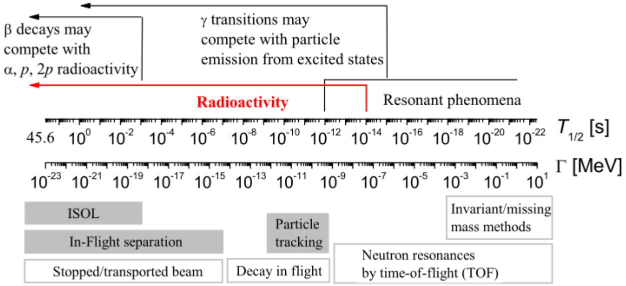
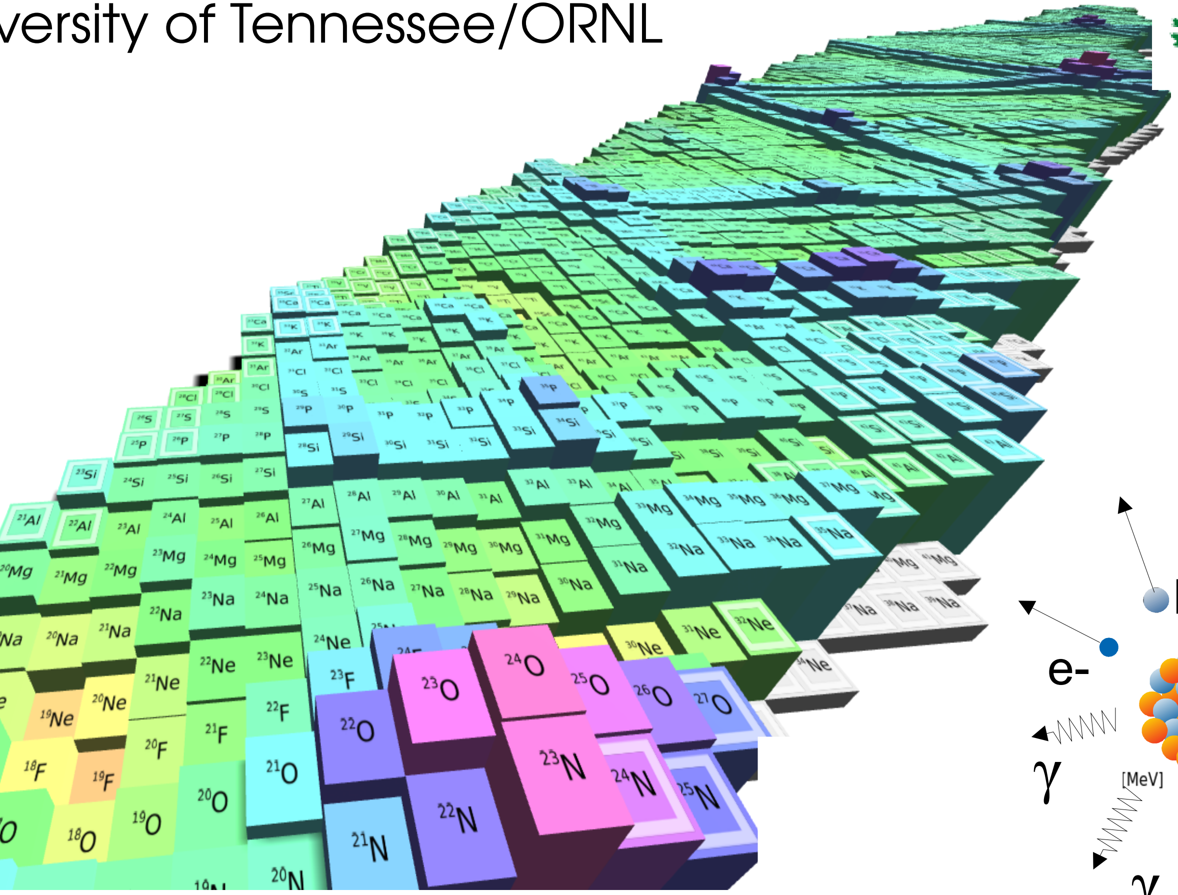
Beyond "existence measurements" ...
Decay spectroscopy of exotic nuclei

