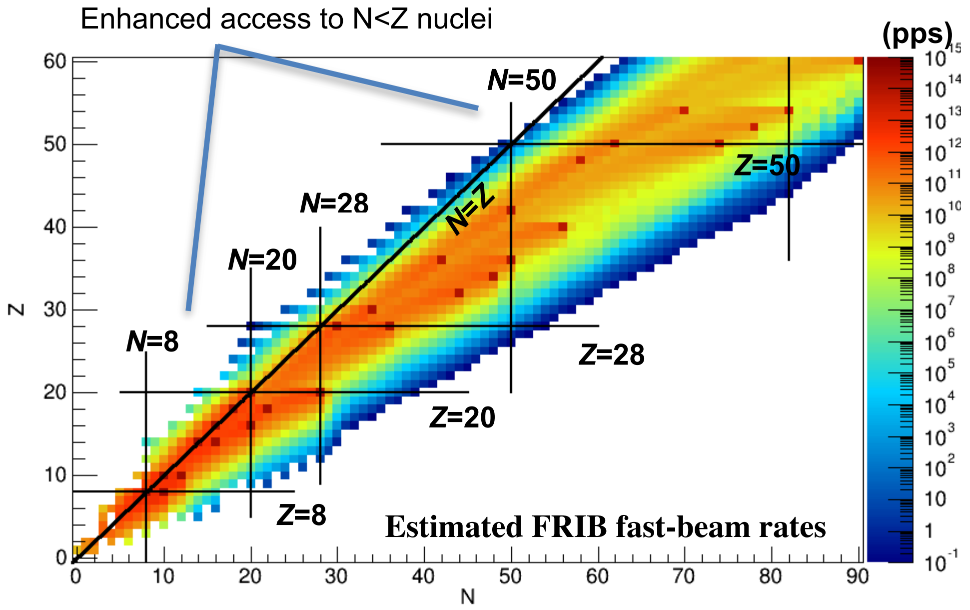


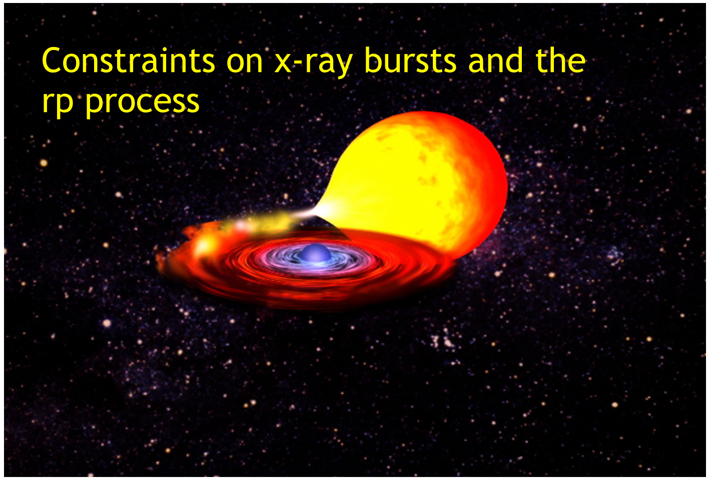
FRIB rates enable energy resolved beta-delayed neutron spectroscopy on r-process nuclei

Accurately charting the proton drip line

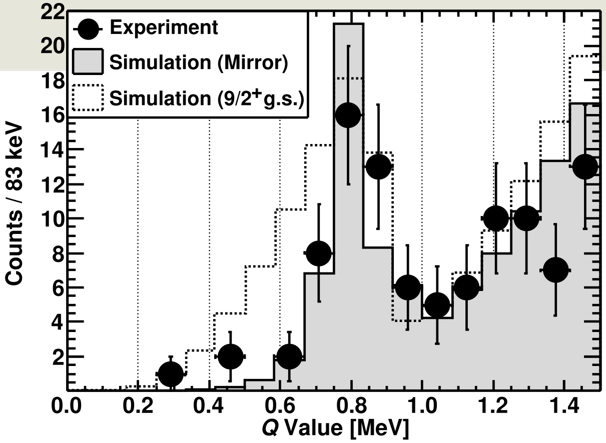
Andrew M. Rogers - *Department of Physics, UMass Lowell*

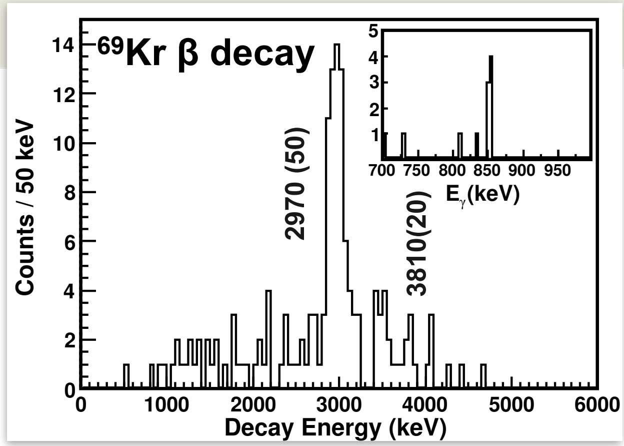
- *What are the **limits of stability** and how does structure change for unbound systems?*
- *Fully defining the **rp process** pathway.*
- *Exploring and testing **mirror symmetry** for mid-mass nuclei.*
- We have an opportunity to accurately define and obtain detailed data on nuclei at and beyond the proton drip line. (Perhaps not possible on the *n*-side)

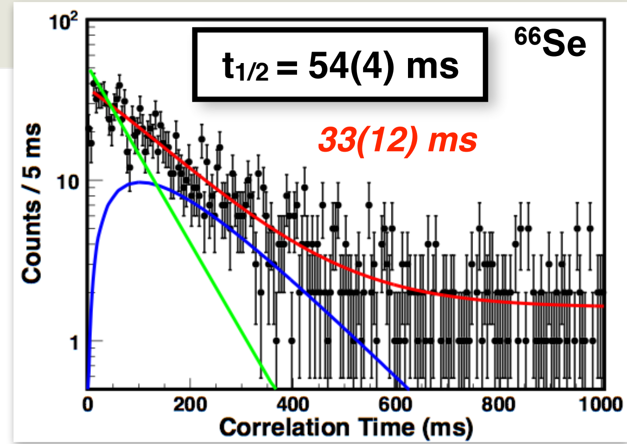




Present status of recent studies



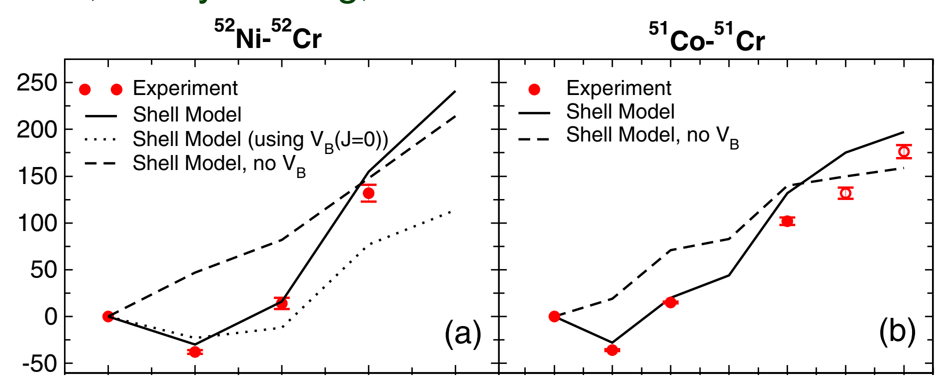




A.M. Rogers. et. al, PRL 106, 252503 (2011) A.M. Rogers et al., Physical Review C 84, (2011)

- Good progress on first direct measurement of ^{69}Br (A.M. Rogers et. al) and direct mass measurement of ^{65}As (X.L. Tu et al.).
- New mass measurements along the *rp*-process path (*e.g.* ^{68}Se J. Savory et. al) and β-decay half-lives.
- Probing structure through β decay - New data on IASs, decay feeding, and transitions.

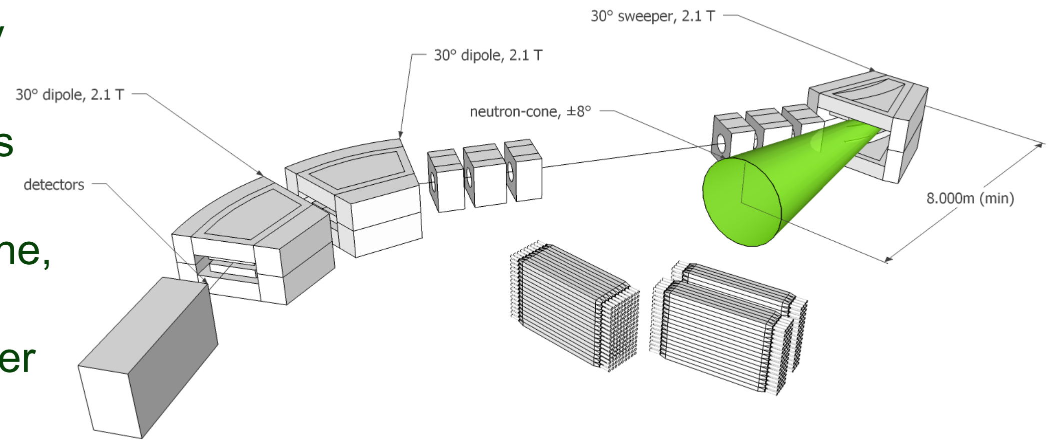
- Mirror symmetry studies for large A along the *N*=*Z* line.
- MEDs obtained through knockout reactions are providing new insight into isospin non-conserving interactions.



P.J. Davis et. al, PRL 111, 072501 (2013)

Future plans and potential resources

T. Baumann HRS concept design



Shorter term

- Studies in the vicinity of ^{73}Rb using decay spectroscopy and β-decay.
  - Strongly constrain the major *rp*-process waiting points.
  - Probe of nuclear structure at the drip line, testing isospin symmetry.
- New beam development at NSCL for better production of neutron-deficient nuclei.

Longer term

- We need ***intensity***, ***efficiency***, ***selectivity*** to extend studies into the most exotic regions.
  - ATLAS intensity upgrade to improve our searches with fusion evaporation.
  - FRIB intensities will allow us to reach the most extreme values of T_z and perform spectroscopy.
- To match to the higher beam energies at FRIB will require new detectors systems.
  - High-Rigidity Spectrometer (HRS) - new charged particle arrays to couple to gamma arrays.
  - Decay spectroscopy at FRIB.

Ground-State Electromagnetic Nuclear Moments (μ, Q) & Mean-square charge radius $\delta\langle r^2\rangle^{AA'}$ by Laser Techniques

- μ arises from orbital-angular momentum and intrinsic spin
  - Q and $\delta\langle r^2\rangle^{AA'}$ represent the nuclear-charge distribution

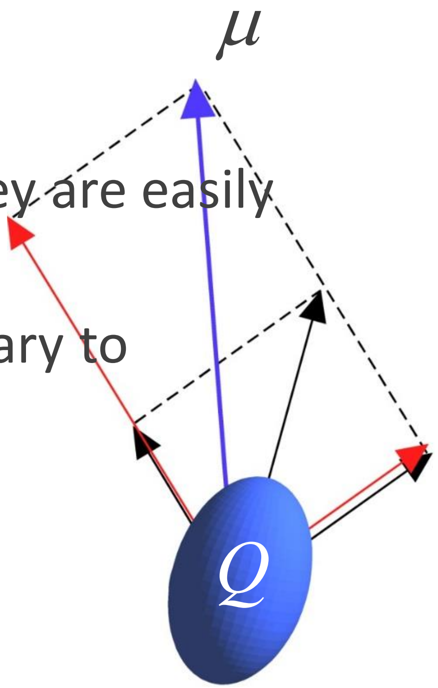
Science: Nuclear Structure and its Variation toward the Driplines

Why: μ, Q and $\delta\langle r^2\rangle^{AA'}$ are

- Sensitive to details of the nuclear wavefunction.
- Originating from well-known electromagnetic interactions, so that they are easily applied in various theories.
- One-body operators acting on a single nuclear state and complementary to transition moments.
- Sensitive to shape and difference between *A* and *A'* (deformation)

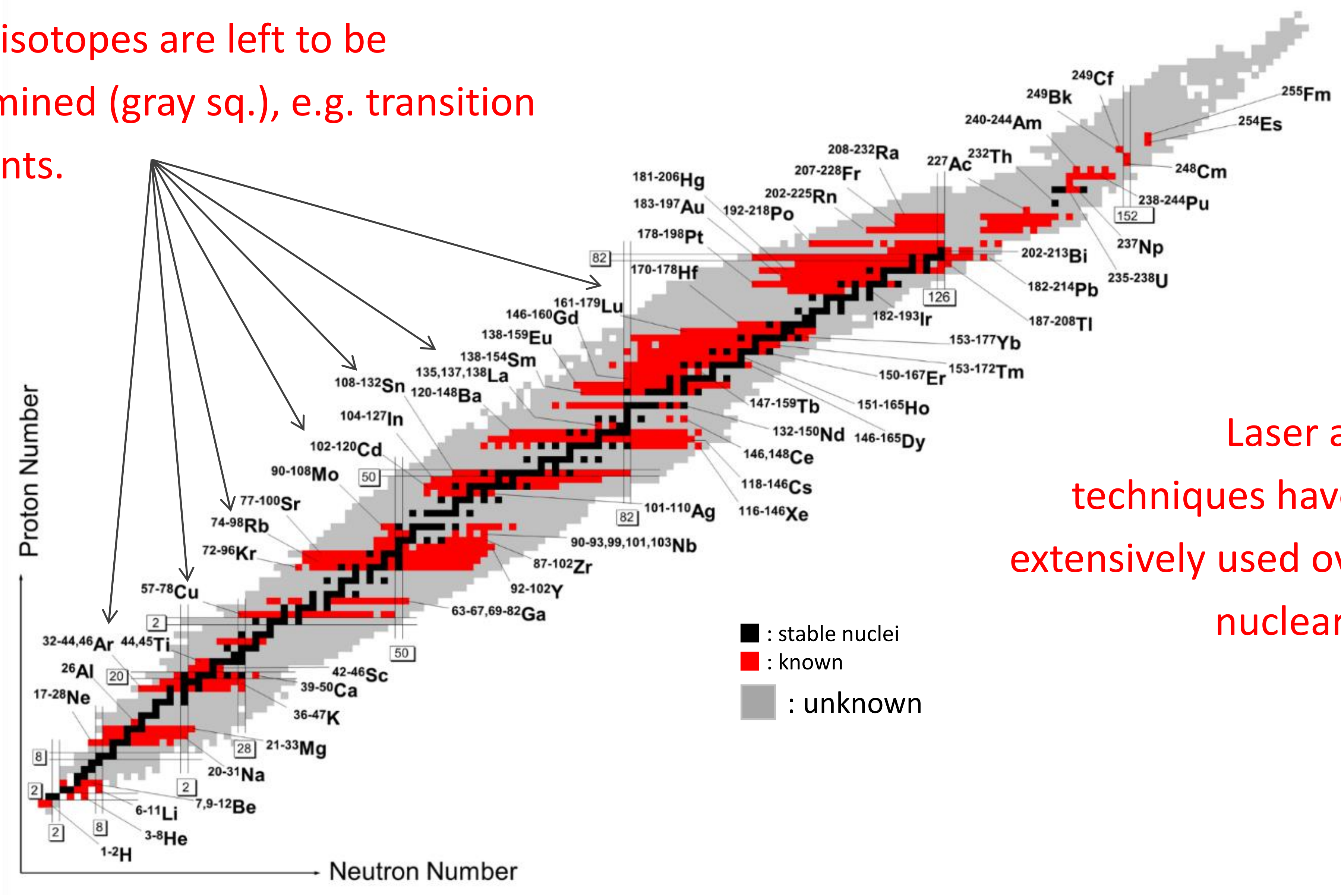
Approach: to advance our understanding

- Measurements of key nuclei in the proximity of closed shells
- Systematic measurements, and/or extension of known, chains of isotopes



Present Status of μ, Q & $\delta\langle r^2\rangle^{AA'}$

Many isotopes are left to be determined (gray sq.), e.g. transition elements.



Laser assisted techniques have been extensively used over the nuclear chart.

K. Minamisono, Joint DNP Town Meeting, Mitchell Institute, Texas A&M Univ. Aug. 21-23, 2014.

K. Blaum et al., PST152, 014017 (2013).

How?: experiment

Laser assisted techniques + stopped (~60 keV) beams @ NSCL/FRIB

10^5 /s

- collinear laser spectroscopy
- bunched beam coincidence laser spectroscopy
- optical pumping + bNMR
- optical pumping + b-decay asymmetry detection

BECOLA (existing) at NSCL/FRIB

1 /s

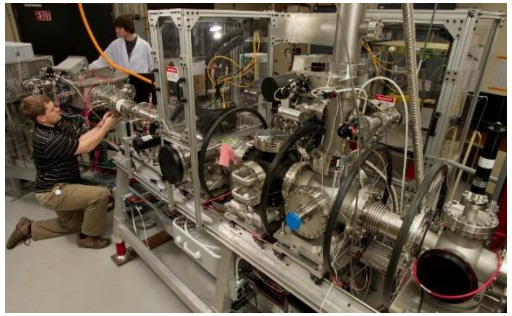
- collinear resonant laser ionization spectroscopy

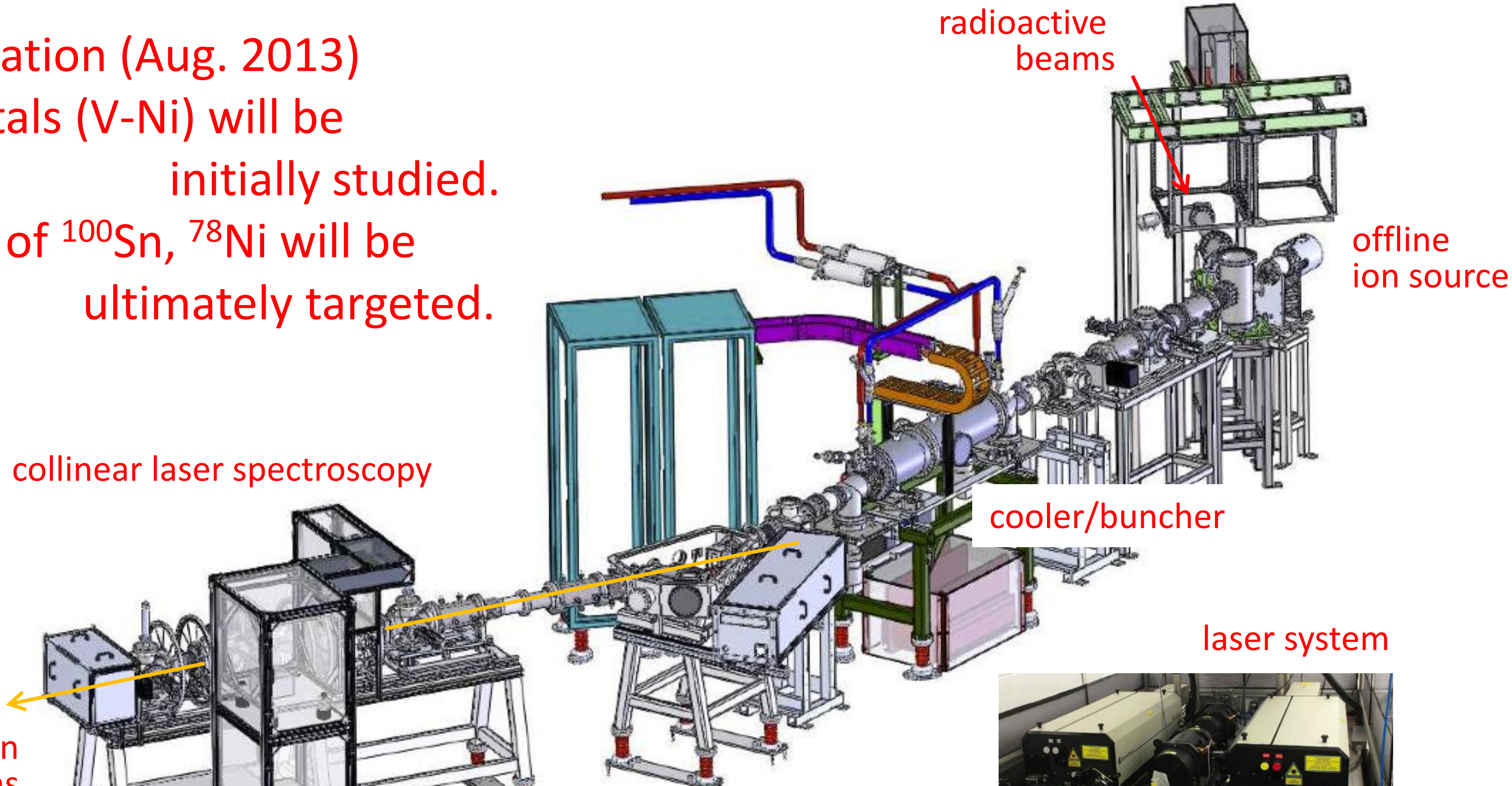
CRIS (to be built, $1.5M) at FRIB

Highly sensitive and selective techniques

BECOLA facility @ NSCL, MSU
- BEam COoling and LAser spectroscopy -

- Started online operation (Aug. 2013)
- Light transition metals (V-Ni) will be initially studied.
- Laser spectroscopy of ^{100}Sn, ^{78}Ni will be ultimately targeted.





laser system

K. Minamisono, Joint DNP Town Meeting, Mitchell Institute, Texas A&M Univ. Aug. 21-23, 2014.

K. Minamisono et al, NIMA 709, 85 (2013).

Laser spectroscopy: light nuclei and neutron rich fission isotopes

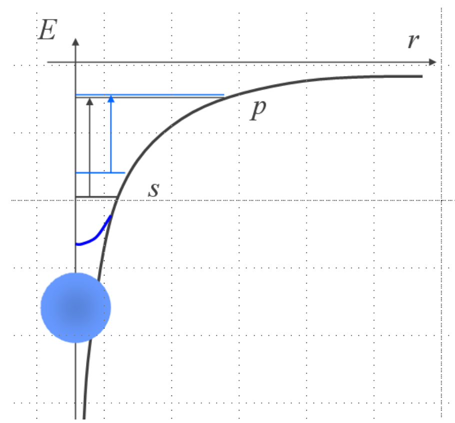
Peter Mueller

Laser Spectroscopy & Nuclear Structure

- ***Nuclear ground state properties*** from atomic spectroscopy
- ***Model independent,*** precision measurement

- Atomic ***isotope shifts*** -> ***charge radii***

$$\delta\nu_{FS} = -\frac{2\pi}{3} Ze^2 \cdot \Delta|\Psi(0)|^2 \cdot \delta\langle r^2\rangle^{AA'}$$

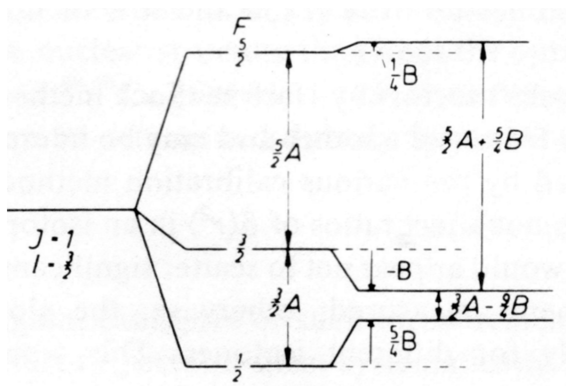


- Atomic ***hyperfine structure***

  -> ***nuclear spin and moments*** (single-particle & collective)