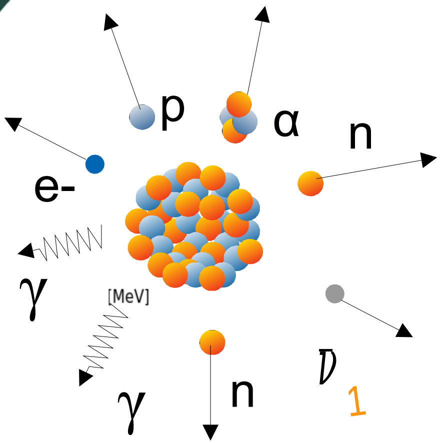
Robert Grzywacz
University of Tennessee/ORNL



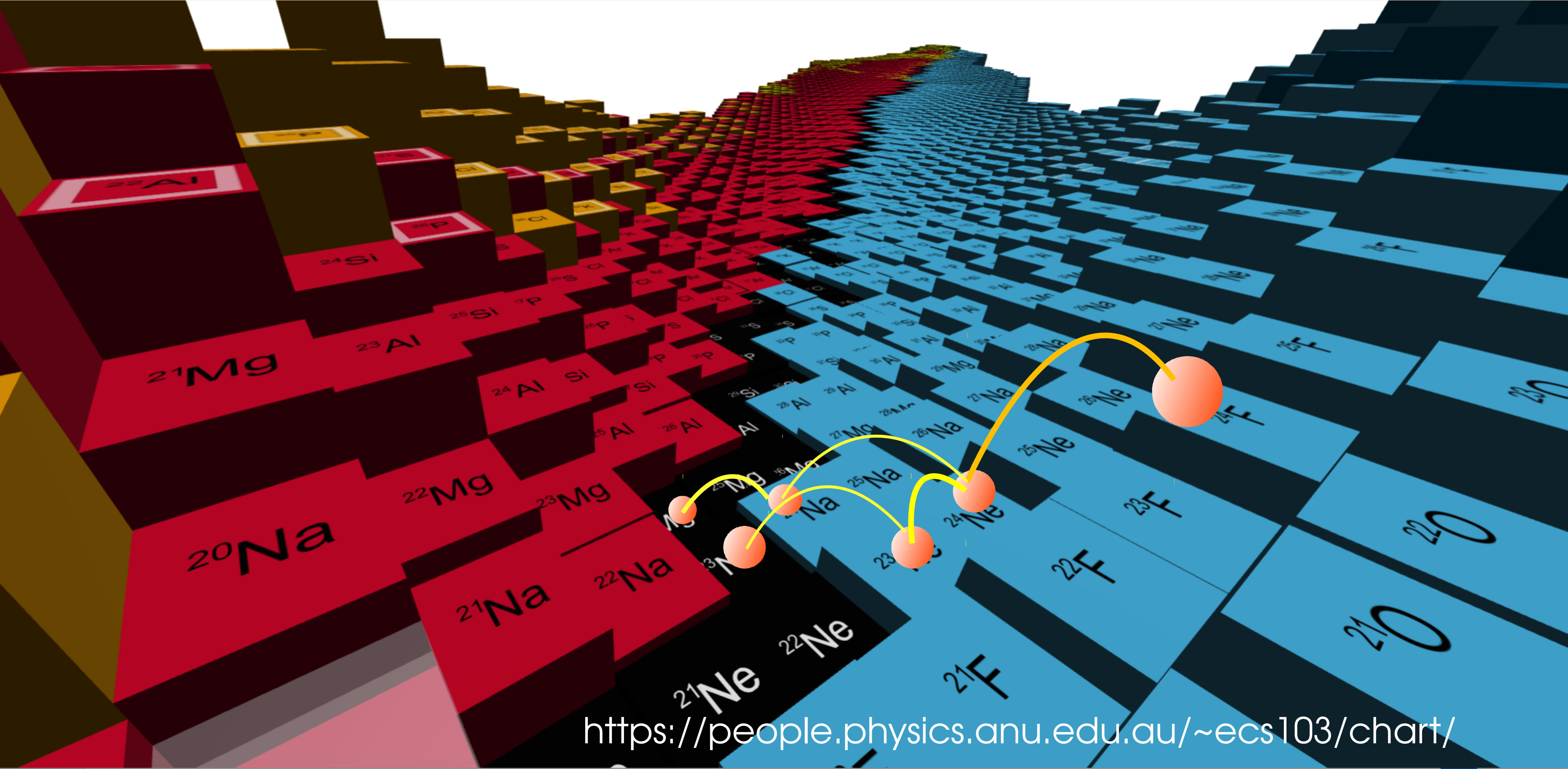
"...radiation is emitted ***spontaneously*** by a system whose nuclear and atomic degrees of freedom are ***close to equilibrium***."