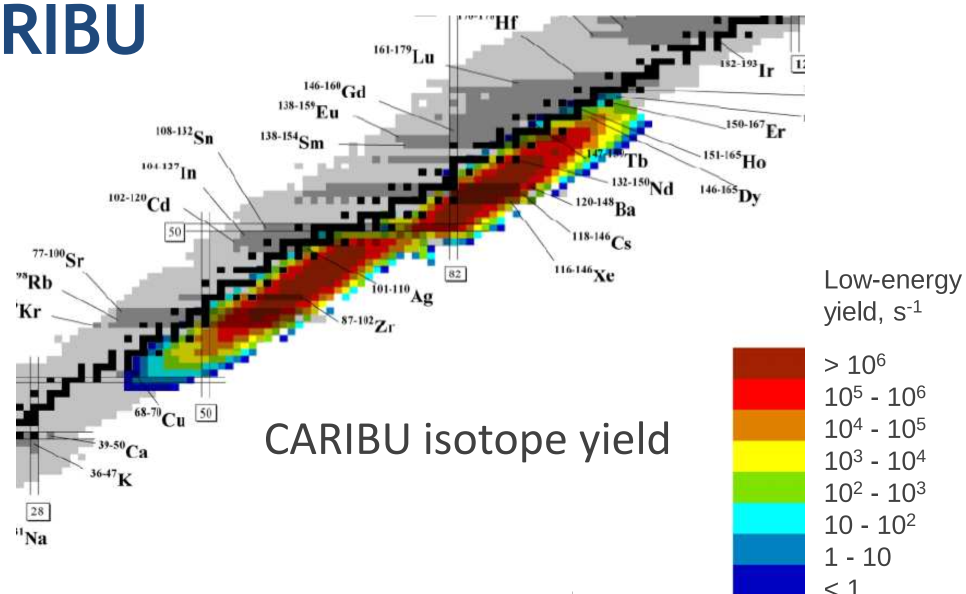
$$\Delta E_{HFS} = \frac{A}{2} C_1(I, J, F) + \frac{B}{4} C_2(I, J, F) + \ldots$$

$$A = \frac{\mu_I H_e(0)}{I \cdot J} \qquad B = eQ_s \left\langle \frac{\partial^2 V_e}{\partial z^2} \right\rangle$$



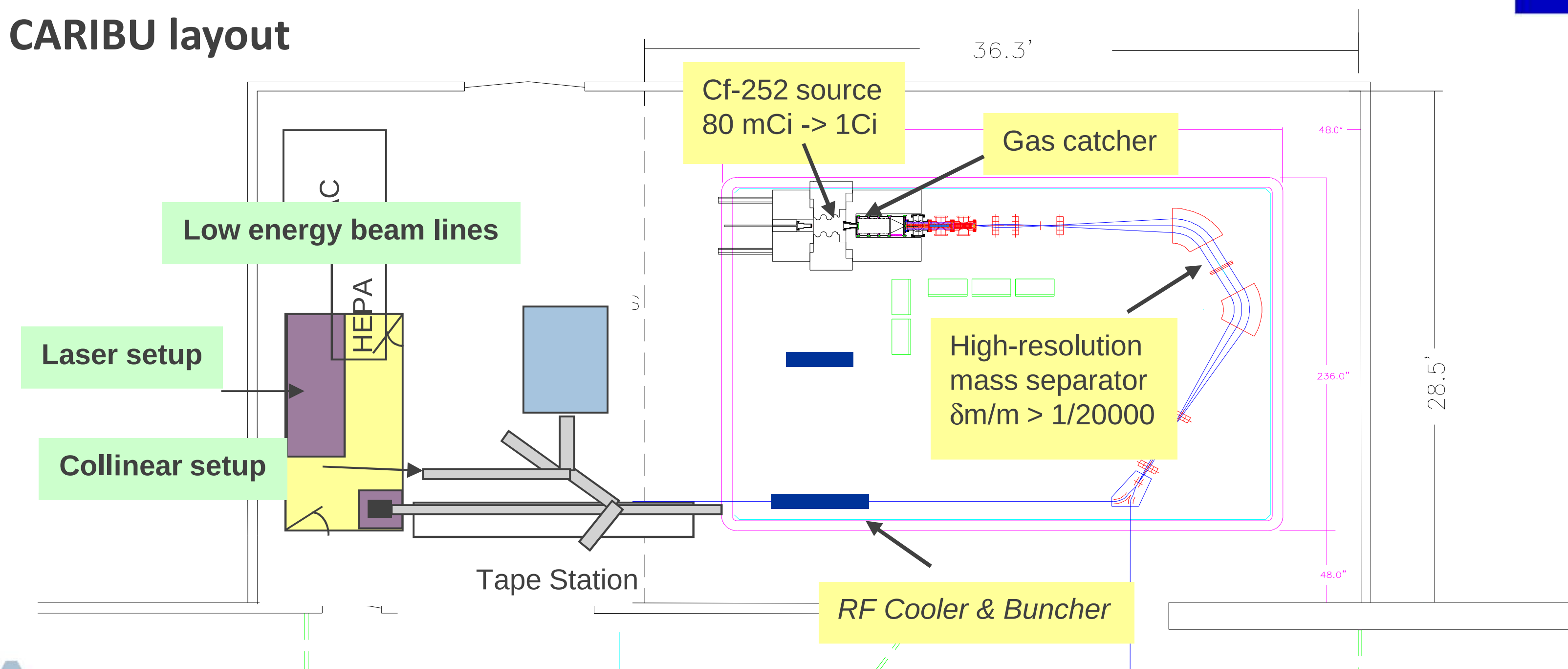
Laser Spectroscopy @ CARIBU

- > 1 Ci ^{252}Cf fission source + gas catcher and isobar separator
- access to neutron rich isotopes including refractory elements
- cooled, bunched ion beam @ ~ 10 keV
- Low energy experimental area to be expanded into former tandem hall



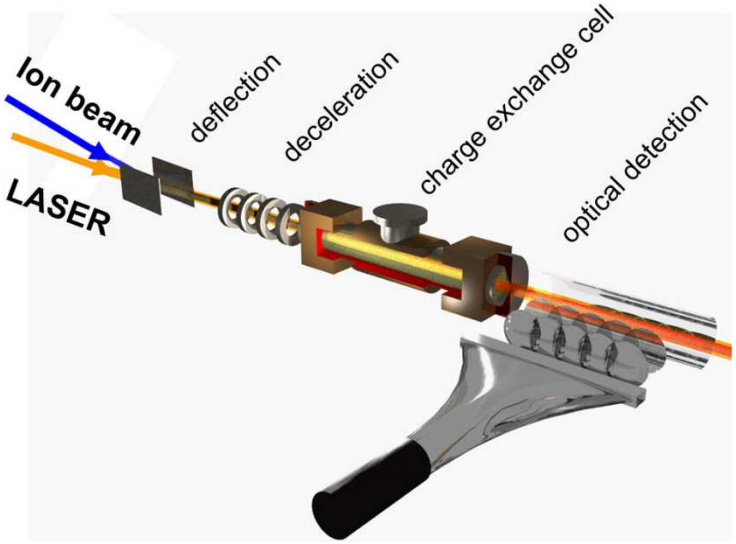
CARIBU isotope yield

CARIBU layout



Laser Spectroscopic @ CARIBU

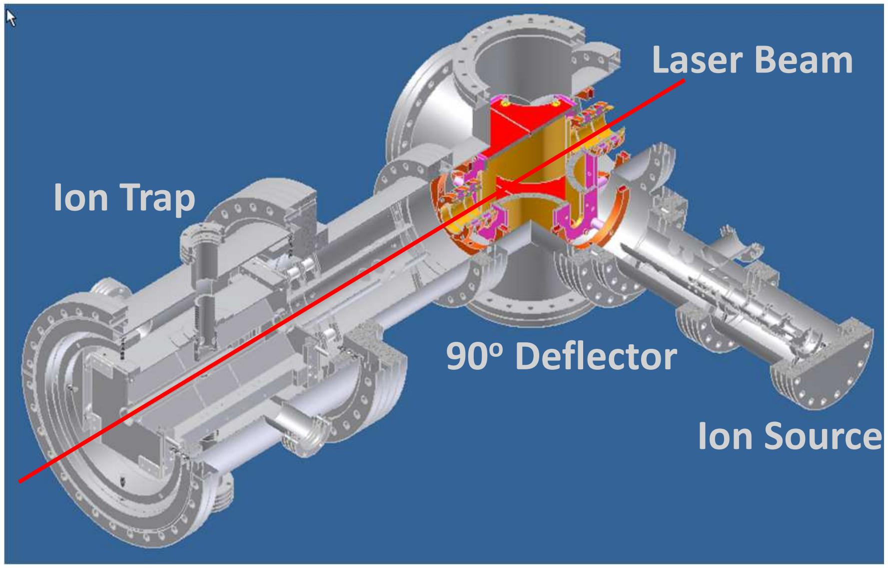
Collinear spectroscopy



- High spectroscopic resolution
- High sensitivity through bunched beams
- Measure for the first time: Pd, Sb, Rh, Ru
- Extend isotopic chains: Y, Zr, Nb, Mo

- Ion beam line elements designed (with Mainz University & TU Darmstadt)
- Offline tests in 2014, Installation in 2015

In-trap spectroscopy



- High sensitivity: few to single ion
- Open geometry, LN_2 cooled linear Paul trap
- Buffer gas cooling

- Ion source and deflector constructed
- Ion trap designed
- Off-line tests with Ba^+ 2015/16

Laser spectroscopy of ^{8}B

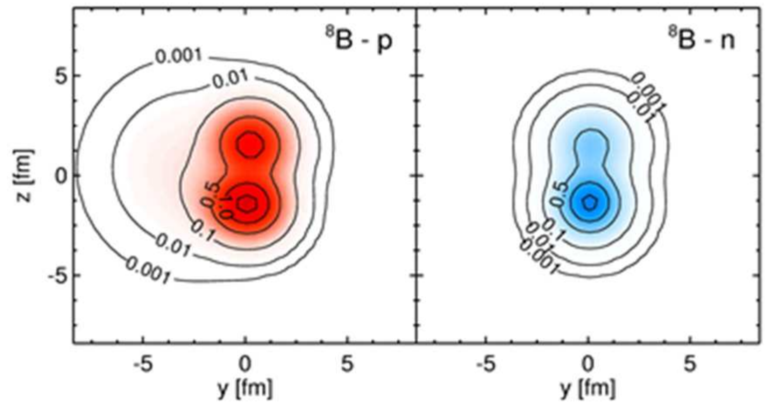
A. Leredde[1], Ch. Geppert[3], *A. Krieger*[2,3], P. Mueller[1], W. Nörtershäuser[2]

[1] Physics Division, Argonne National Laboratory
[2] Institut für Kernphysik, TU Darmstadt
[3] Institut für Kernchemie, Universität Mainz

Argonne NATIONAL LABORATORY

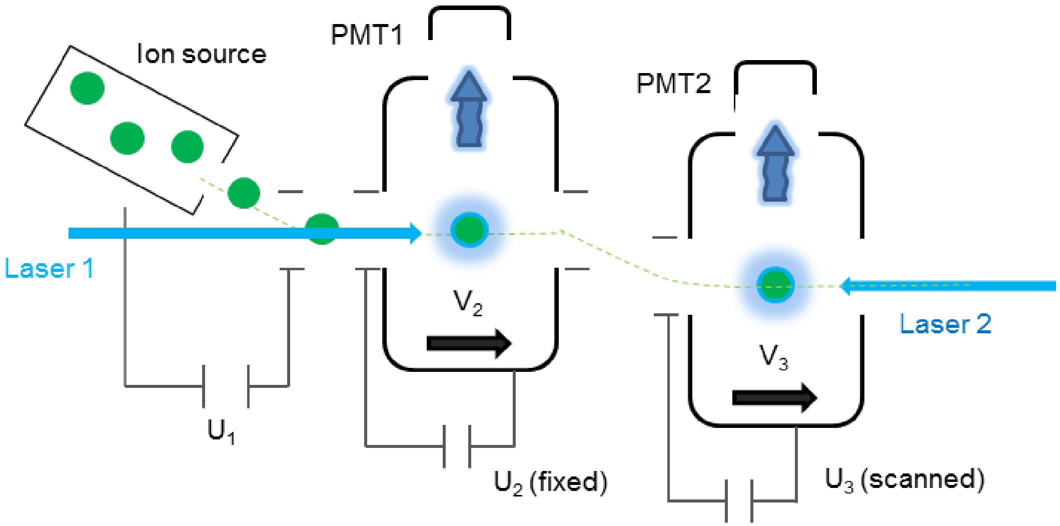
TECHNISCHE UNIVERSITÄT DARMSTADT

JG|U



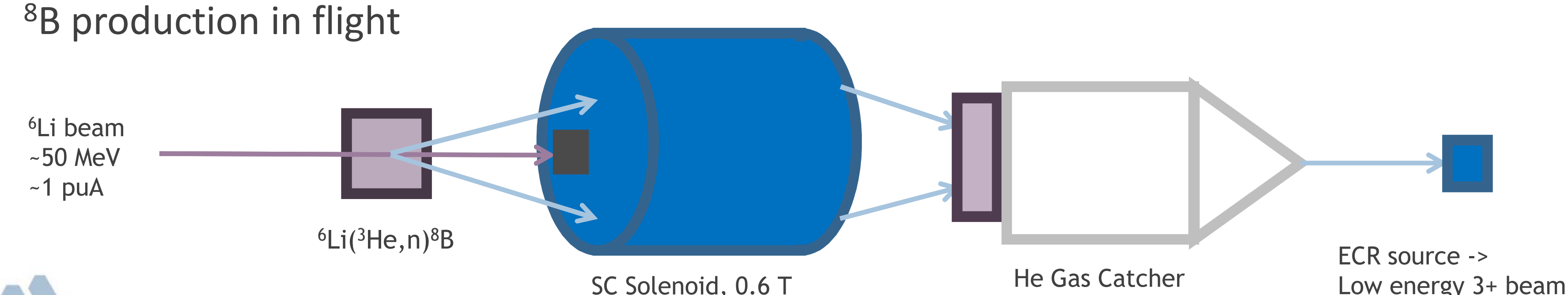
Intrinsic densities of the proton-halo candidate ^{8}B calculated in the fermionic molecular dynamics model (courtesy of T. Neff – GSI).

Collinear laser spectroscopy

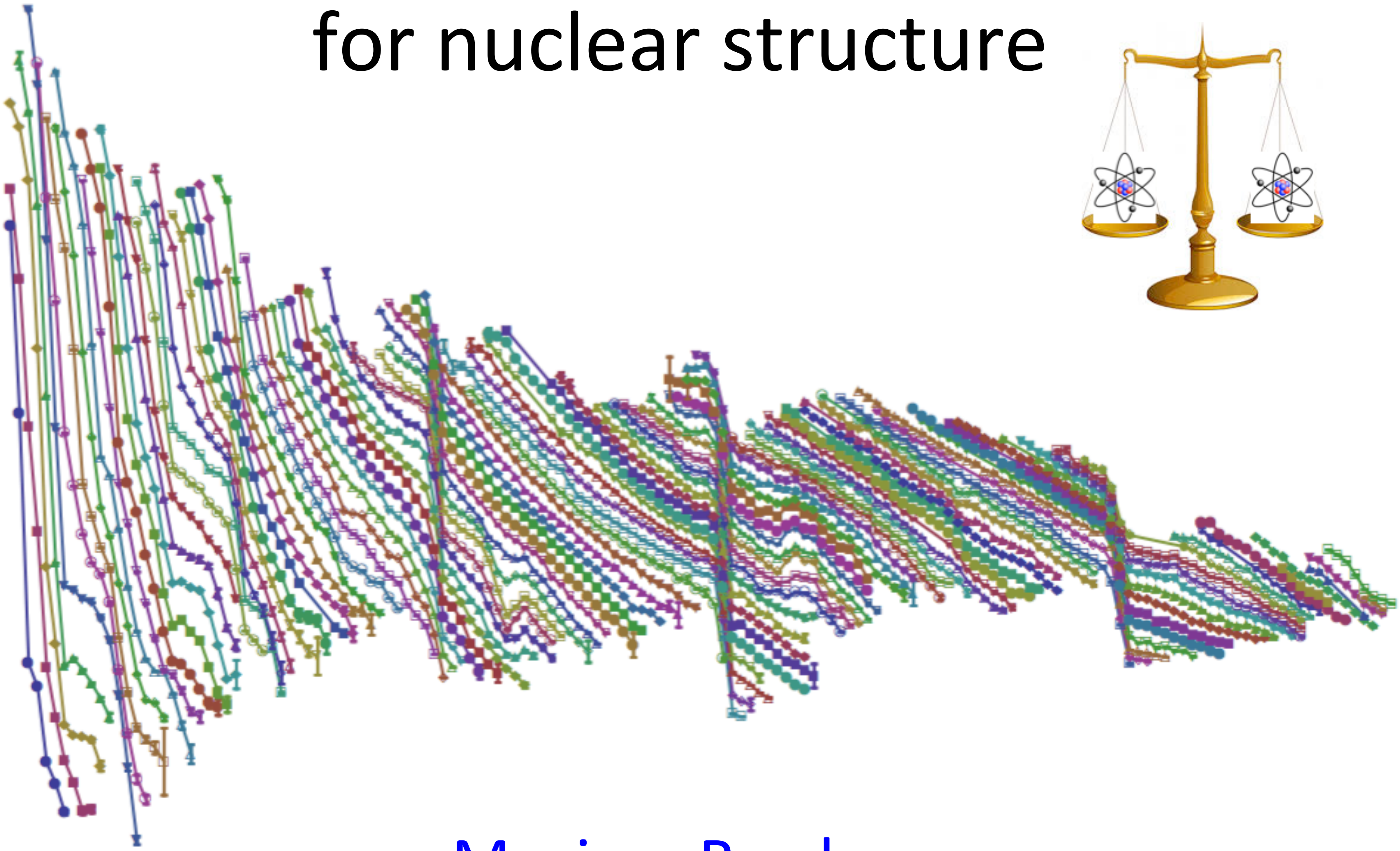


- ^{8}B production in flight & gas catcher
- Charge breeding in ECR source
- Spectroscopy on helium-like transition in B^{3+}
- Collinear spectroscopy with velocity selective pump/probe

^{8}B production in flight



High precision mass measurements for nuclear structure



Maxime Brodeur

University of Notre Dame

Mass measurements for nuclear structure

High precision mass spectrometry (MS) is important as it can unveil changes in nuclear structure such as:

- Erosion & quenching of shell closure (N = 20, 28, …)
- Emergence of new shell closure (N = 16, 32, 34, …)
- Deformation, collectivity, pairing, long-lived isomers…

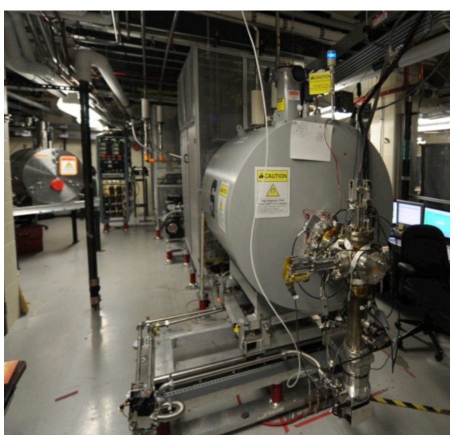
As these changes occur far from the valley of stability, it requires the use of rare isotope beams.

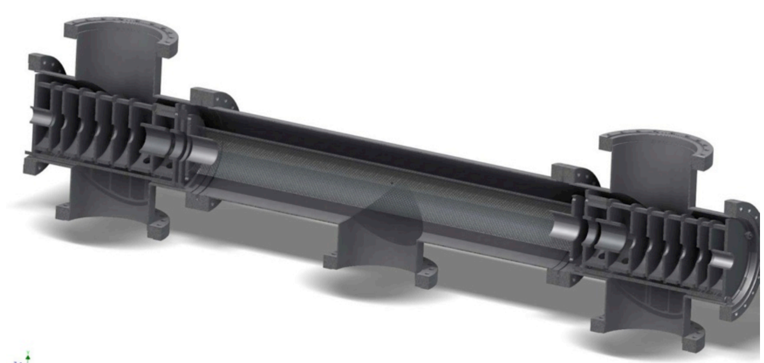
Among various production methods, fast beam production (coupled to gas cells) represent the best path forward, because:

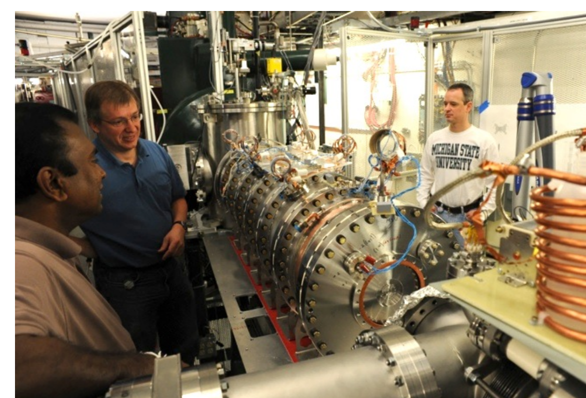
- Element-independent production way
- Access to many areas of interest on the nuclear chart

Technical progress is being made

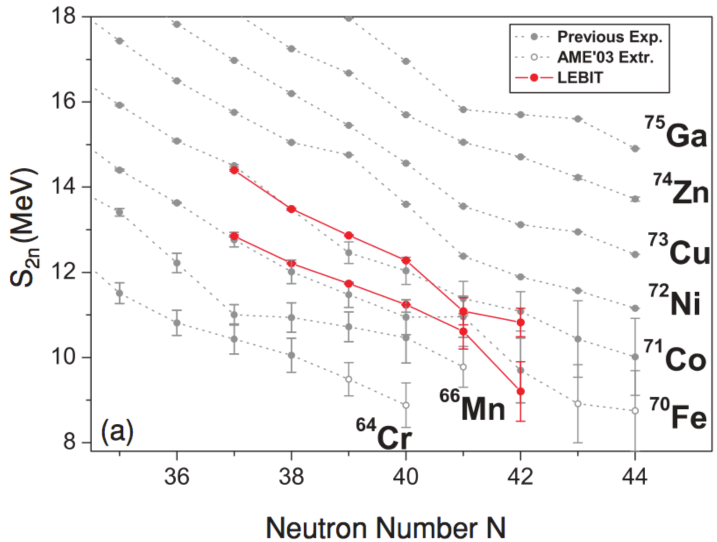
- NSCL developments tailored to leverage FRIB beams
  - Penning trap mass measurements (PTMS) of rare isotopes from fast beam production demonstrated at LEBIT – only facility of this kind worldwide
  - New single-ion Penning trap (SIPT) will provide ultimate sensitivity – path towards ^{78}Ni and ^{100}Sn
  - Advanced beam stopping for more efficient and purer beams
- Other developments provide access to new isotopes
  - PTMS of fission products provided by CARIBU demonstrated at CPT/ANL
  - Multi-reflection time-of-flight mass spectrograph (MR-ToF) underway at ANL, foreseen at NSCL, and being designed at Notre Dame
  - Penning trap at TAMU can be used for mass measurements