Rev. Mod. Phys., 84, (2012)



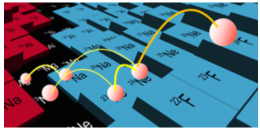


Most nuclei are radioactive ...



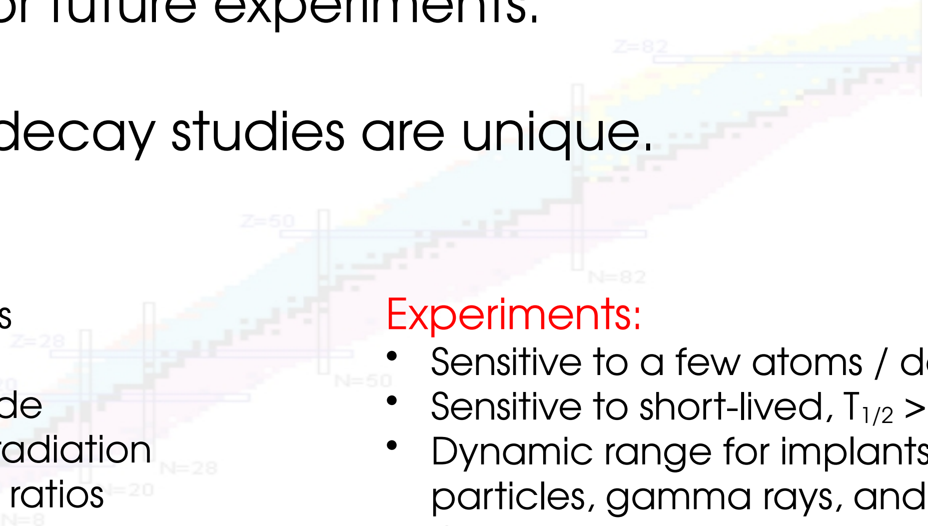
https://people.physics.anu.edu.au/~ecs103/chart/

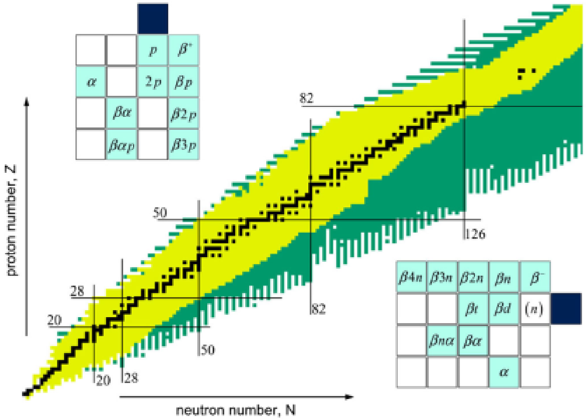
Decay spectroscopy - discover and explain



Decay studies generally access the most exotic isotopes at FRIB.
First step with/after isotope/isomer identification
Do not rely on secondary reactions.
Provides very first test of nuclear models and sets the stage for future experiments.

Capabilities of decay studies are unique.