Precision MS examples for nuclear structure

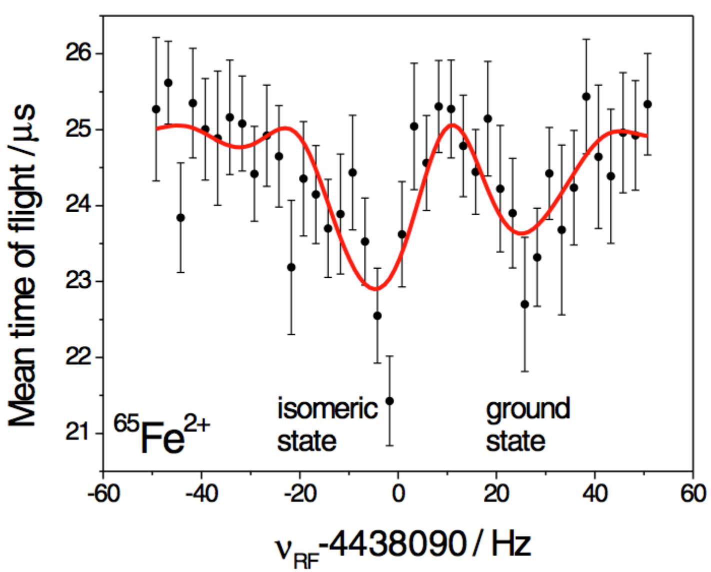


Weakening and vanishing of N = 40 shell closure in Co and Fe

R. Ferrer *et al.*, PRC **81**, 044318 (2010)

Discovery of a nuclear isomer in ^{65}Fe

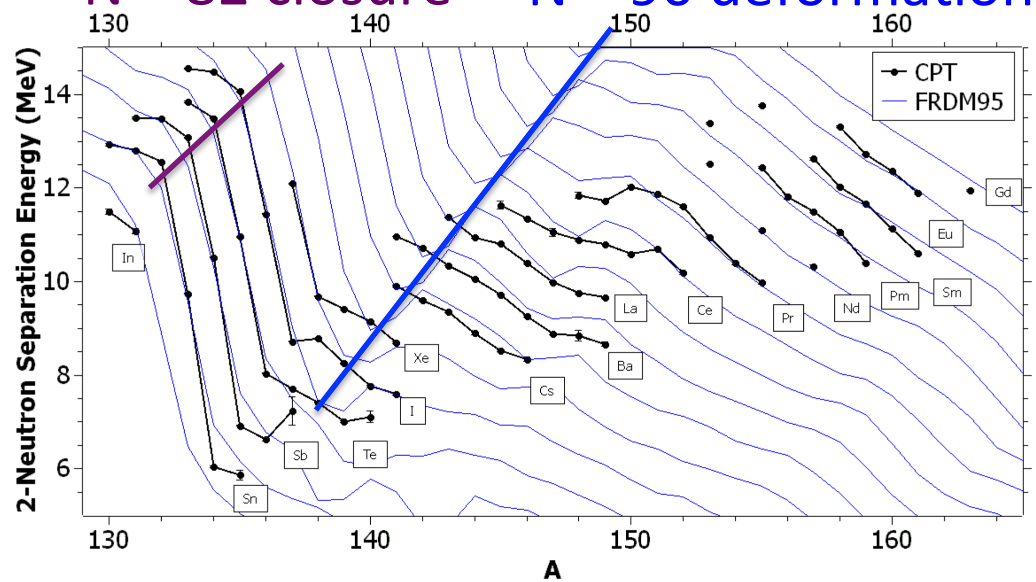
M. Block *et al.*, PRL **100**, 132501 (2008)



FRDM over-predicted N = 90 deformation

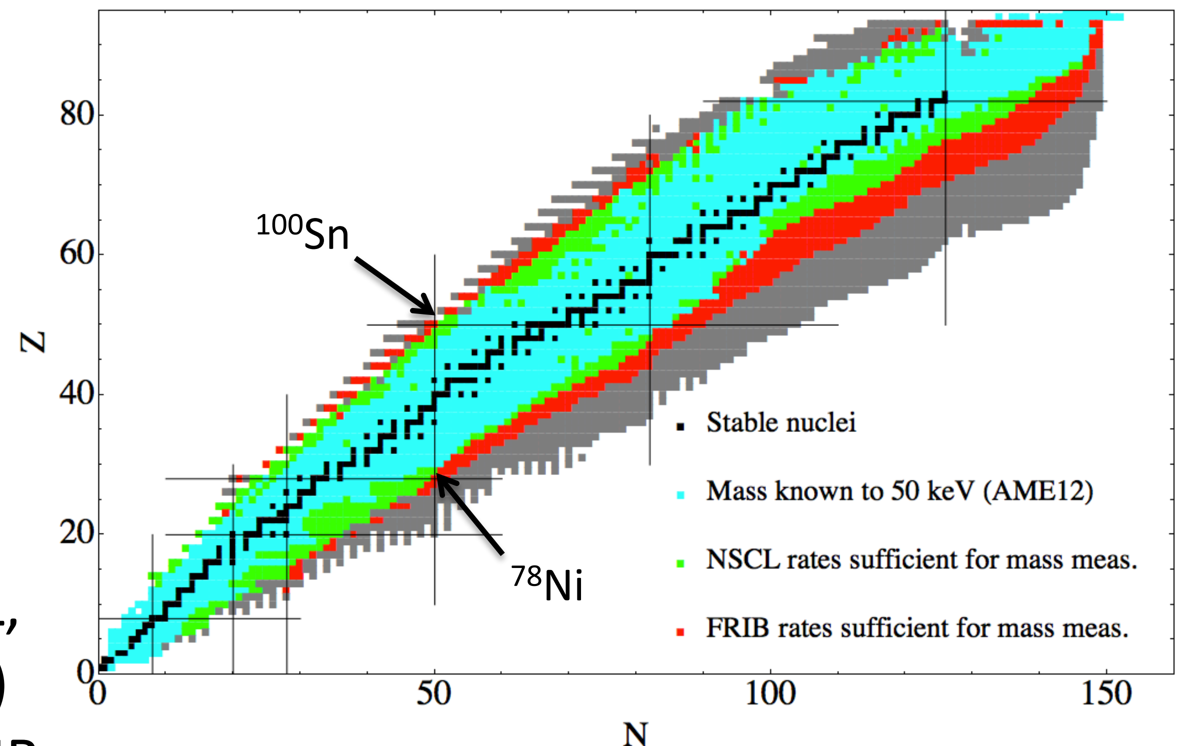
J. Van Schelt *et al.*, PRC **85**, 045805 (2012)

N = 82 closure N = 90 deformation



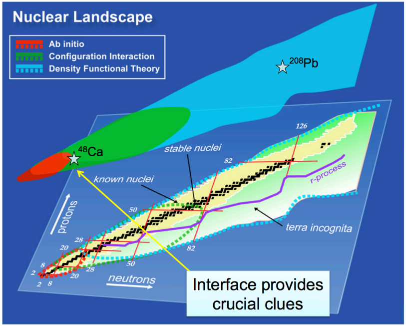
Perspectives and needs for precision MS

- Further development of beam stopping and precise and fast MS techniques will be key to maximizing FRIB science opportunities
- Current MS facilities (LEBIT, CPT) or those under developments (SIPT, MR-ToFs) prepare the path for precision MS at FRIB for nuclear structure, nuclear astrophysics and fundamental symmetries
- Fast-beam TOF-MS will provide broad surveys of mass landscape
- Additional rare isotope beam facilities (e.g. at ANL, TAMU, Notre Dame) will complement FRIB

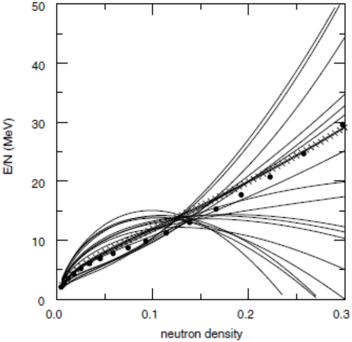


Neutron skins contain rich amount of isovector nuclear structure information

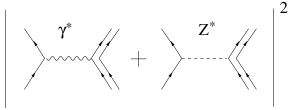
…but difficult to access experimentally with definite systematics



Brown, PRL 85, 5296 (2000)



σ ~

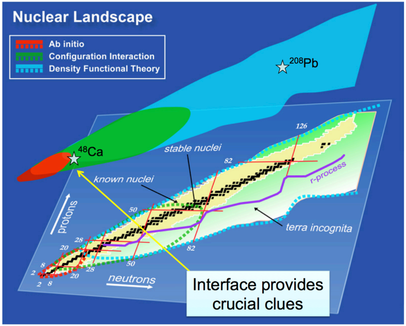


Parity violation gives clean access to neutron form factors

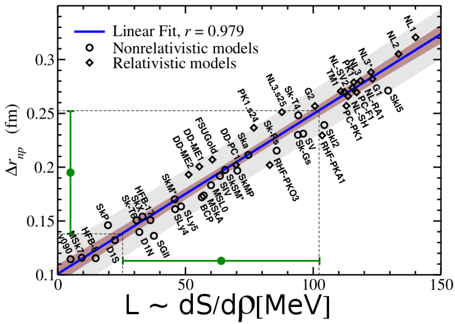
$$A_{\rm PV} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\left[1 - 4\sin^2\theta_W - \frac{F_n(Q^2)}{F_p(Q^2)}\right]$$

Neutron skins contain rich amount of isovector nuclear structure information

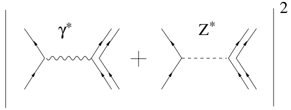
…but difficult to access experimentally with definite systematics



Roca-Maza *et al.* PRL 106 252501 (2011)



$\sigma \sim$



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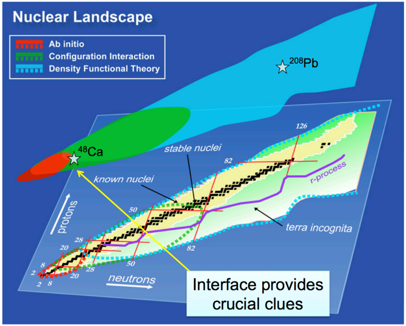
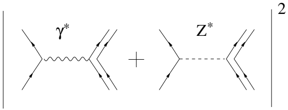


- ^{208}Pb provides information on dense, infinite nuclear matter EOS
- Relevant to neutron stars, DFT calculations
- ^{48}Ca now in regime of microscopic calculations
- Information on 3 neutron forces, weak S-O coupling, ...

$\sigma \sim$



Parity violation gives clean access to neutron form factors

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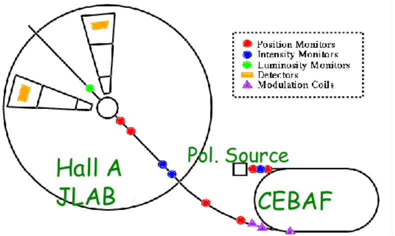
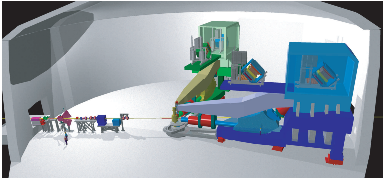
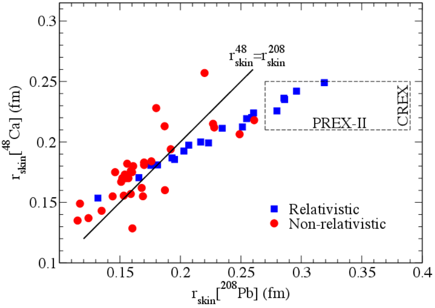
Jefferson Lab is premiere facility to measure neutron skins to high precision - PREX and CREX





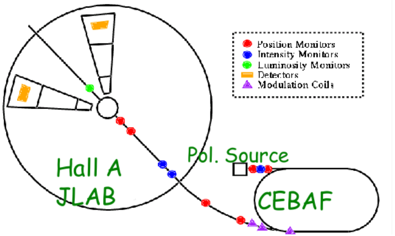


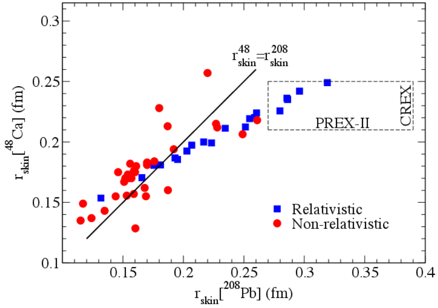
Horowitz *et al.* EPJ A 50 (2014) 48

Jefferson Lab is premiere facility to measure neutron skins to high precision - PREX and CREX

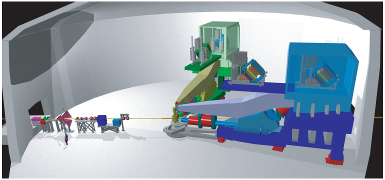
PREX and CREX

- $\sim$1 ppm PV asymmetries
- ^{208}Pb to 0.06 fm in 35 days
  ^{48}Ca to 0.02 fm in 45 days
- PREX rated as "high impact" for JLab PAC41
- Both anticipated to run $\sim$2016





Horowitz *et al.* EPJ A 50 (2014) 48



Heavy and superheavy nuclei: implications for theory.

Witek Nazarewicz (MSU/ORNL)

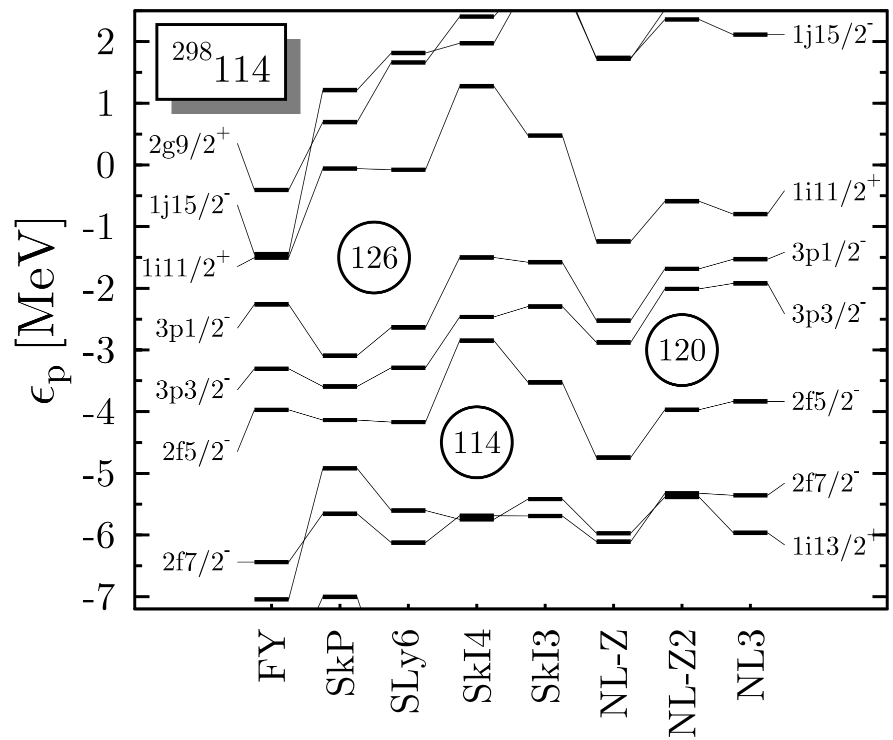
Nuclear Structure and Reactions Session, 2014 LENP Town Meeting

- Superheavy element synthesis and studies
  - What are the limits of nuclear stability?
  - Where are the next spherical shell closures? What is the landscape of the island of stability?
  - Are there long-lived ($t_{1/2}$ > days) superheavy elements?
- Fission

Shell structure and Coulomb frustration

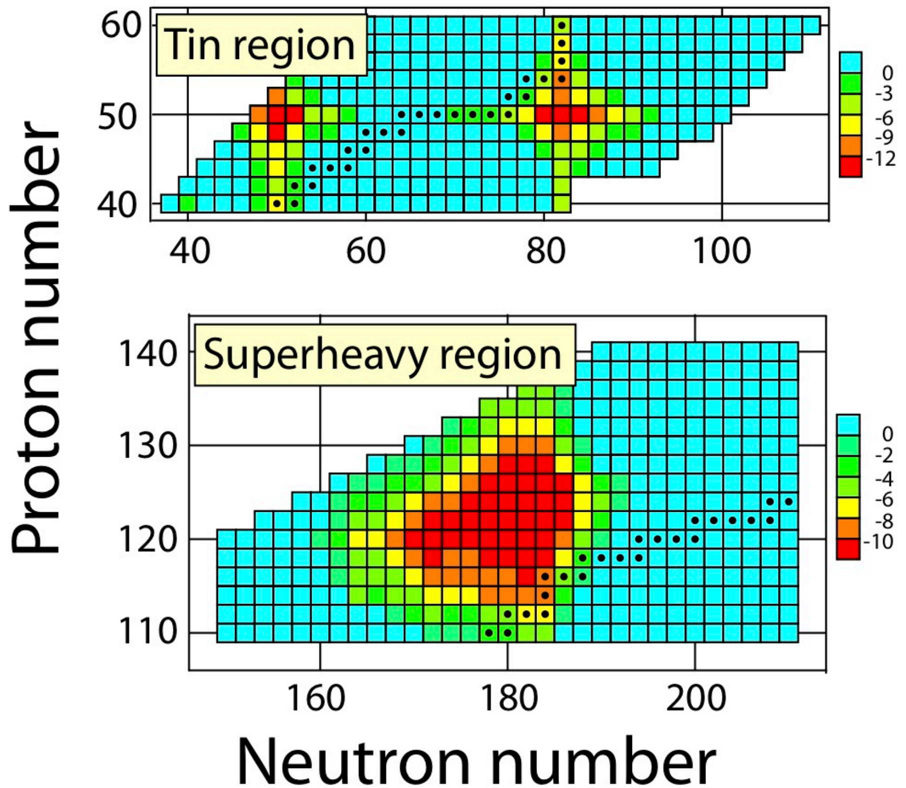
Small shifts of single-particle levels can impact shell structure significantly

Level density



M. Bender et al.
Phys. Rev. C 60, 034304 (1999)

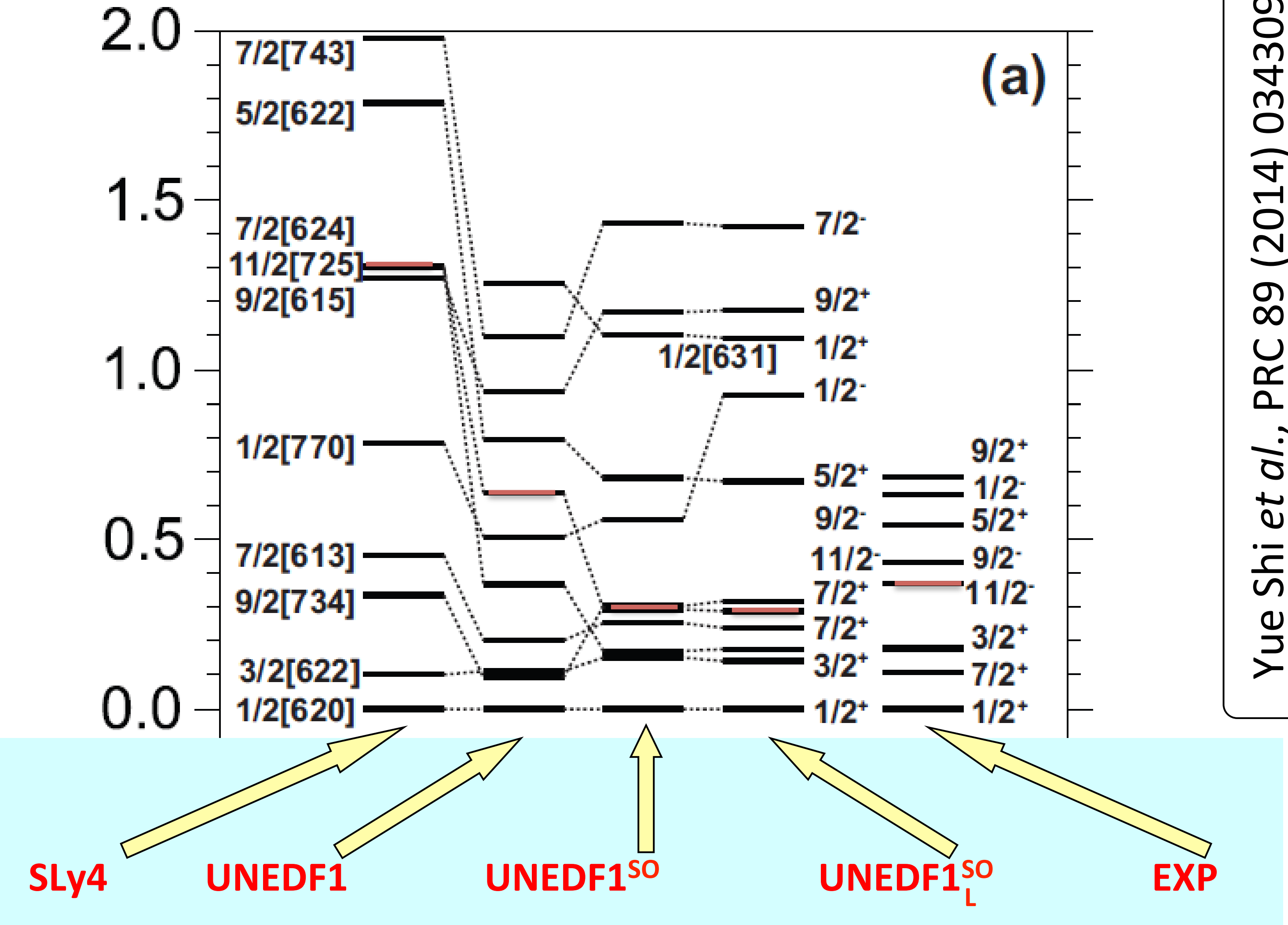
Shell energy



M. Bender et al.
Phys. Lett. B 515, 42 (2001)

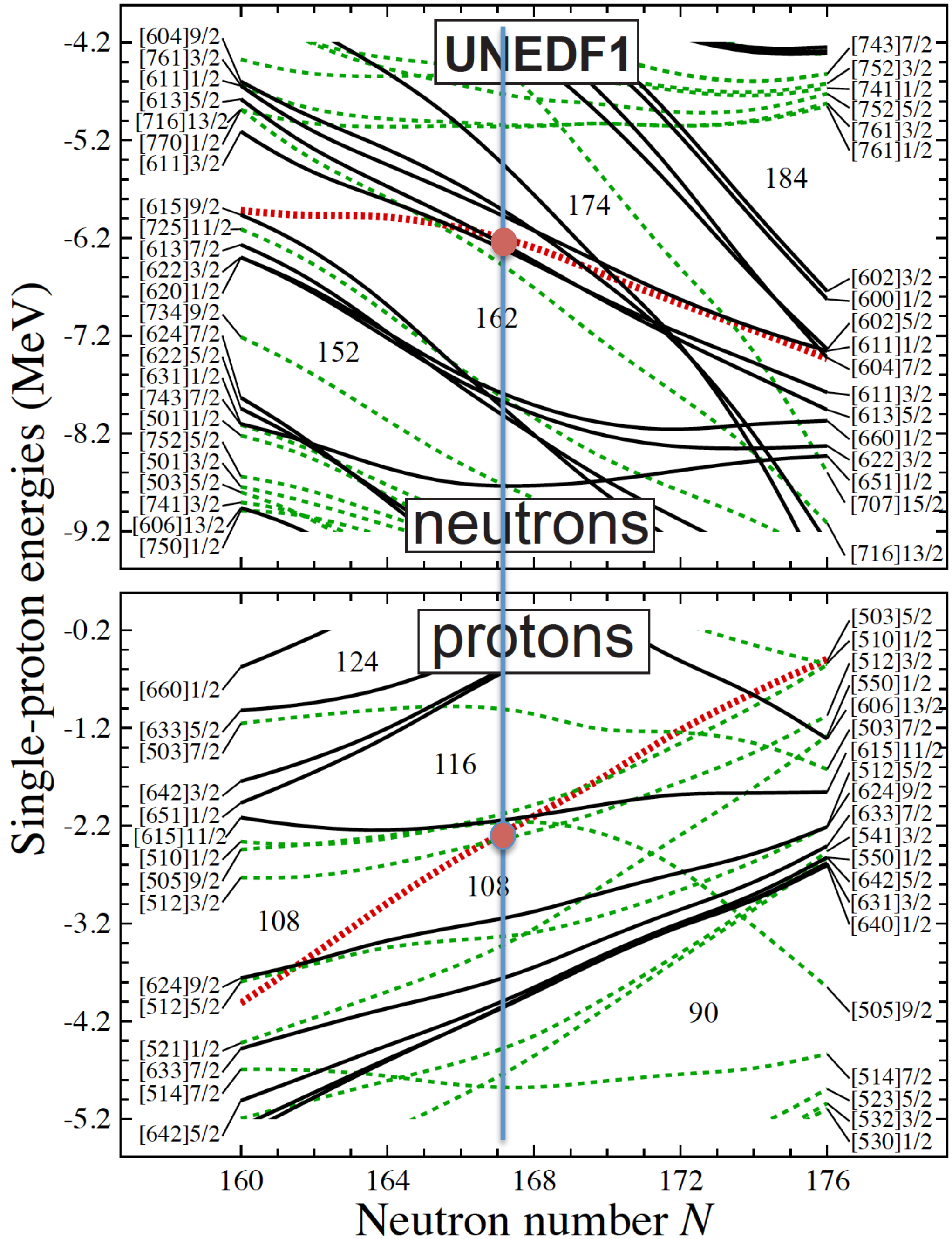
Because of the presence of highly-degenerate high-j levels and the smallness of the gaps in the single-particle spectrum, significant binding originates from the bunching of low-j orbits near the Fermi energy, not from the gaps

Neutron quasi-particle spectra in $^{251}Cf_{153}$



Yue Shi *et al.*, PRC 89 (2014) 034309

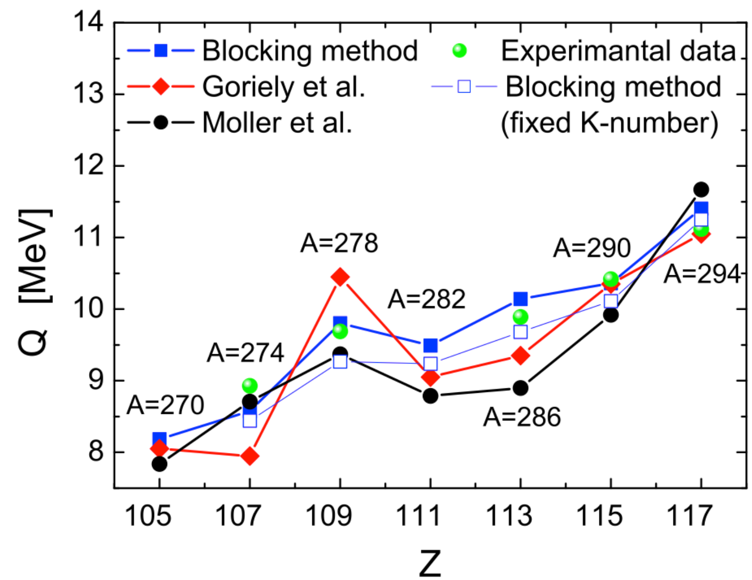
Yue Shi, *et al.*, PRC 90, 014308 (2014)



High-K states in SHE

- unique structural indicators
- isomerism
- impact Q_{α}

see also Jachimowicz et al.
Phys. Rev. C 89, 024304 (2014)



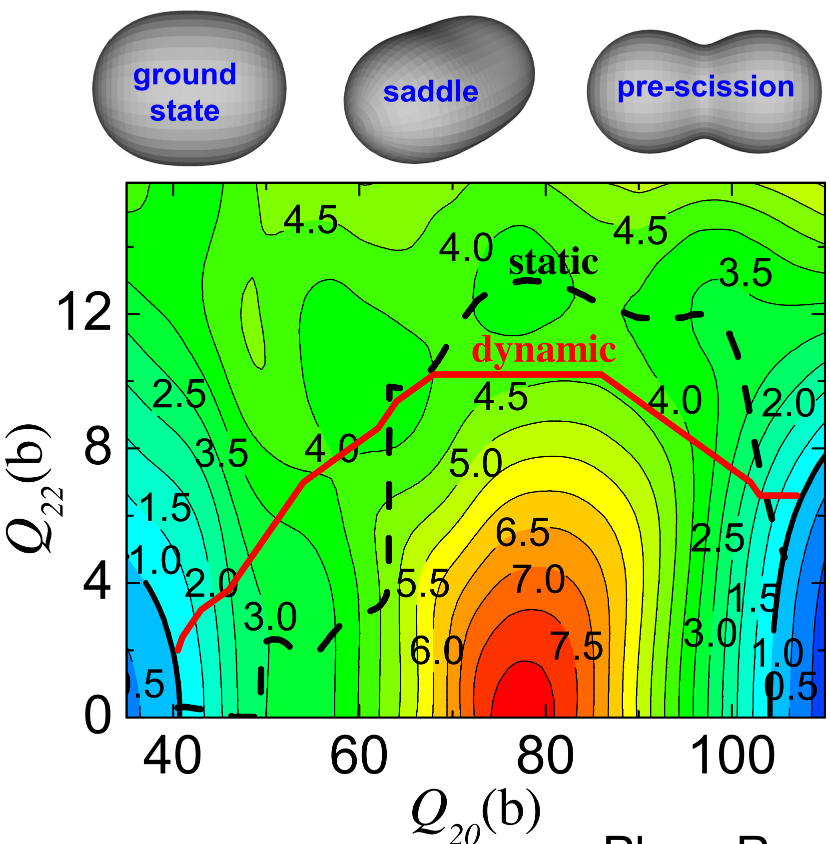
Fission half-lives: depend on potential, friction, and inertia terms

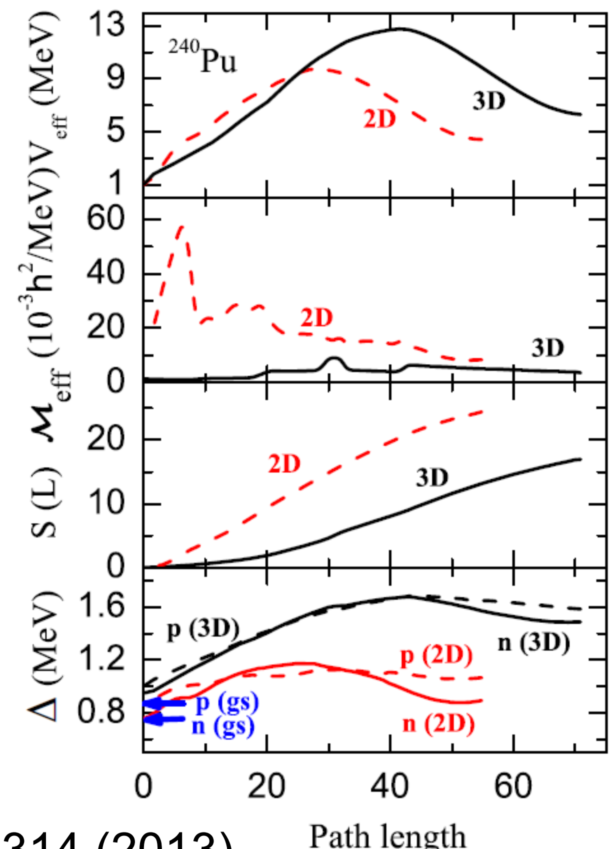
$$S = \int_{(s)} \left\{ 2\left[V(q) - E\right] \sum_{ij} B_{ij}(q) q_i' q_j' \right\}^{1/2} ds$$

collective inertia (mass parameter)

multidimensional space of collective parameters

Several collective coordinates
The action has to be minimized

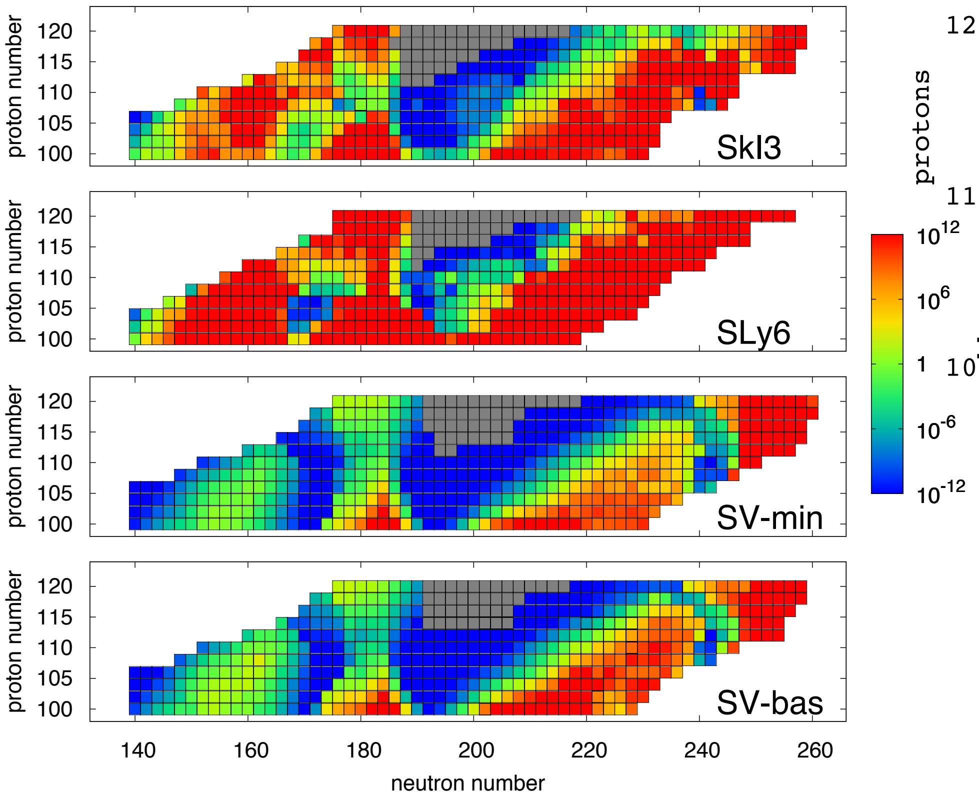


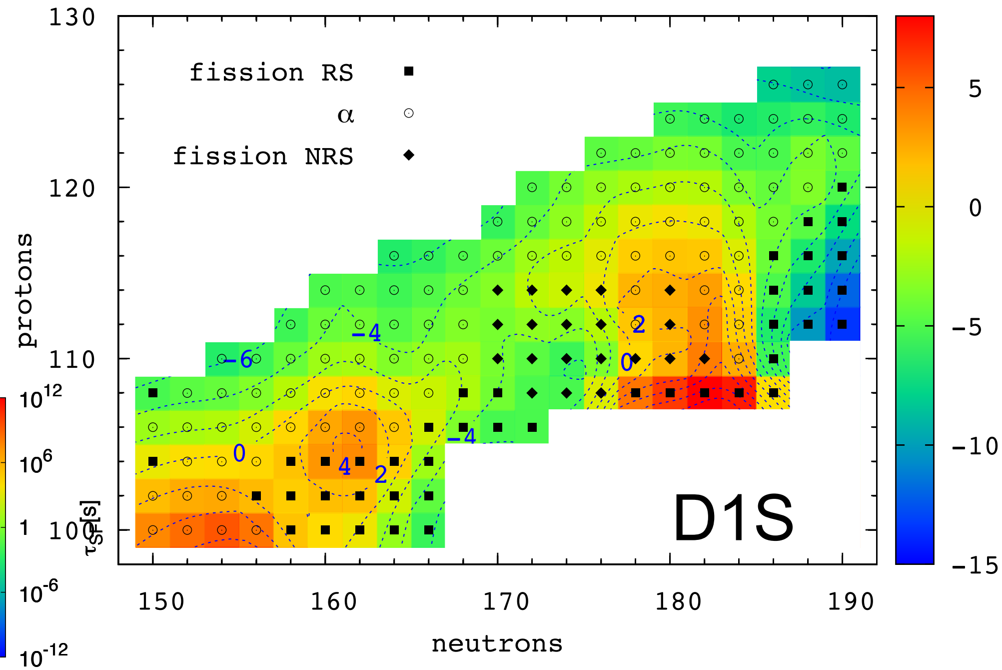


Phys. Rev. C 88, 064314 (2013)

Spontaneous Fission Lifetimes: huge theoretical uncertainties!

Phys. Rev. C 85, 025802 (2012)





Phys. Rev. C 86, 014322 (2012)

Fission of neutron rich nuclei impacts the formation of heavy elements at the final stages of the r-process through the recycling mechanism. The fission recycling is believed to be of particular importance during neutron star mergers where free neutrons of high density are available.

Prospects and Needs

Challenges (theory):

- Development of universal energy density functional
- Consistent description of various experimental fission data
- Ability to carry out reliable extrapolations in mass and isospin

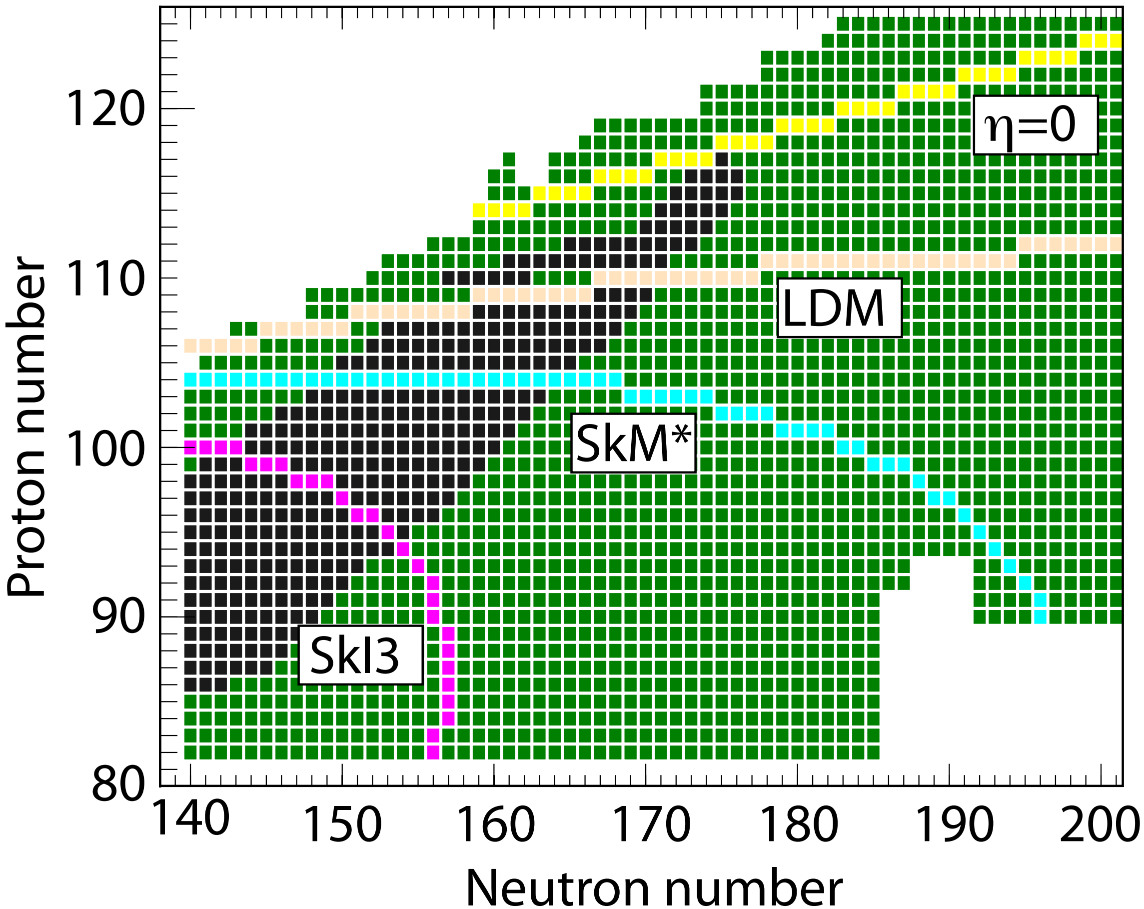
Challenges (experiment):

- Spectroscopic data on Z>106 (including gammas and X-rays)
- Going towards N=184, Z=110
- Fission data on neutron-rich nuclei to pin down surface symmetry energy
- Data for fission yields (Z,N), TKE's, at various regions and E*

Surface symmetry energy and fission of neutron-rich nuclei

N. Nikolov et al., Phys. Rev. C 83, 034305 (2011)

$$E_{\text{ssym}} \propto (N-Z)^2 \times \text{surface}$$



$$x = \frac{E_{\text{Coul}}(\text{sph})}{2E_{\text{surf}}(\text{sph})} \approx \frac{Z^2}{47A\,(1-\eta I^2)}$$

$$I = \frac{N-Z}{A}$$

$$\eta \equiv -\frac{a_{\text{ssym}}}{a_{\text{surf}}}$$

Nuclear structure inputs to the fission process

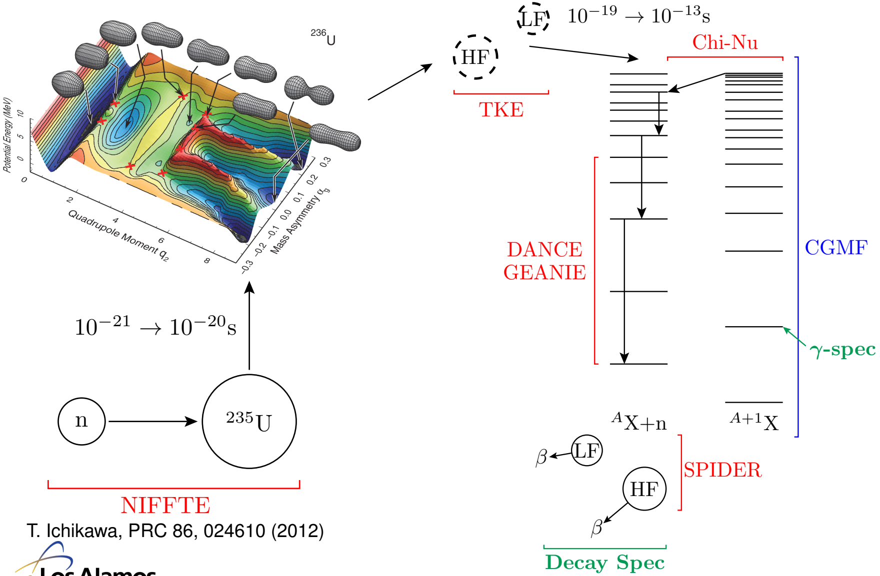
S. Mosby[1]

[1]LANSCE-NS

August 22, 2014

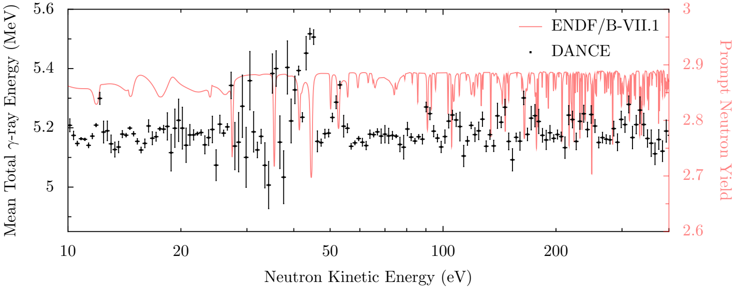
2014 Low Energy Nuclear Physics Town Meeting

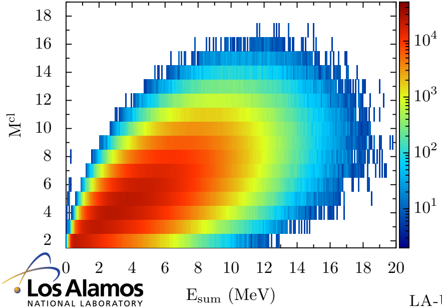
How to study a fissioning nucleus



T. Ichikawa, PRC 86, 024610 (2012)

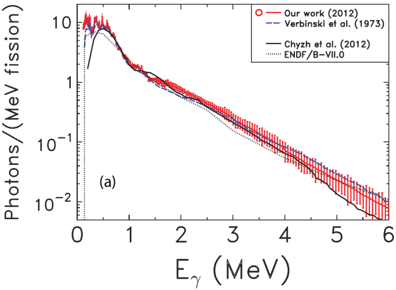
What DANCE taught us (so far)

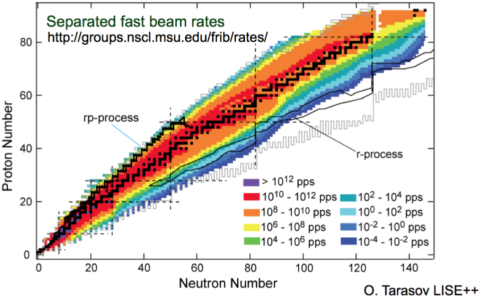


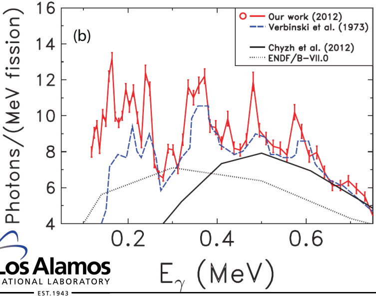


- Details of prompt fission neutron, gamma spectrum change resonance to resonance
- Anti-correlated
- Idea: (n,γf) (e.g. Lynn 1965)
- Connect pre, post-scission information

Need more structure inputs







- Calculations depends on lines, density of states for cascades
- Discrete lines offer a diagnostic tool
- RIB experiments could fill this in

R. Billnert *et al*, Phys. Rev. C **87**, 024601 (2013)

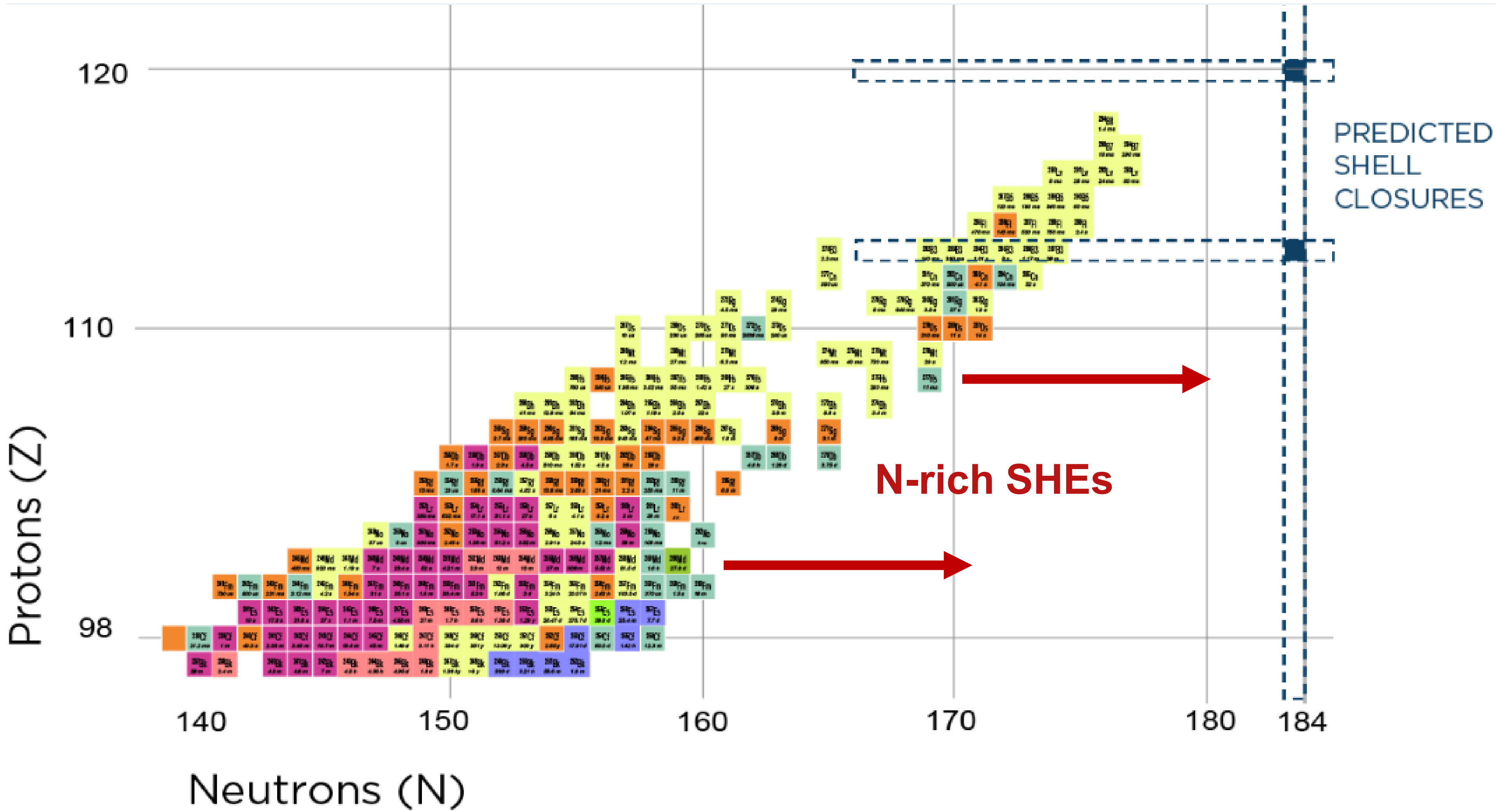
Acknowledgements

DANCE:

T. A. Bredeweg (C-NR)
A. Chyzh (LLNL)
A. Couture (LANSCE-NS)
R. Henderson (LLNL)
M. Jandel (C-NR)
J. M. O'Donnell (LANSCE-NS)
J. Ullmann (LANSCE-NS)
C. Y. Wu (LLNL)

This work benefited from the use of the LANSCE accelerator facility. Work was performed under the auspices of the U.S. Department of Energy at Los Alamos National Laboratory by the Los Alamos National Security, LLC under Contract No. DE-AC52-06NA25396 and at Lawrence Livermore National Laboratory by the Lawrence Livermore National Security, LLC under Contract No. DE-AC52-07NA27344.