Rev. Mod. Phys., 84, (2012)

Decay measurements

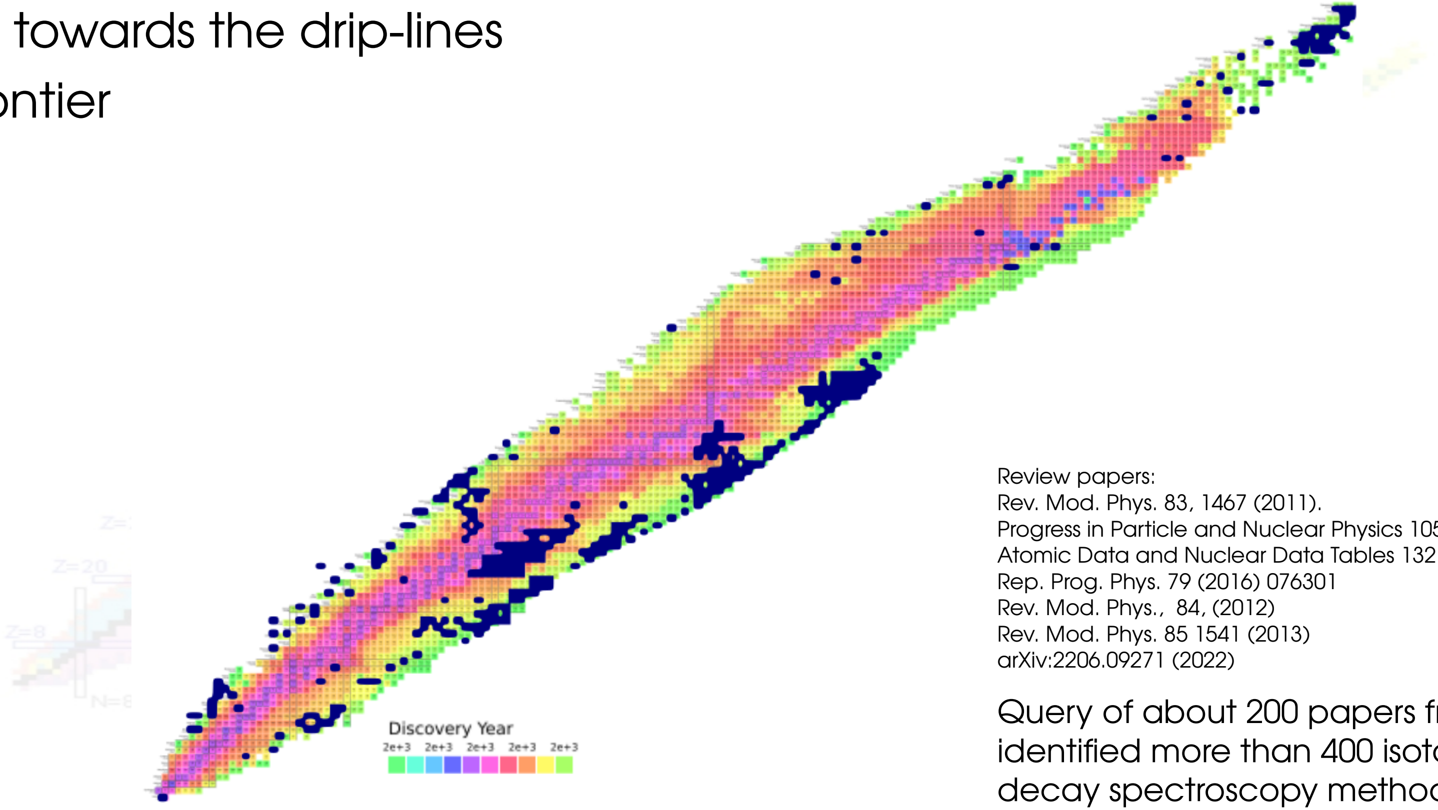
- Nuclear lifetime
- Primary decay mode
- Energy of emitted radiation
- Relative branching ratios
- Decay sequences
- Correlations, angular distributions

Experiments:

- Sensitive to a few atoms / day
- Sensitive to short-lived, $T_{1/2}$ > 100-ns isotopes
- Dynamic range for implants, decays, charged particles, gamma rays, and neutrons
- Complete measurements through discrete and total-absorption spectroscopy