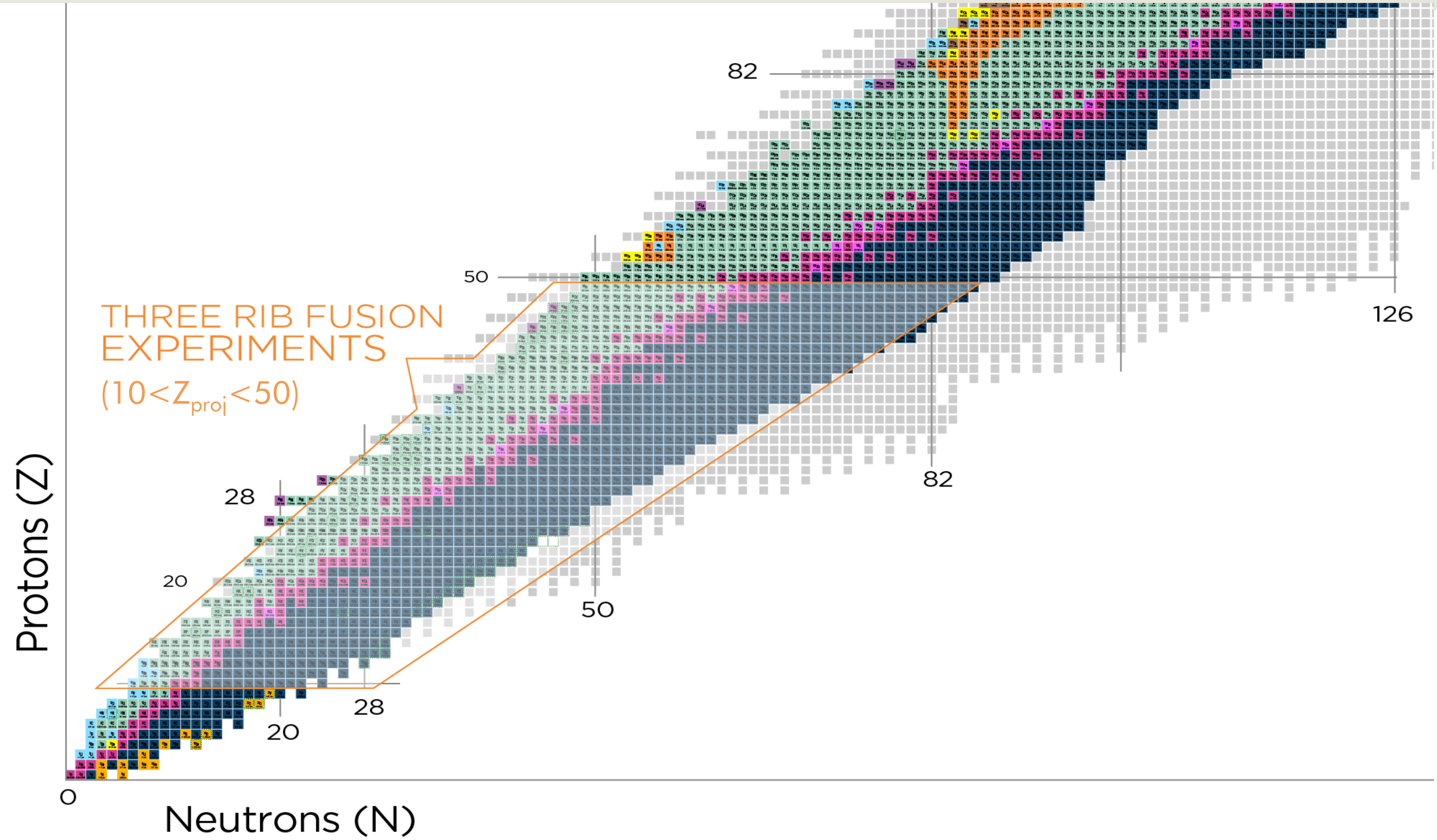
Fusion with RIBs



Production of SHE with RIBs

- Scientific Opportunities with Rare-Isotope Facility in U.S (2006)
  - ✓"The identified goals for a FRIB include … searching for new superheavy systems at the limits of mass and charge"
- Nuclear Science Long Range Plan (2007)
  - ✓"FRIB will play a critical role in …. the production of neutron-rich superheavy elements to allow the study of their lifetimes and decays."
- Nuclear Physics: Exploring the Heart of Matter (2013)
  - ✓"There is a range of options for synthesizing heavy elements with exotic beams."
- Search for Superheavy Nuclei (Annu. Rev. Nucl. Part. Sci. 2013)
  - ✓"Many of the cold fusion cross sections with RIBs…could be a factor of 20 higher than with stable beams"
  - ✓"Therefore, the measurements of reaction [capture] cross sections with RIBs will be an important study to undertake in the future".

Production of SHE with RIBs

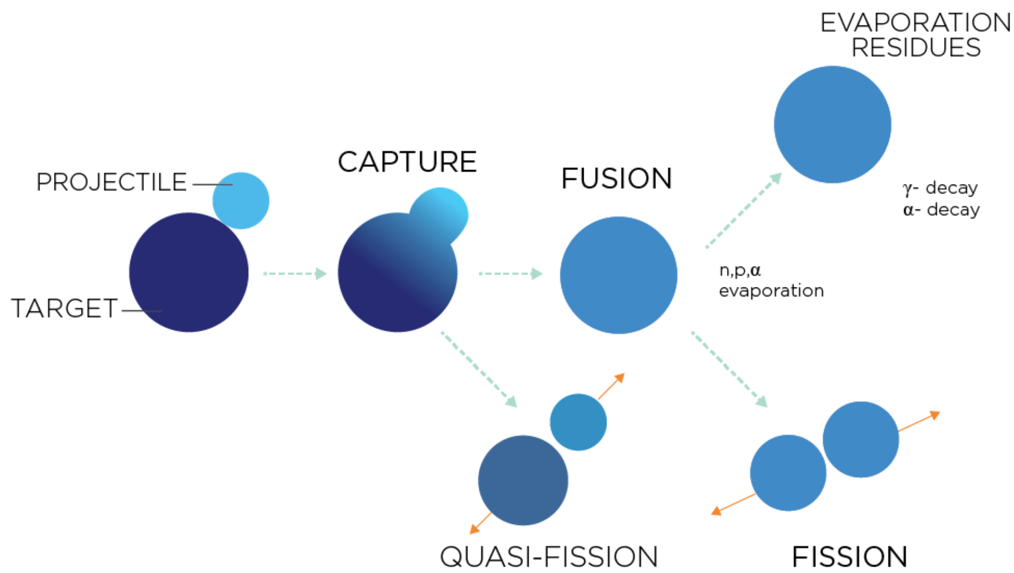


Production of SHE with RIBs

- Predictions for ReA-FRIB indicate that synthesis of new neutron-rich “light SHE” (Z < 105) will be possible [Loveland PRC 2007, J.Phys.Conf. 2013].
- Opportunities to extend studies of the N=162 deformed shell closure [Dvorak PRL 2006] and new long-lived n-rich nuclei (chemical studies).
- First synthesis of the new SHE isotopes using RIBs will represent a crucial step forward towards defining what will eventually be required to reach the “island of stability”.

- At current RIB facilities (NSCL-ReA, ANL-AIRIS/CARIBU) can study fusion mechanism - capture, fusion-fission, and quasifission.

- At next generation RIB facilities (FRIB-ReA) consider first production of heavy/superheavy elements from RIBs.



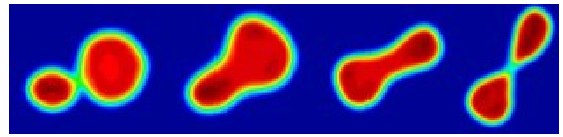
Current/Future Plans

Current Facilities: Define the most promising experiments for production of new neutron-rich isotopes of SHEs from RIBs at FRIB.

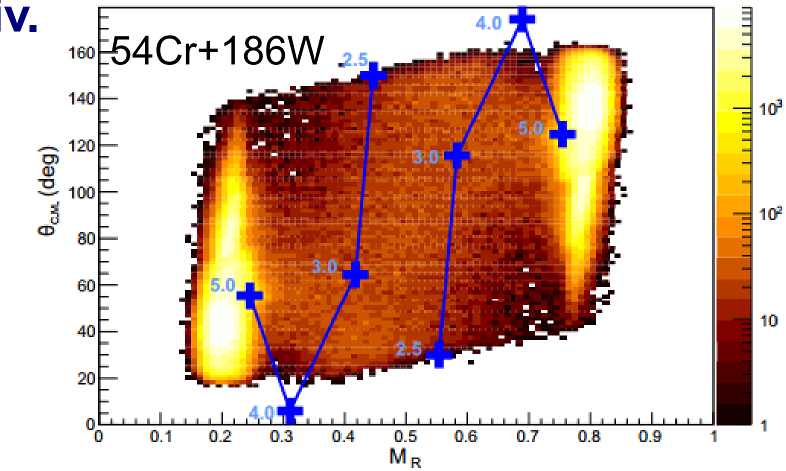
RIBs also offer opportunity to advance our understanding of fusion process for stable beam experiments.

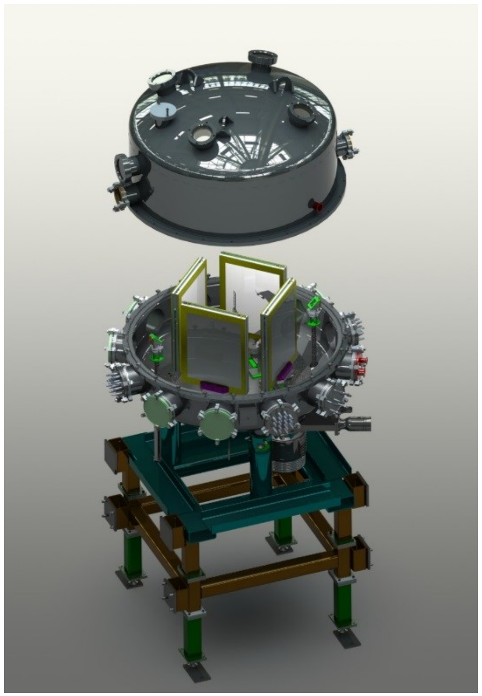
Theoretical Advancements for SHE reactions: Current predictions based on phenomological approaches and have large uncertainties.

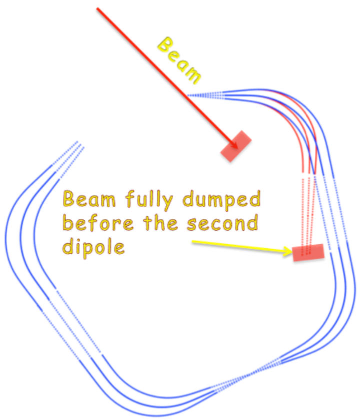
TDHF approach: Microscopic description of dynamics of heavy-ion fusion. New results show ability to reproduce quasifission characteristics. Well suited for RIB studies.



Oberacker & Umar
Vanderbilt Univ.





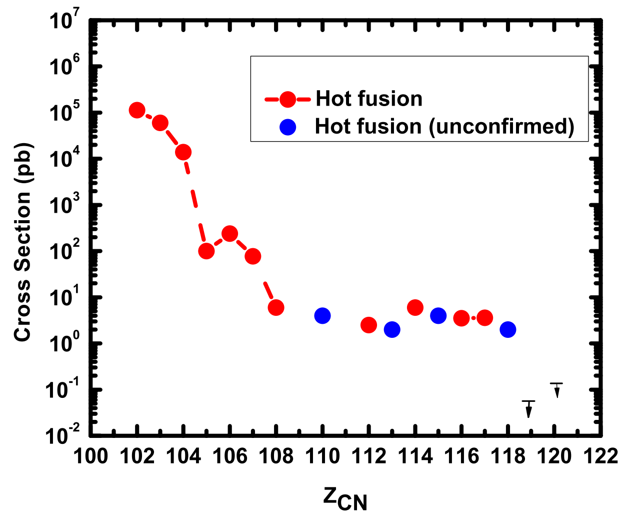


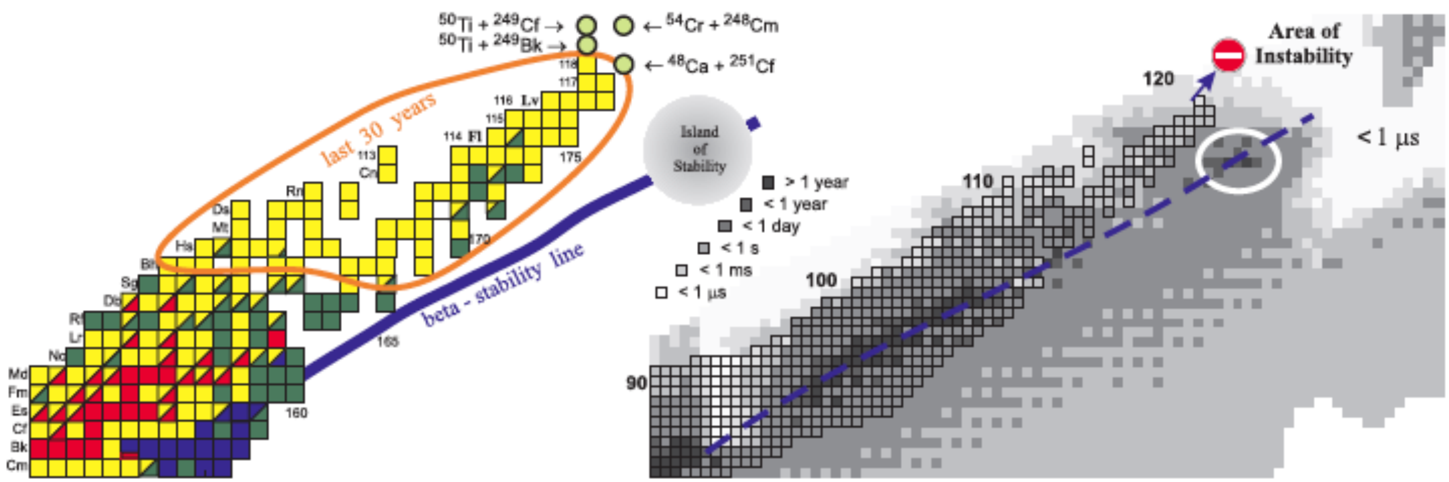
Next-gen Facilities: Produce new n-rich heavy/superheavy isotopes from RIB fusion.
Requirements: Separator → ISLA @ ReA12

Making neutron-rich heavy nuclei

W. Loveland
Oregon State University

Motivation for making new n-rich heavy nuclei





Zagrebaev, Karpov. Greiner, J. Phys. Conf. Series 420, 012001 (2013)

How to get there

- Radioactive Nuclear Beams (RNBs)

➢FRIB 5 atom/day list

- ^{264}Rf $^{252}Cf(^{16}C,4n)$
- ^{265}Db $^{249}Bk(^{20}O,4n)$
- ^{268}Sg $^{252}Cf(^{20}O,4n)$
- ^{267}Bh $^{252}Cf(^{21}F,6n)$

Targeted Radioactive Beams

- Special opportunities may exist if RNB facilities focus on producing a beam of particular interest.
- Example: ^{46}Ar (from ^{48}Ca fragmentation)

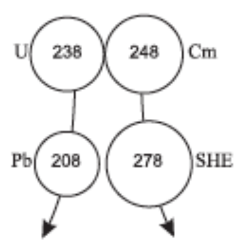
FRIB "fast beam rate" 1.1×10^{10}

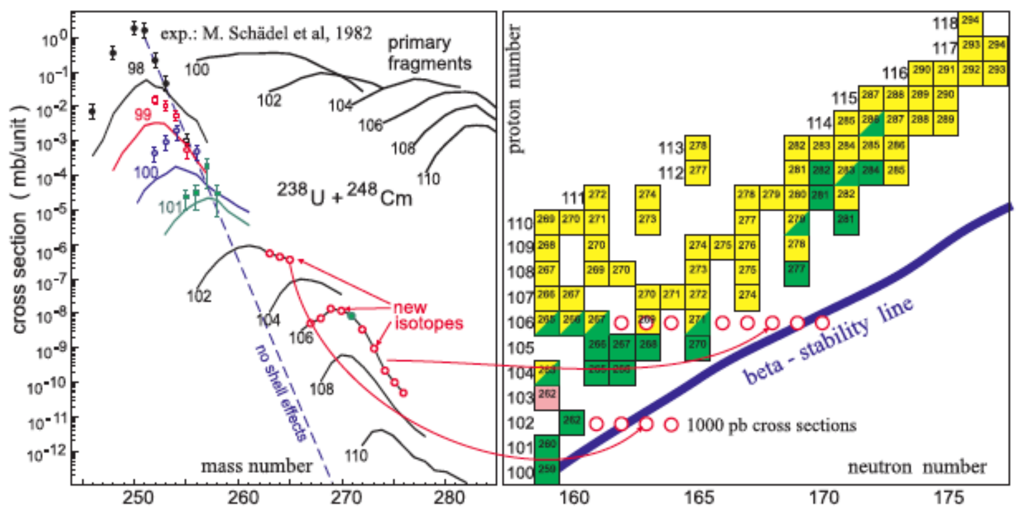
FRIB "reaccelerated beam rate" 2.3×10^{7}

Reaction	Beam Intensity (p/s)	Cross Section (pb)	Atoms/day
^{238}U(^{48}Ca,3n) ^{283}Cn	3×10^{12}	0.7	0.5
^{244}Pu(^{46}Ar,4n) ^{286}Cn	1.1×10^{10}	250	0.6
^{244}Pu(^{46}Ar,3n) ^{287}Cn	1.1×10^{10}	140	0.3

Multi-Nucleon Transfer (MNT)

- Expts of 1970s and 1980s at LBNL and GSI led to n-rich Fm and Md nuclei at 0.1 μb levels.
- Zagrebaev and Greiner pointed out role of shell structure in enhancing yields and utility of running reactions near the barrier.





There have been about a half dozen expts to check these predictions.
In all cases the measured cross sections exceed the predicted cross sections by about an order of magnitude.

MNT (continued)

- N=126

Surprises

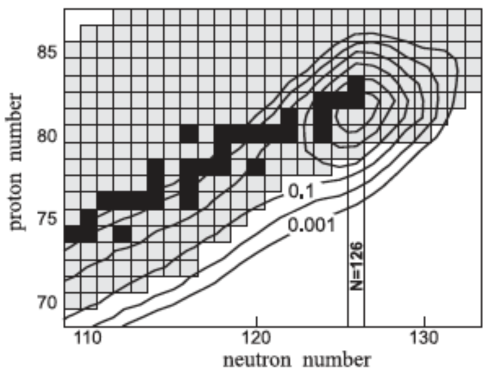
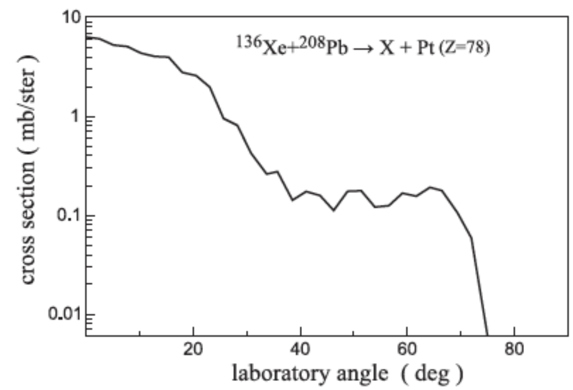
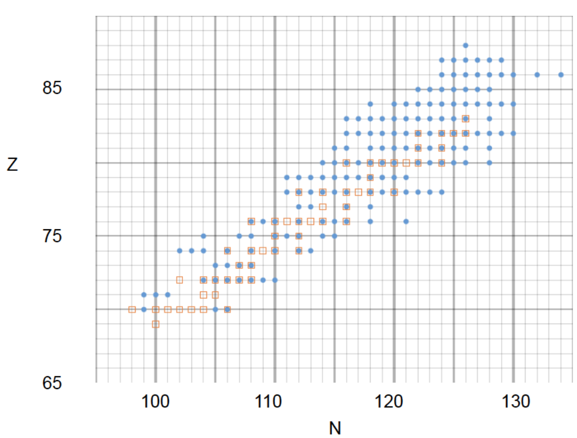


FIG. 4. Landscape of the total cross section $d^2\sigma/dZdN$ (mb, numbers near the curves) for production of heavy fragments in collisions of ^{136}Xe with ^{208}Pb at $E_{c.m.} = 450$ MeV. Contour lines are drawn over 1 order of magnitude.





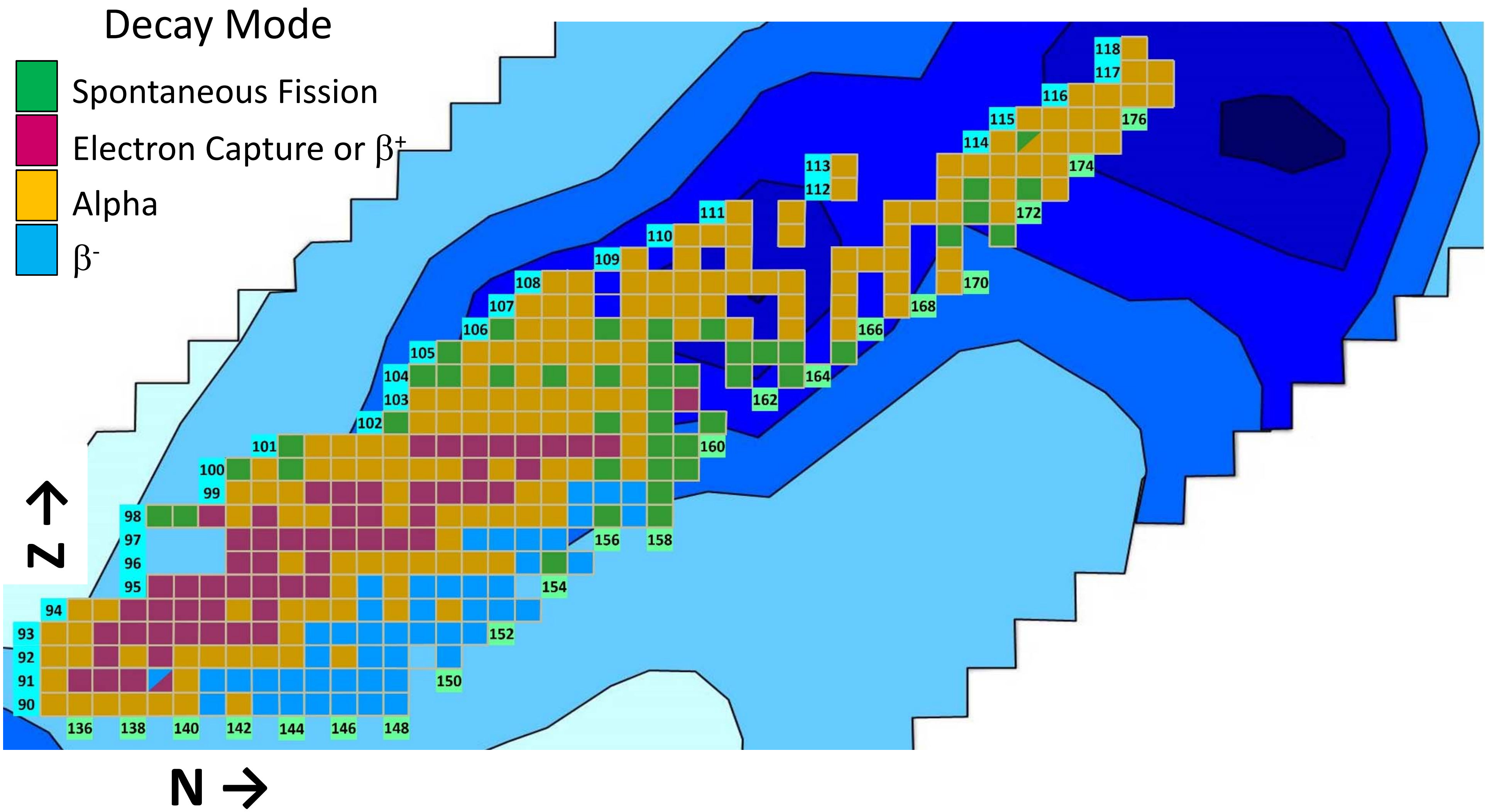
Recent Gammasphere Expt.

Superheavy Element Spectroscopy

Jacklyn M. Gates

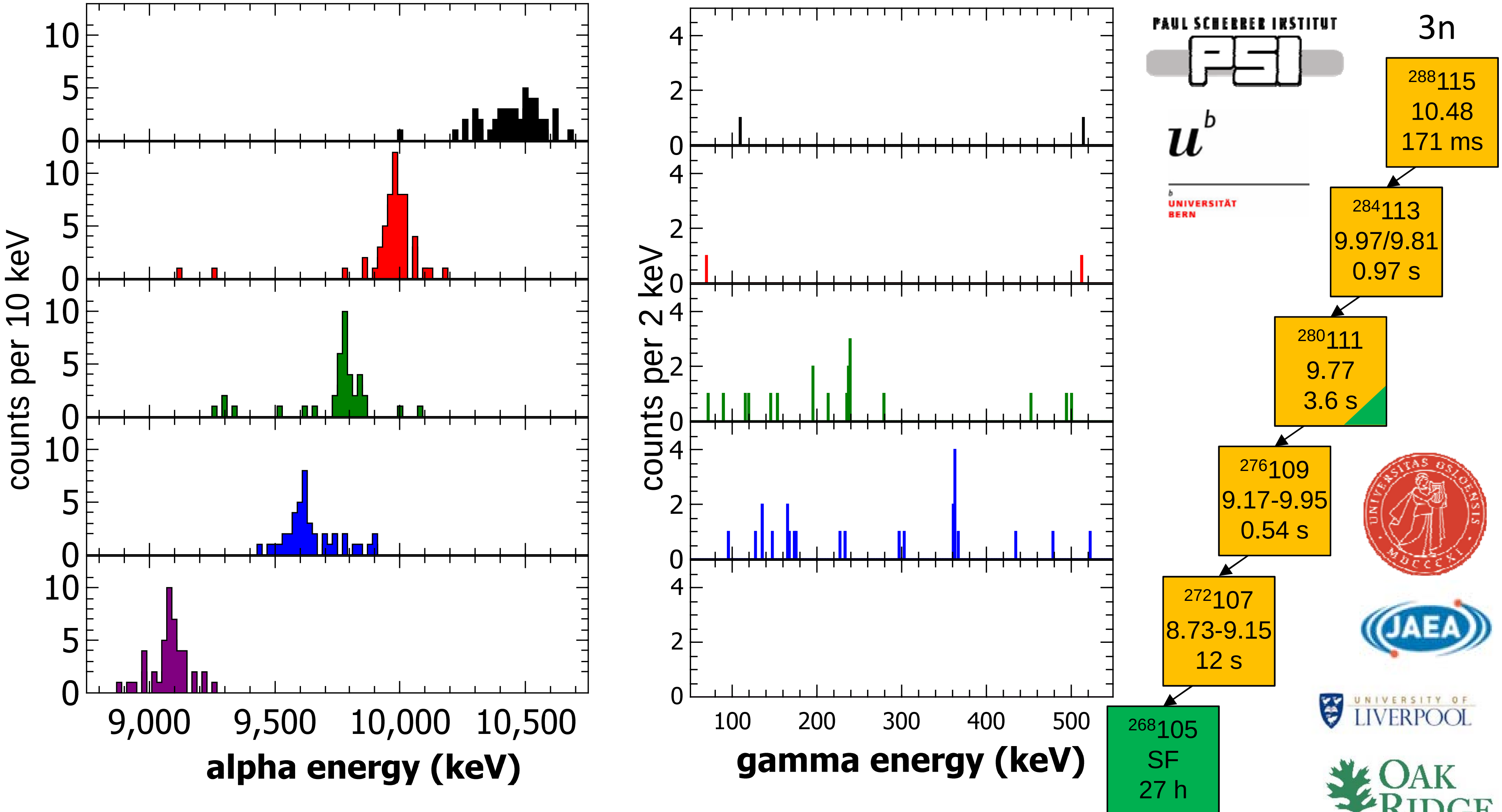
Lawrence Berkeley National Laboratory

Chart of the Nuclides: Today

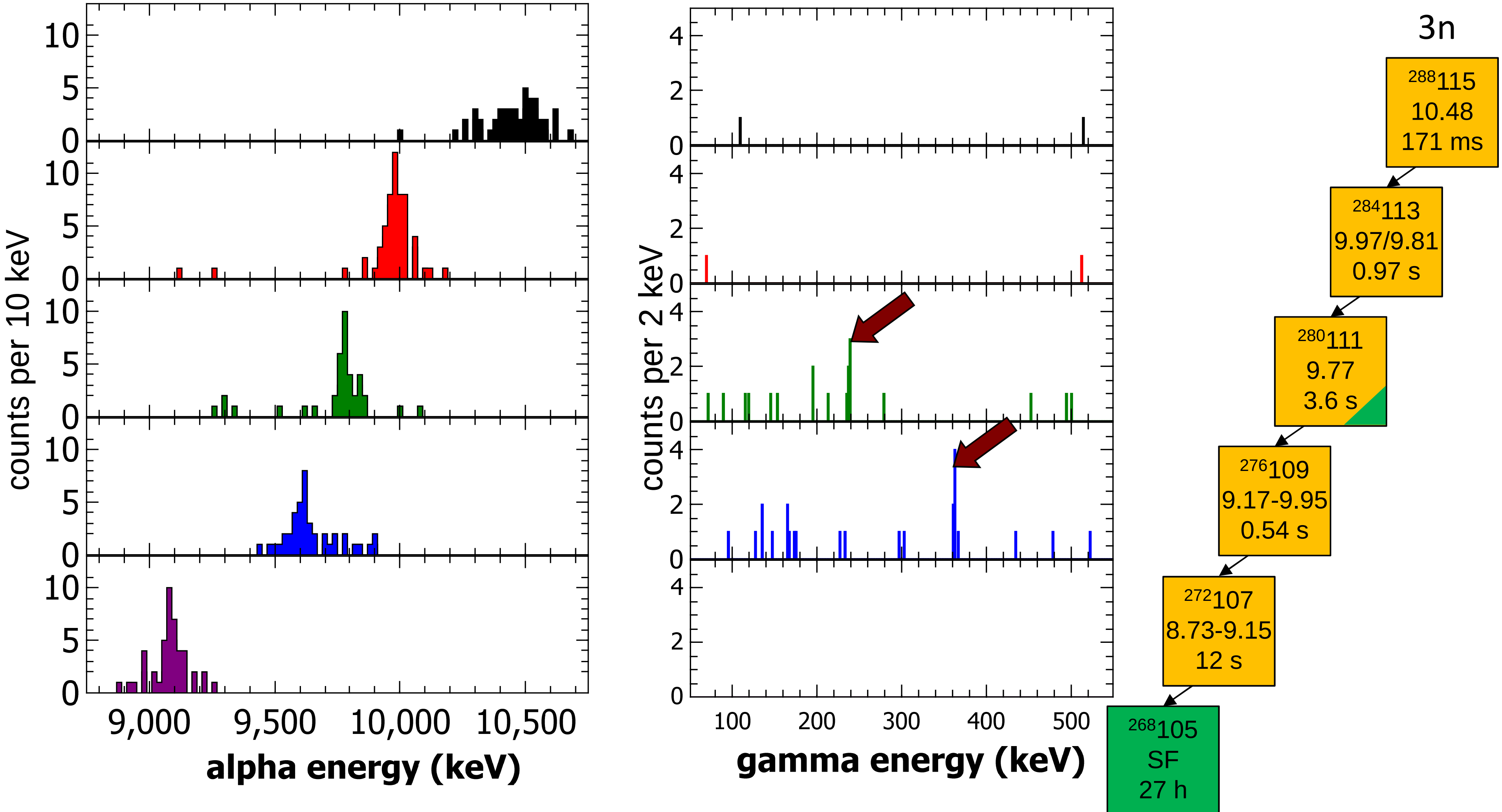


Shell effects from Sobiczewski et al:
Phys. Rev. C 63 (2001) 034306

First Spectroscopy Experiments on E115



First Spectroscopy Experiments on E115



65 events of 288-115 observed

Decay to (and from) exited states in 276-109 and 272-107 observed

Able to determine multipolarity of some transitions

Summary and Look to the Future

We can do spectroscopy with superheavy elements!

– at rates of 1 atom/day

- Upgrades planned or underway to several accelerators will allow access to SHE at rates of 5-10/atoms/day
- In the near future we should have access to level schemes, spins and parities, single particle states, rotational spectra…and x-rays

What we need to take full advantage of accelerator upgrades

- Targets capable of withstanding 10 pμA beam
- Separator for high intensity beams
- Spectroscopy systems that function under high (>50 kHz) rates

Online Chemistry of Superheavy Elements

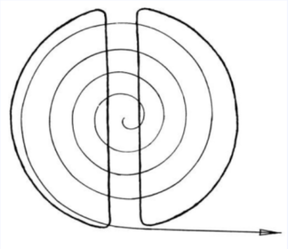
C. M. Folden III
Cyclotron Institute, Texas A&M University
August 22, 2014

Introduction

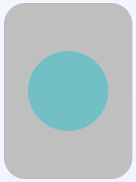
- Chemical properties of superheavy elements have been critical to our understanding of the periodic table.
- A number of extremely important experiments have been performed on elements Cn and Fl, and other high-statistics experiments performed on Rf, No, and Md.
- There is a lack of an American presence in this field.
- Experiments require a high-intensity accelerator, a gas-filled separator, a recoil transfer chamber, a chemistry lab, and significant development time.
- There funding of students for this work has been uneven.
- Automated radiochemistry has potential applications in homeland security.

Isotope Production and Integration of Automated Systems

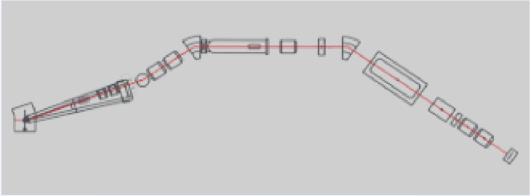
- Goal: Integrate chemical automation methods with isotope production, separation, and transport at the Texas A&M University Cyclotron Institute.



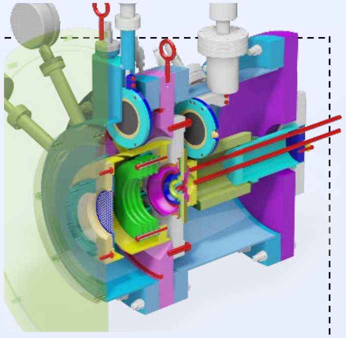
Cyclotron (Texas A&M University)



Target



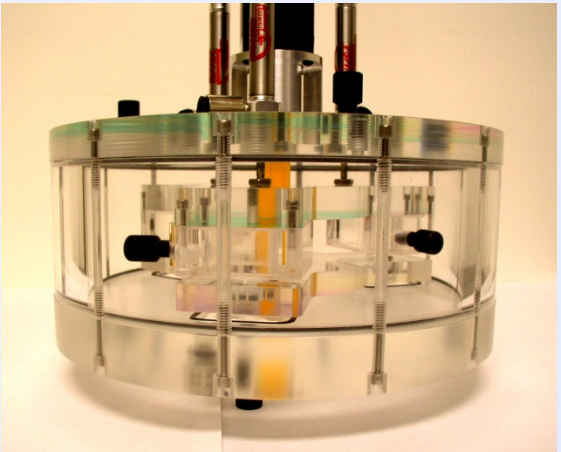
MARS Physical Pre-Separator



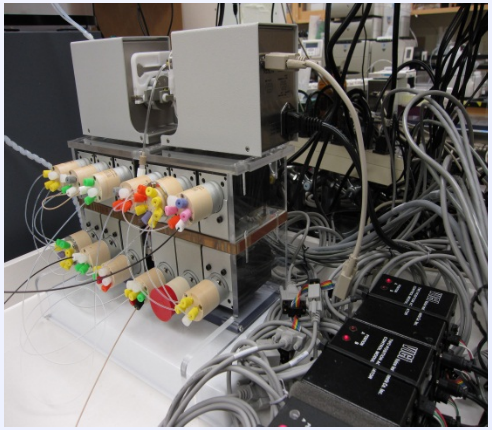
Recoil Transfer Chamber (RTC)

CYCLOTRON INSTITUTE
TEXAS A&M UNIVERSITY

- **Gas-liquid interface and automated radiochemistry developed for use at CAMS**
- **Leverage existing capability and adapt to atom-at-a-time chemistry**
- **Meets requirements for rapid chemistry**

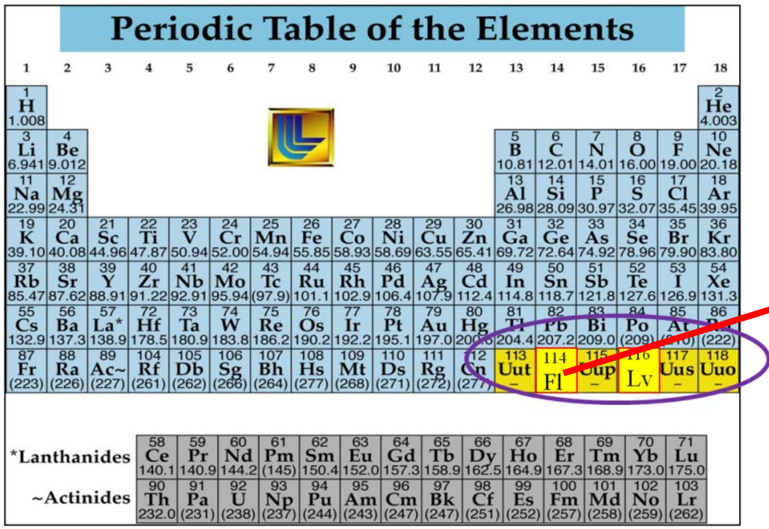


Gas-Liquid Interface for Transferring Transactinides to Automated Radiochemistry (GLITTAR)



Super Heavy Element Liquid Automation (SHELA)

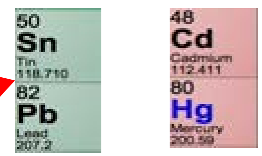
Studies of Flerovium Homologs with Macrocycles



Flerovium

Homologs

Pseudo-Homologs



Extractants

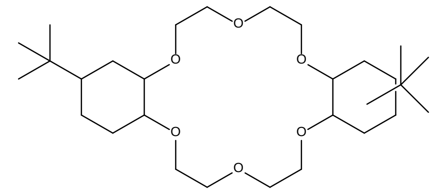


Figure. Eichrom Pb resin extractant, di-t-butylcyclohexano-18-crown-6.

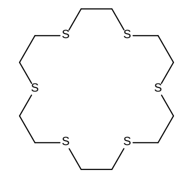


Figure. Hexathia-18-crown-6.

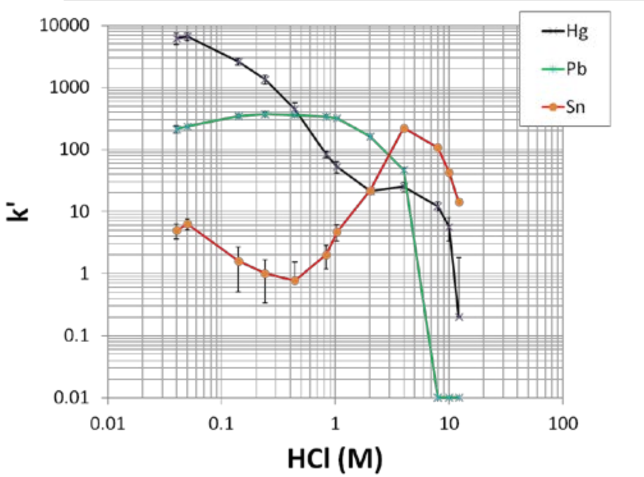


Figure. The batch uptake (k') of ^{212}Pb(II), ^{113}Sn(IV) and ^{197m}Hg(II) as a function of hydrochloric acid media on Pb resin (50-100 μm) with a 3 hour equilibration time.

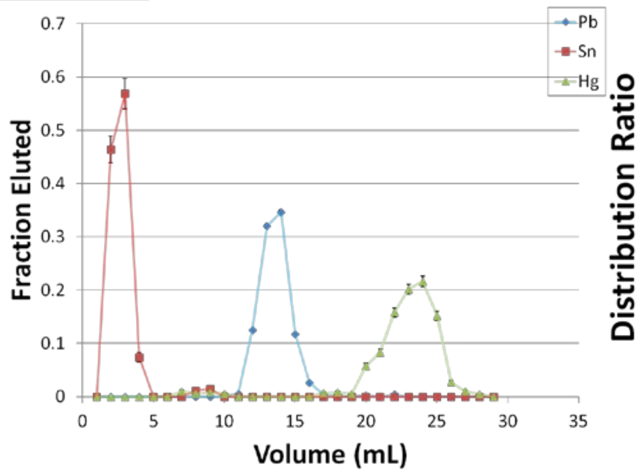


Figure. Separation of Pb(II), Sn(IV) and Hg(II) with 2 mL pre-packed Pb resin (50-100 μm) on vacuum box with 2 mL/min flow rate and 1 hour equilibrium time between elutions.

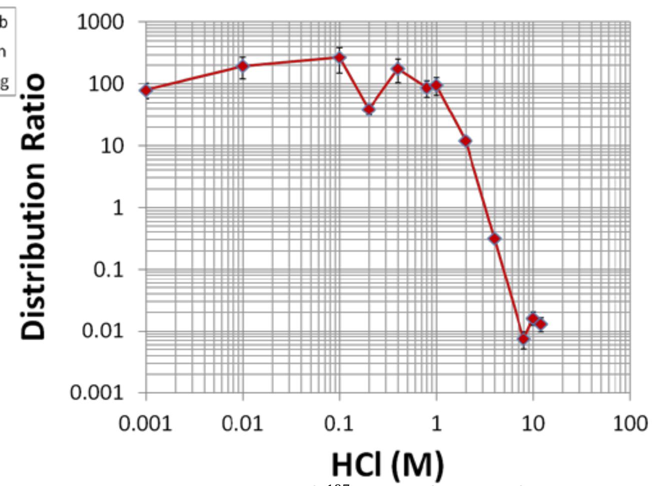


Figure. Extraction of ^{197m}Hg as a function of hydrochloric acid media from 0.003 M hexathia-18-crown-6 in dichloromethane with a 3 hour equilibration time.

Slide courtesy of R. Sudowe (UNLV).

Long-Term Directions

- Determine if elements through Z = 114-116 behave like their lighter homologs, and evaluate the influence of relativistic effects.
- Measure the range and stability of oxidation states through Z = 108.
- Conduct high-statistics SHE chemistry at the SHE Factory in Dubna.
- Use laser spectroscopy to measure precise values for excited electronic configurations and ionization potentials.
- Inform theoretical treatments of electronic structure and chemical bonding.

Takeaway Messages

- A national collaboration to perform new online chemistry experiments has been formed to bring back an American presence in this field.
- Facilities that complement the major user facilities are needed for training, equipment development, and preparatory experiments.
- The lack of funding for students is a major concern.
- The automated systems that are being developed may have applications in homeland security.