Looking back into last decade

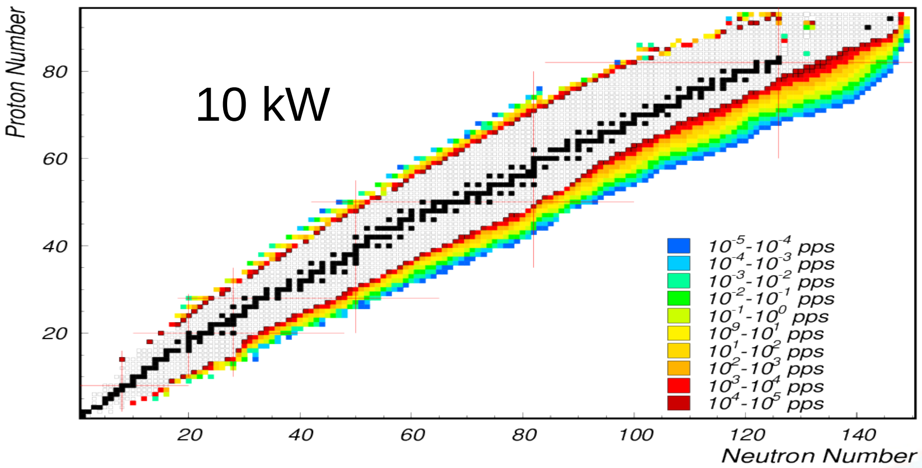
Two-classes of decay experiments:
- exploratory, towards the drip-lines
- precision frontier