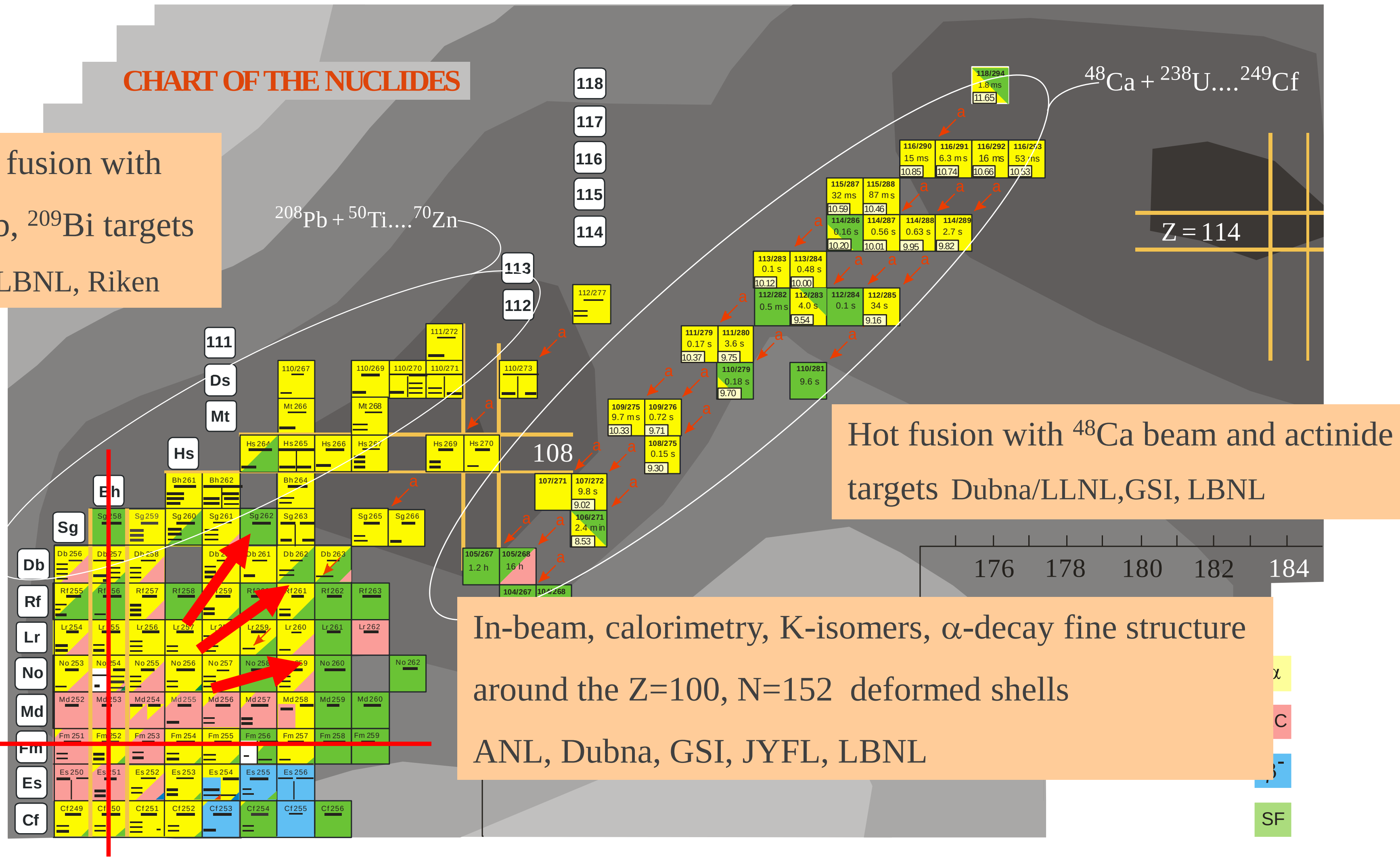
Spectroscopy of Transfermium Nuclei

D. Seweryniak

Argonne National Laboratory

Joint DNP Town Meetings
on Nuclear Structure and Nuclear Astrophysics
College Station, August 21-24,2014

Spectroscopy of Transfermium nuclei



Cold fusion with

^{208}Pb, ^{209}Bi targets

GSI, LBNL, Riken

Hot fusion with ^{48}Ca beam and actinide targets Dubna/LLNL,GSI, LBNL

In-beam, calorimetry, K-isomers, α-decay fine structure around the Z=100, N=152 deformed shells

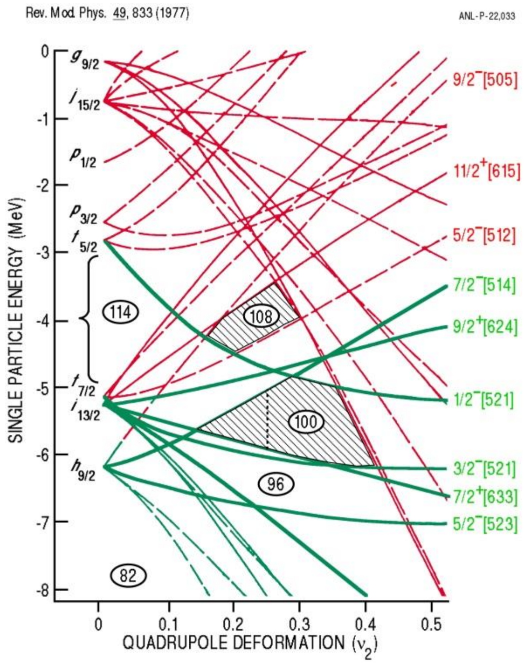
ANL, Dubna, GSI, JYFL, LBNL

Chart courtesy of Y. Oganessian

Experimental probes

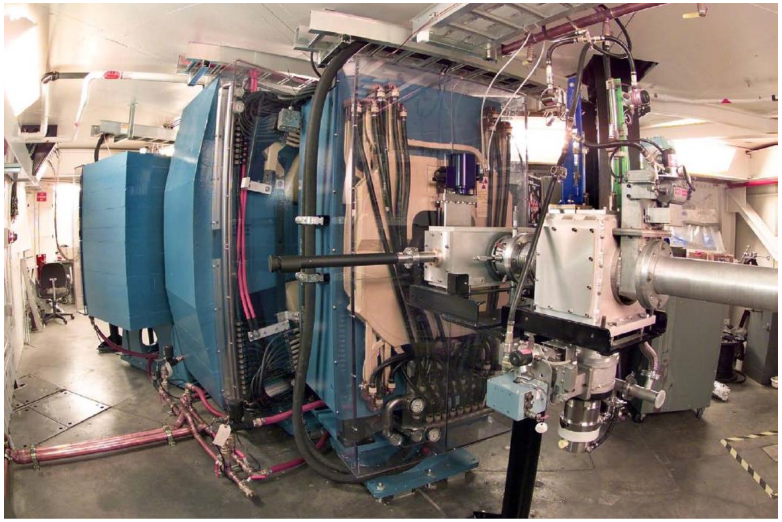
- In-beam spectroscopy
- Calorimetry
- K-isomers
- α decay fine structure
- α decay
- Spontaneous fission

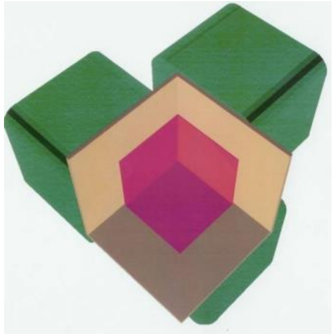
- Moments of inertia
- Fission barriers
- Single-particle energies
- K-hindrance factors
- Alpha decay Q values and lifetimes
- Spontaneous fission lifetimes

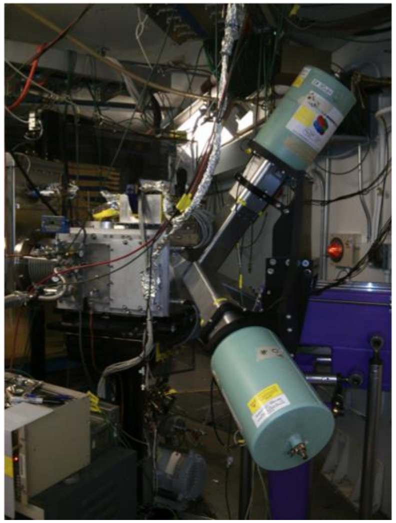


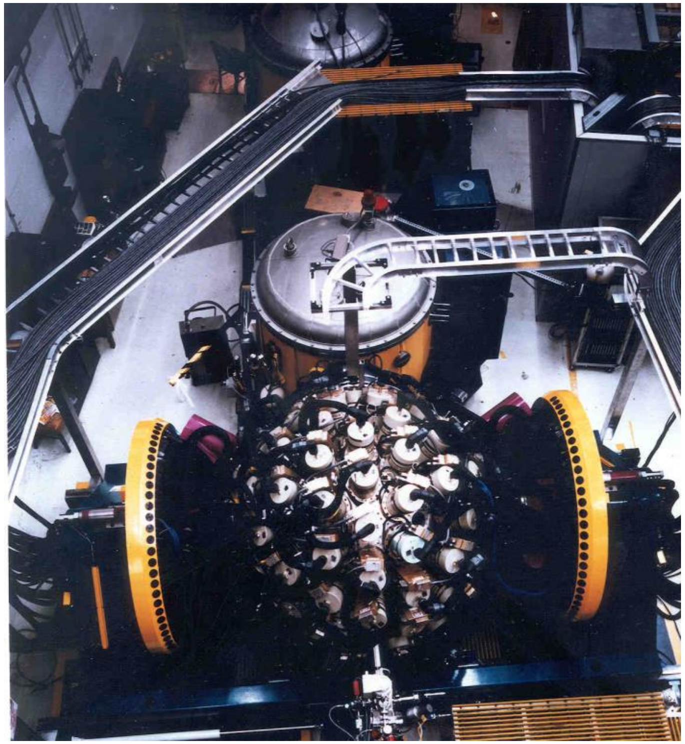
Transfermium nuclei serve as a test ground for nuclear models such as MM, SHF, RMF which are used to predict properties of super-heavy nuclei

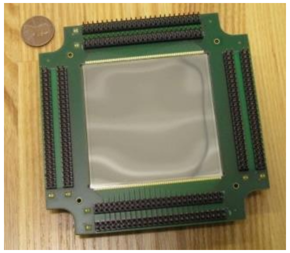
Detection systems

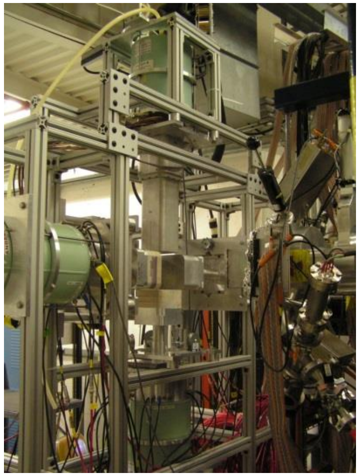










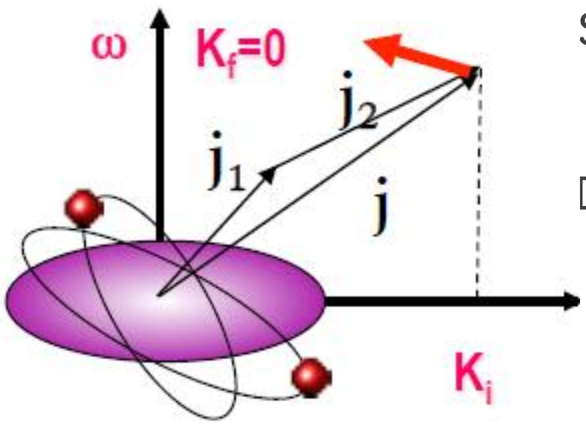


Berkeley Gas-Filled Separator

Fragment Mass Analyzer + Gammasphere

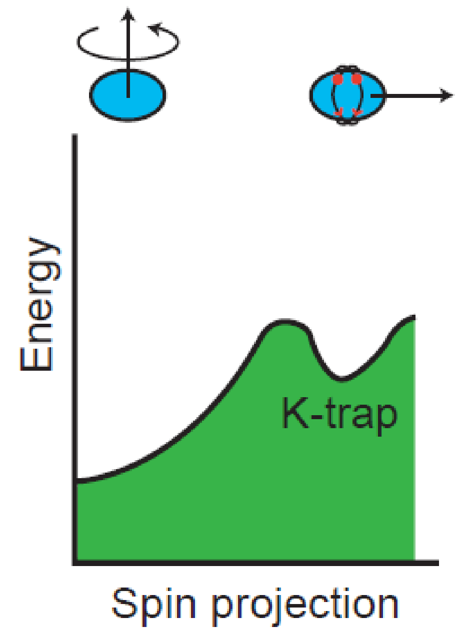
K-isomers in ^{254}Rf

N=152



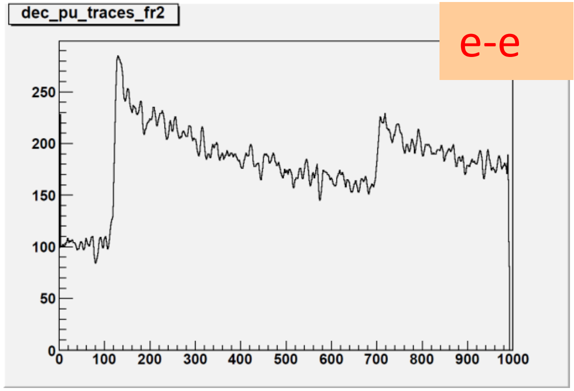
Sg								261
Db					257			
Rf			254		256	257		
Lr			253		255			
No	250		252	253	254	255		
Md			251					
Fm			250					

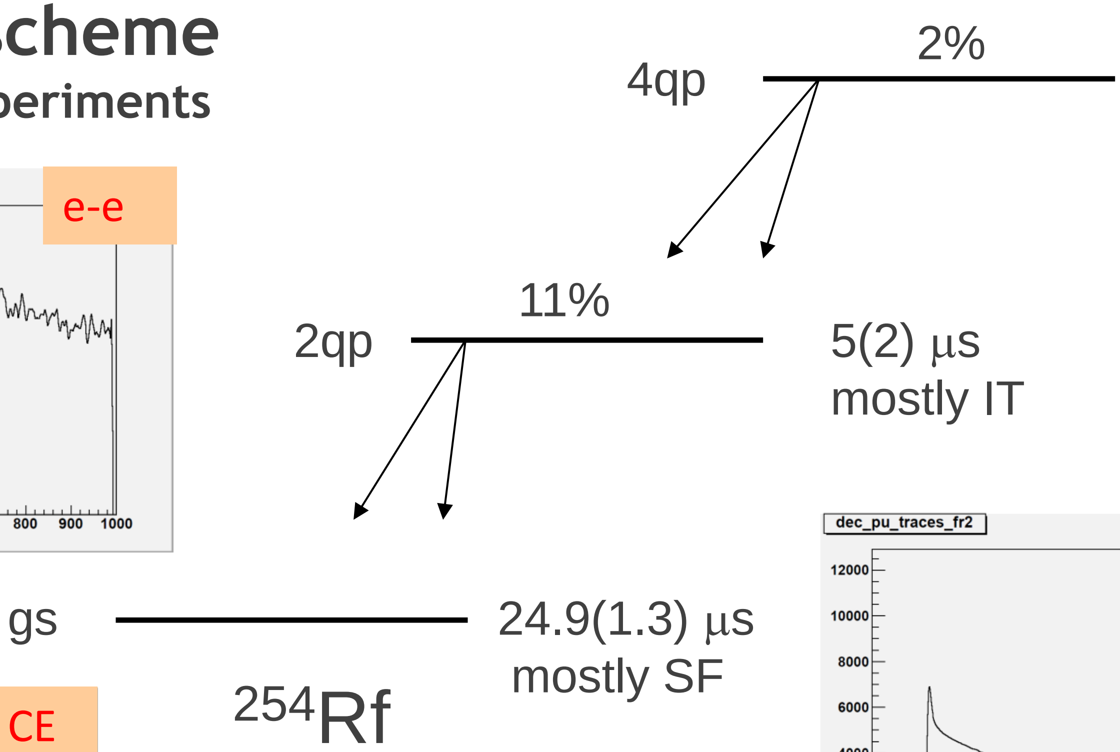
Z=100



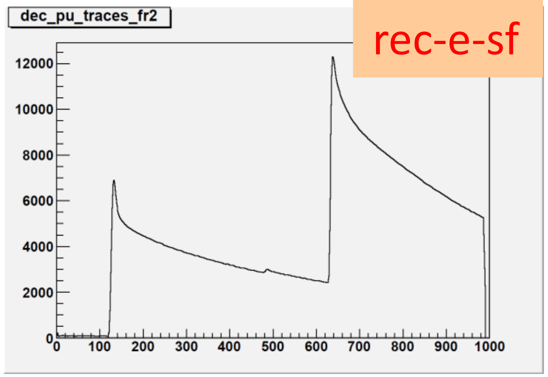
^{254}Rf level scheme

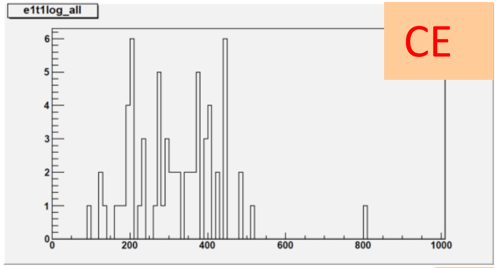
FMA and BGS experiments

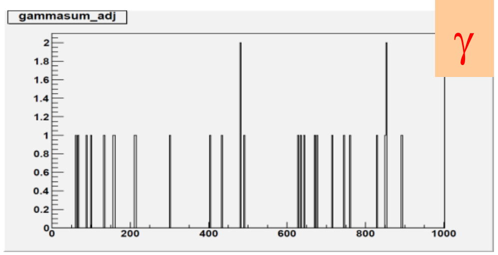




σ = 2 nb







- Compared to lighter N=150 isotones 2-qp decay is ~x10^{4} shorter
- SF partial lifetimes longer for isomers than for gs

Outlook

- More intense beams
  - ATLAS intensity upgrade
- Higher Ge-rates
  - digital Gammasphere
- Efficient separator
  - Argonne Gas-Filled Fragment Analyzer
- Higher prompt γ-ray efficiency
  - GRETA
- Higher delayed γ-ray efficiency
  - Better coverage of the focal plane
  - High-rate capability

→

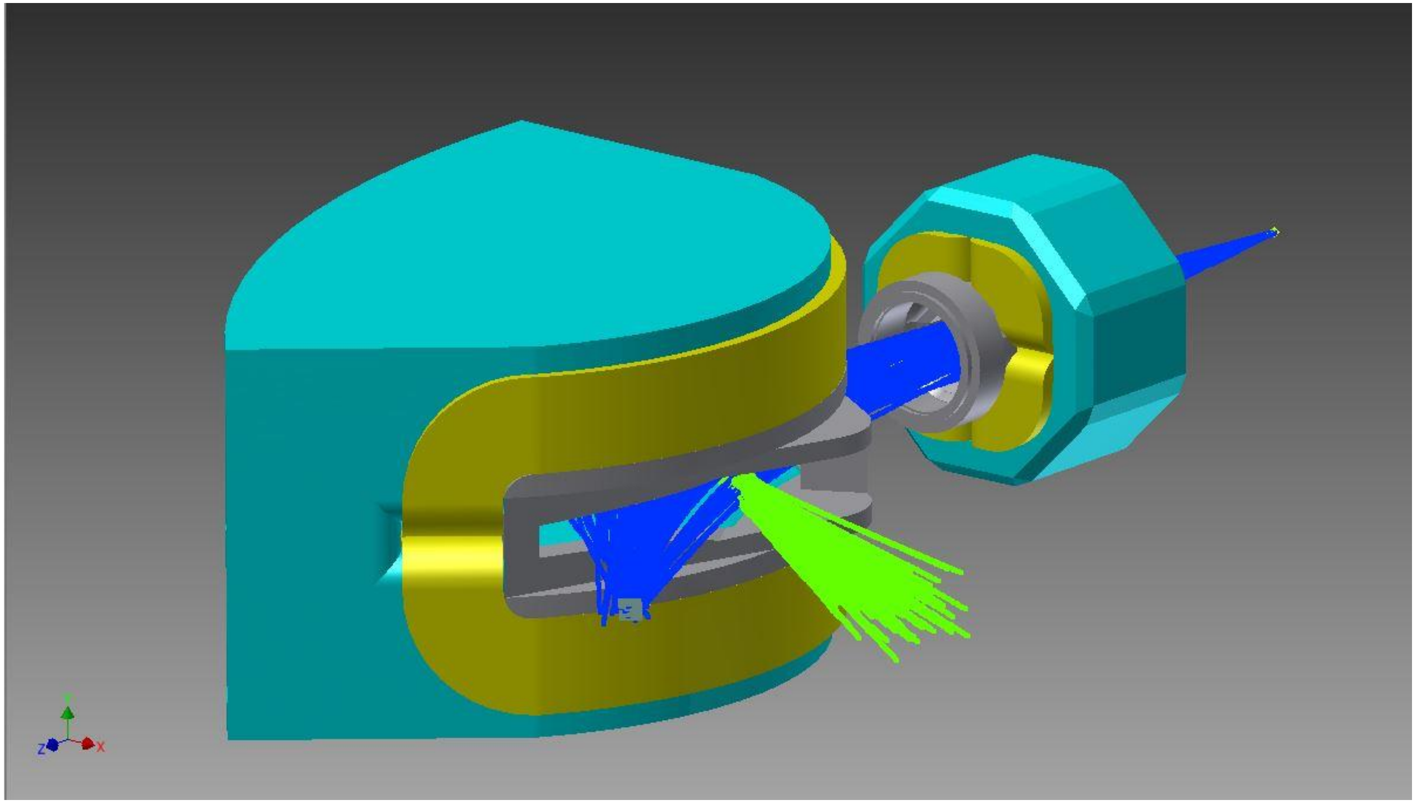
- Heavier elements
- More fissile isotopes
- Detailed studies
- Bands above isomers
- Conversion electron spectroscopy
- …

AGFA - Argonne Gas-filled Fragment Analyzer

$Q_v D_m$ design

38° bend
22.5 msr @ 80cm
(44 msr @ 40 cm)

2.5 Tm max Bρ
4.2 m total length
(3.9 m @ 40cm)



Large solid angle with Gammasphere
Compact focal plane
Short time of flight

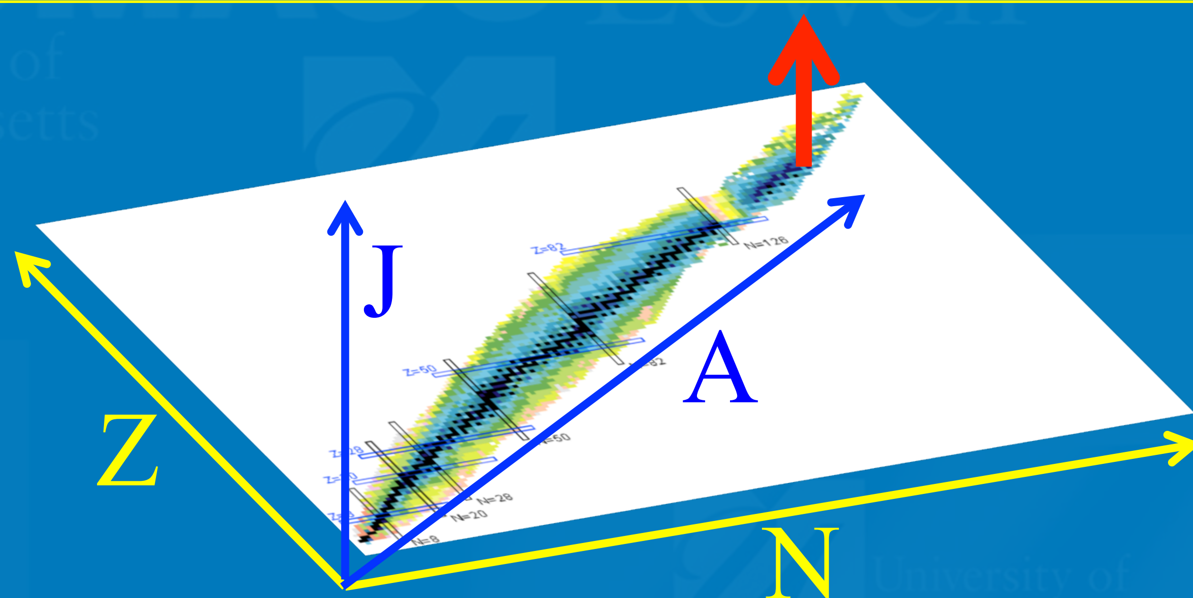
Spectroscopy of Very Heavy Neutron-rich Nuclei

Partha Chowdhury

University of Massachusetts Lowell

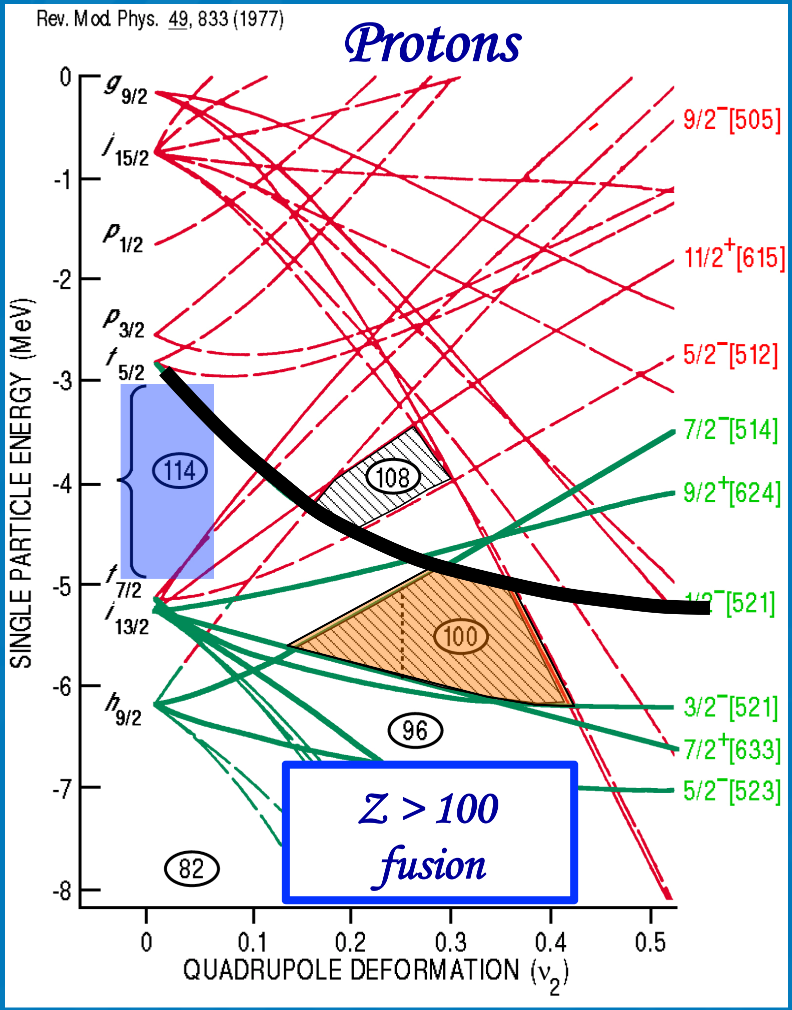
ingredients in the melting pot

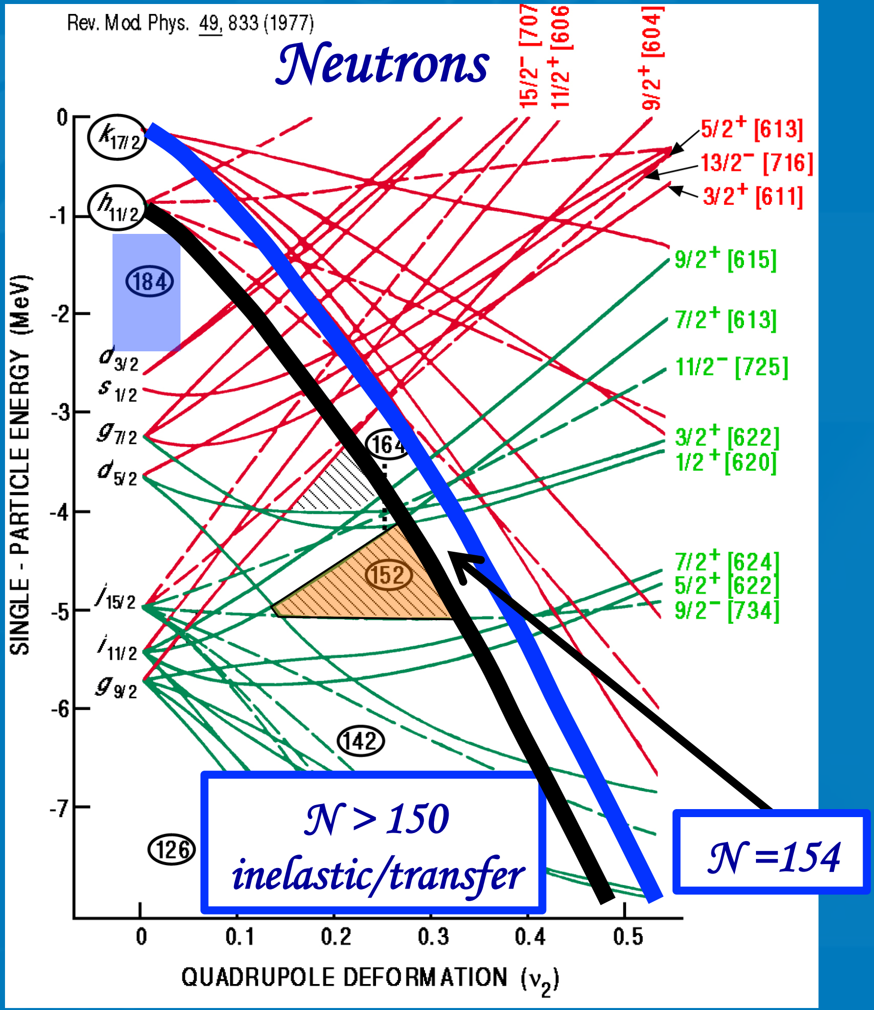
towards superheavies
shell gaps and stability
single particle energies
deformation
angular momentum
pairing
moments of inertia
alignments
higher order shapes
K-isomers
static and dynamic properties
theory and experiment



complementary techniques
fusion versus inelastic/transfer
radioactive targets
spectroscopic challenges
status and outlook

spherical gaps from a deformed perspective

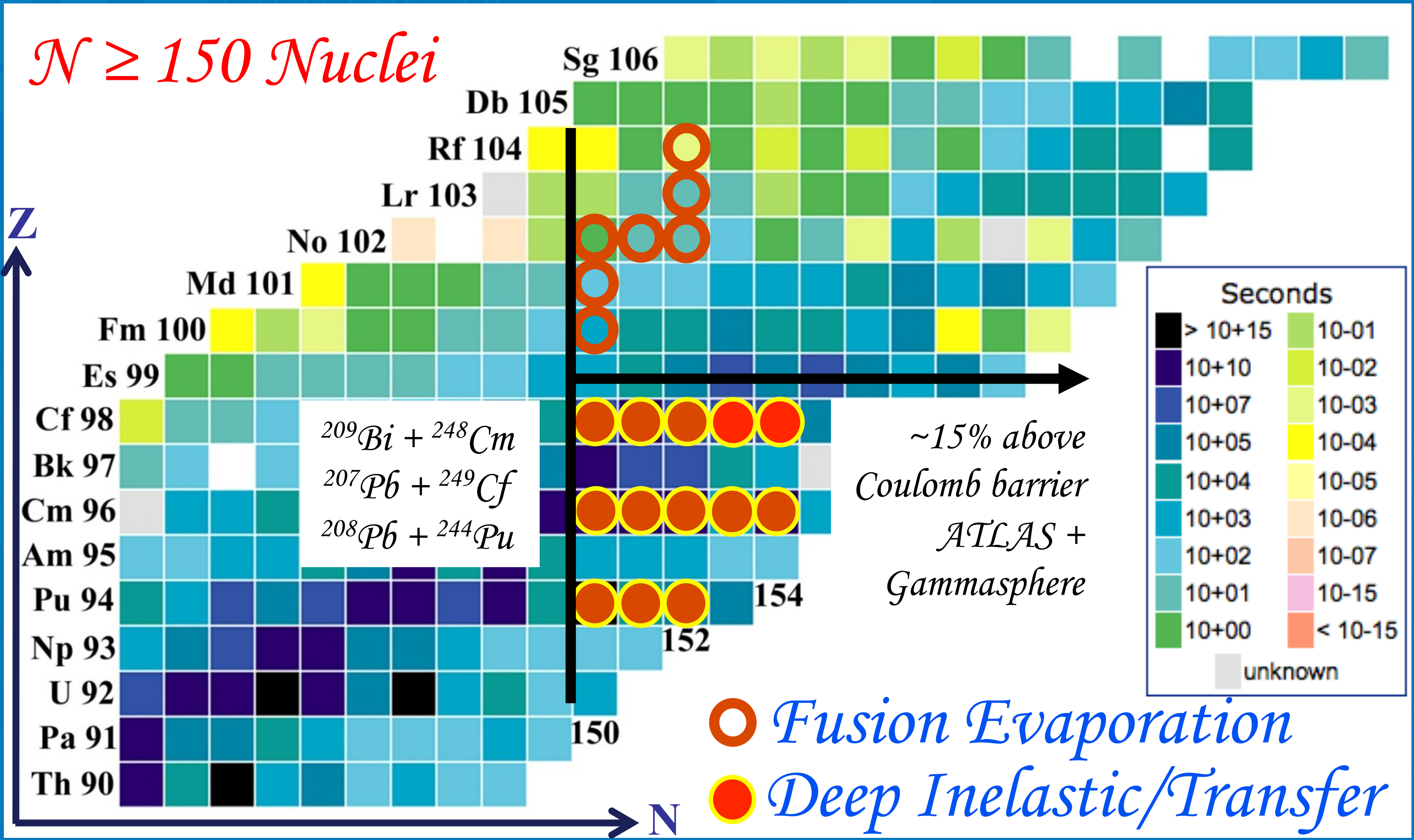




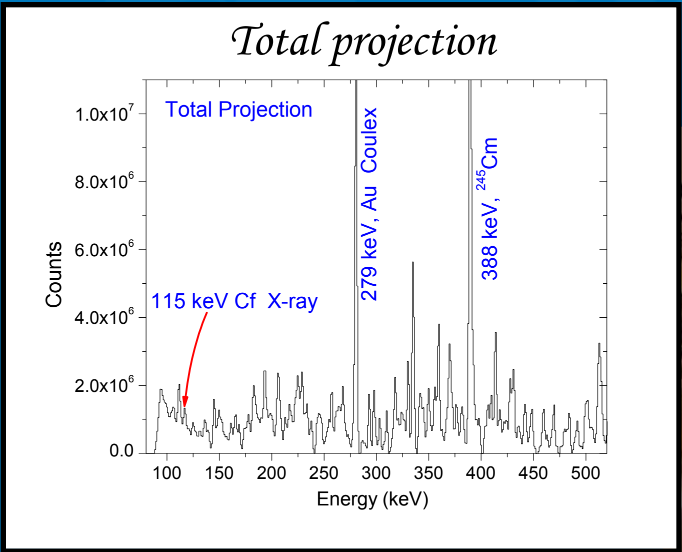
R.R. Chasman and I. Ahmad, Rev. Mod. Phys. 49, 833 (1977) Woods-Saxon

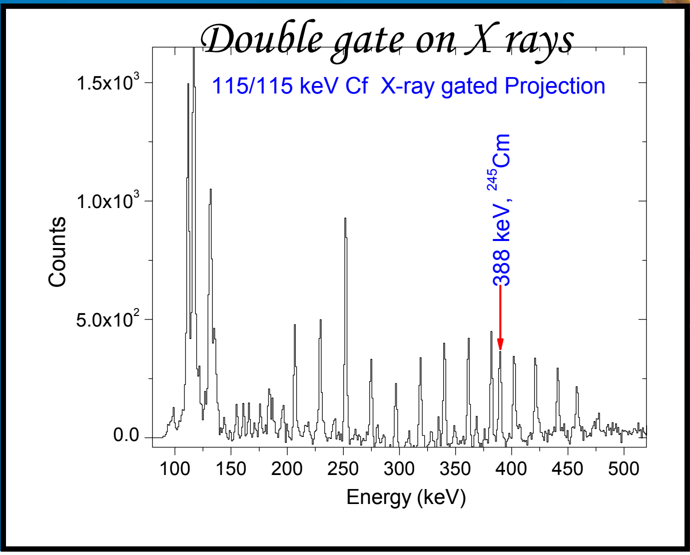
University of Massachusetts UMASS Lowell

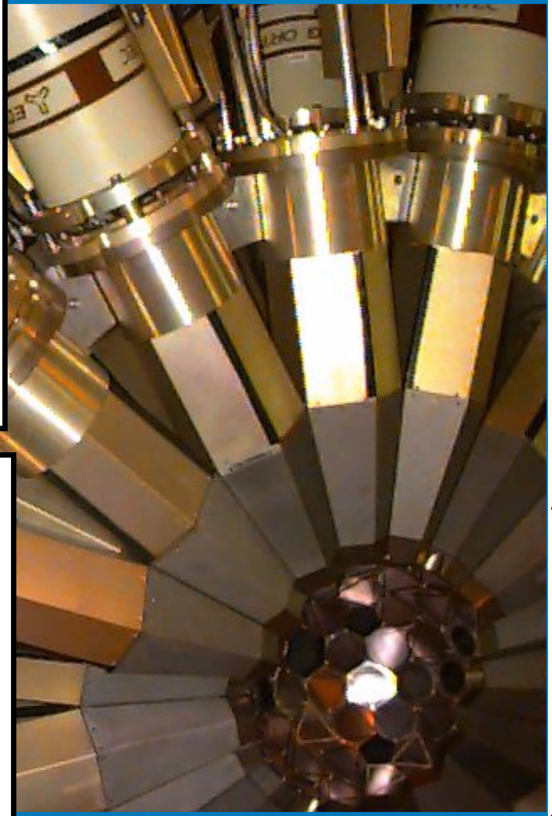
current frontier : the highest neutron orbitals



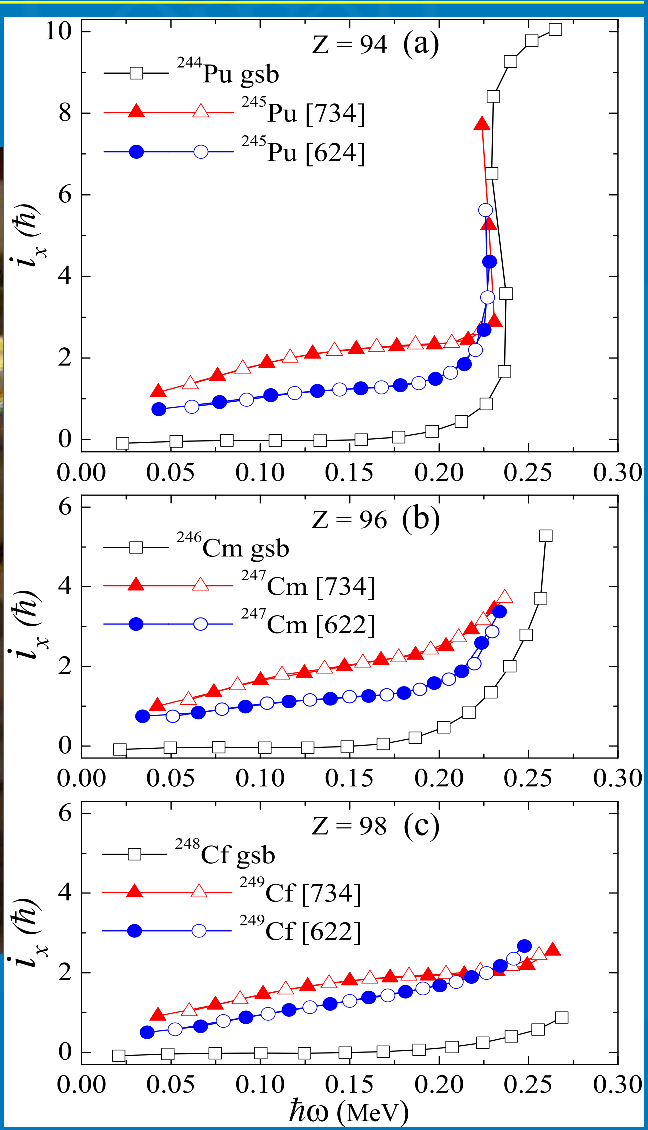
challenging current technology







S.S. Hota et al.,
submitted to Phys. Lett.



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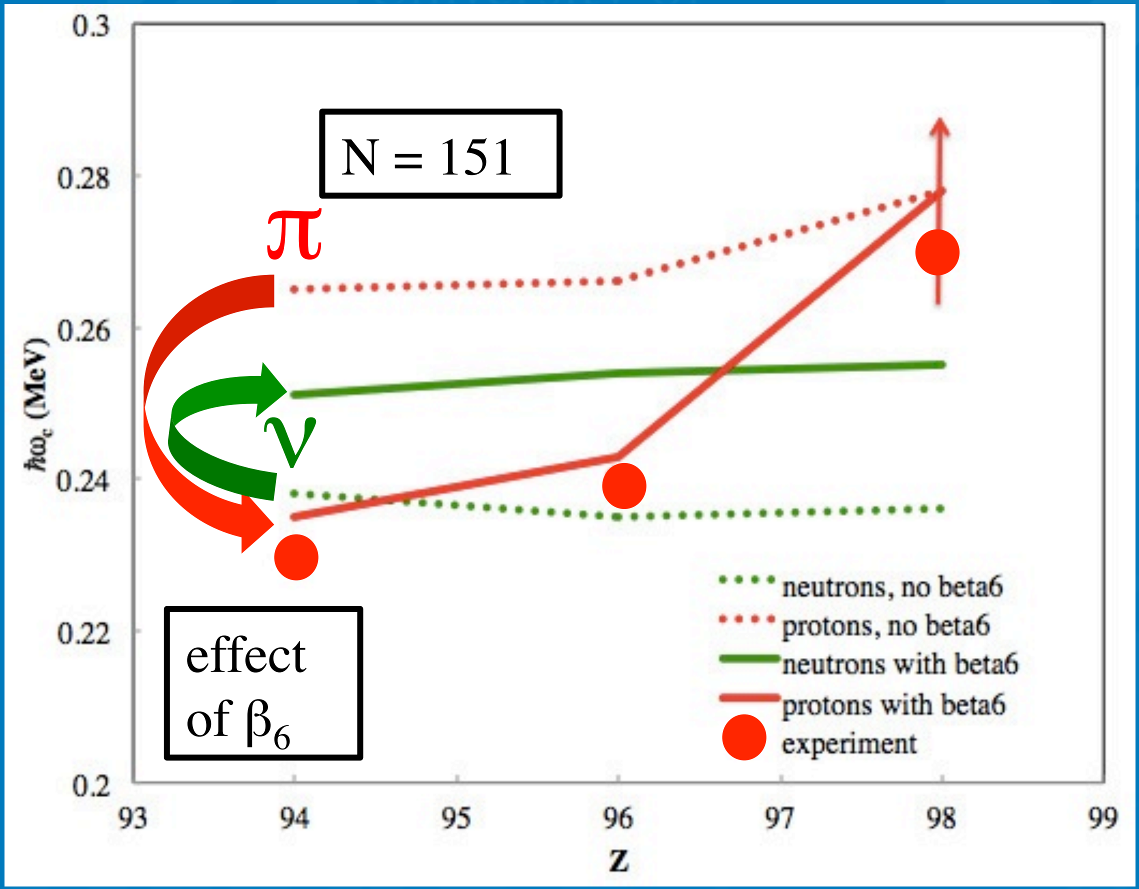
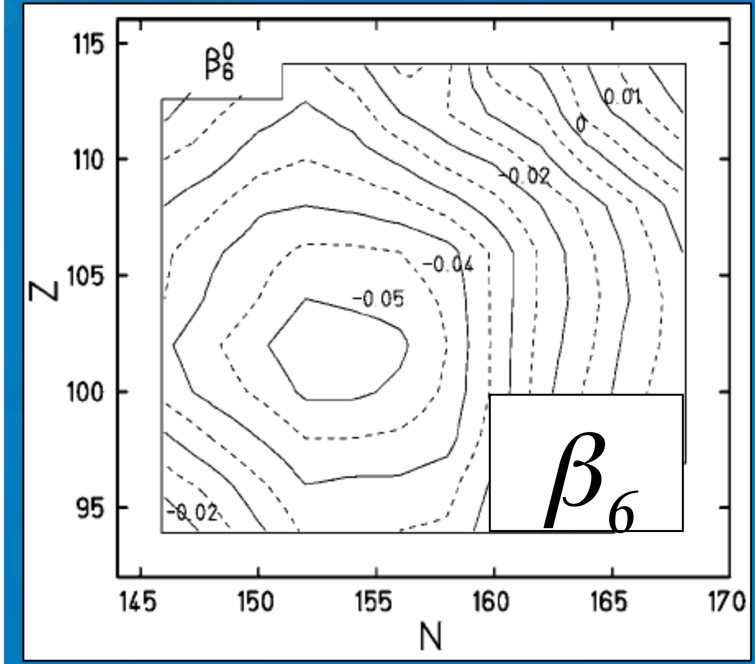
physics example: role of higher order deformations



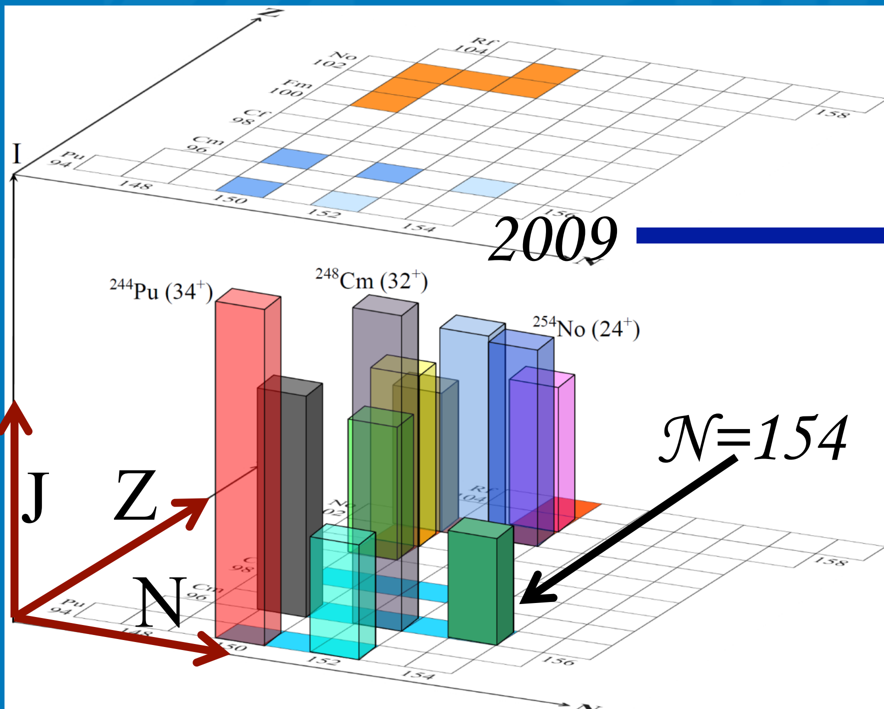
Long-standing puzzle :
Woods-Saxon predicts that neutrons align before protons, contrary to experiment

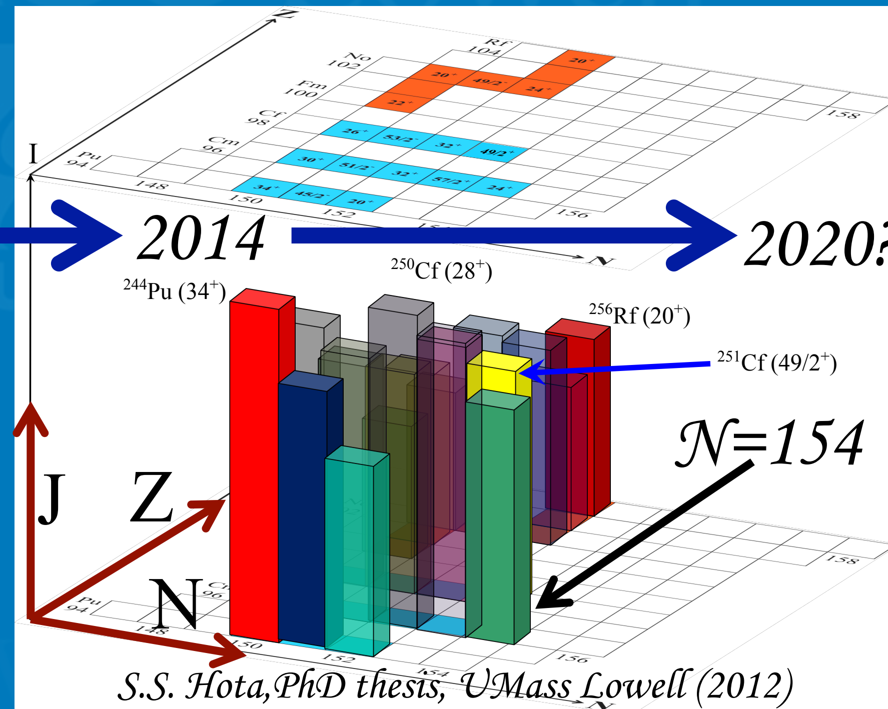


S.S. Hota et al., submitted to Phys. Lett.

A. Sobiczewski et al., PRC 63, 034306 (2001)

evolving knowledge frontier : N > 150





Facilities : rare isotope and stable beams ATLAS, CARIBU, FRIB

Instruments :

Gammasphere

GRETA