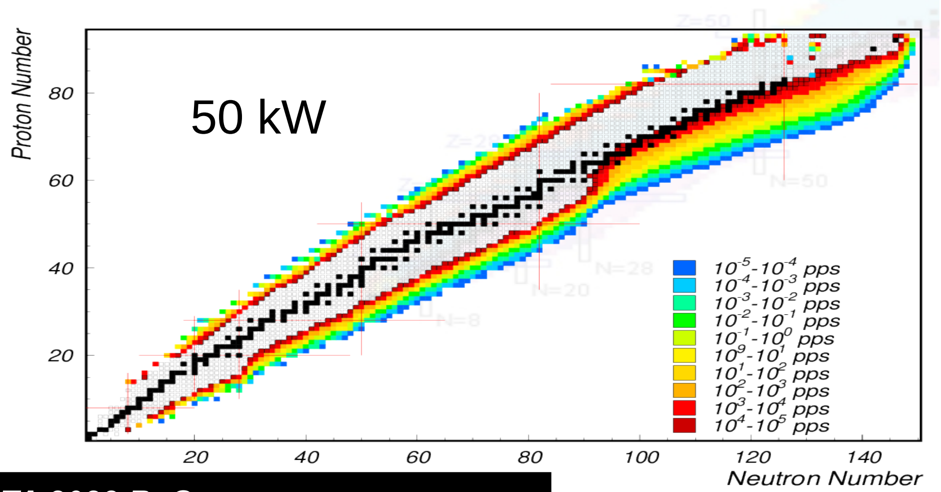


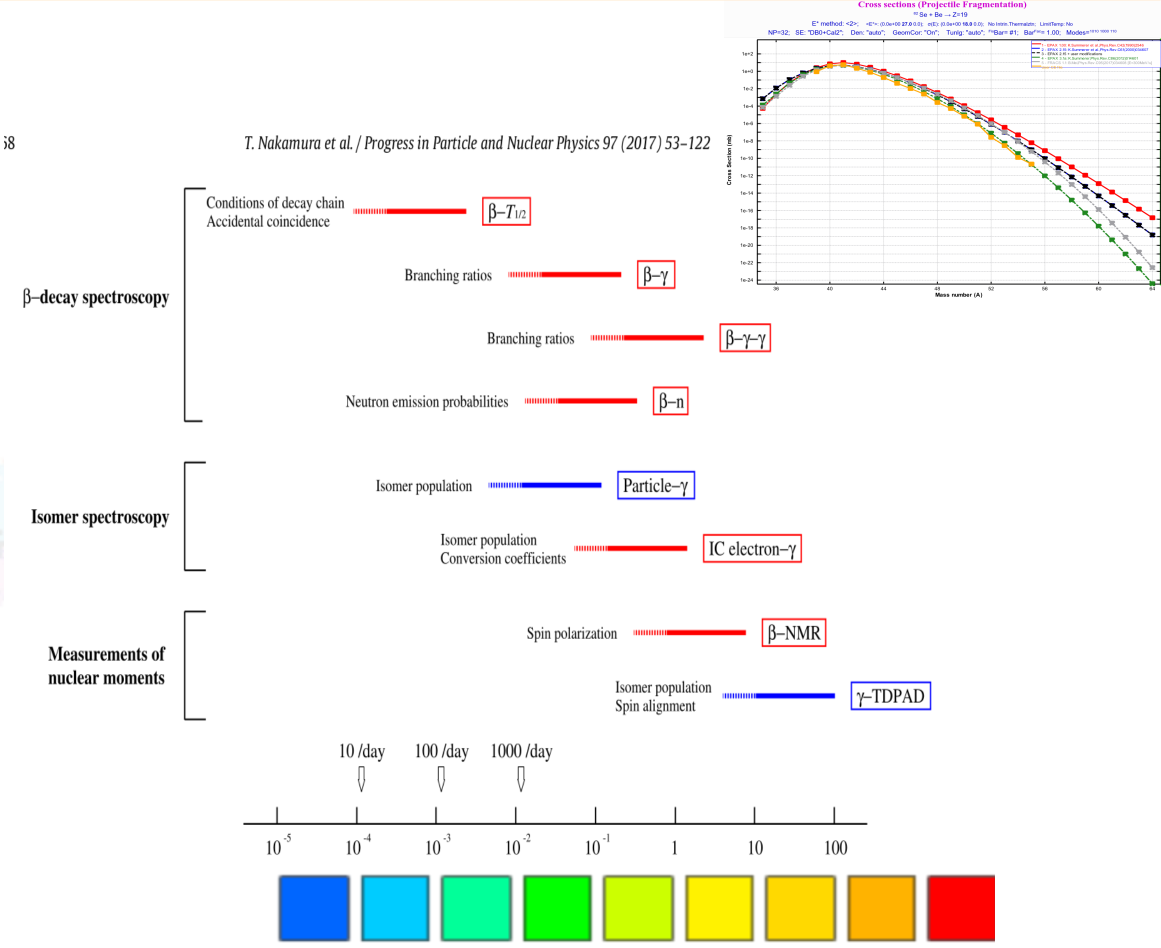
Review papers:
Rev. Mod. Phys. 83, 1467 (2011).
Progress in Particle and Nuclear Physics 105 (2019) 214–251
Atomic Data and Nuclear Data Tables 132 (2020) 101323
Rep. Prog. Phys. 79 (2016) 076301
Rev. Mod. Phys., 84, (2012)
Rev. Mod. Phys. 85 1541 (2013)
arXiv:2206.09271 (2022)

Query of about 200 papers from 2012-2022 identified more than 400 isotopes studied with decay spectroscopy methods.
(Highly incomplete...)

Decay spectroscopy - isotopic reach at FRIB






T. Nakamura et al. / Progress in Particle and Nuclear Physics 97 (2017) 53–122

β–decay spectroscopy
- Conditions of decay chain, Accidental coincidence — β–$T_{1/2}$
- Branching ratios — β–γ
- Branching ratios — β–γ–γ
- Neutron emission probabilities — β–n

Isomer spectroscopy
- Isomer population — Particle–γ
- Isomer population, Conversion coefficients — IC electron–γ

Measurements of nuclear moments
- Spin polarization — β-NMR
- Isomer population, Spin alignment — γ–TDPAD

10 /day, 100 /day, 1000 /day

10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10 100

🟦 🟦 🟩 🟩 🟩 🟨 🟨 🟧 🟥

TA 2023 R. Grzywacz

FRIB Decay Station

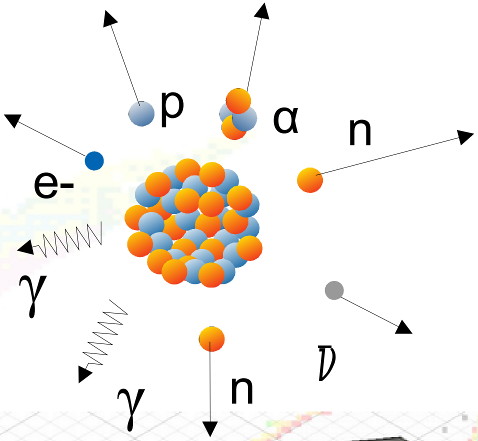
https://fds.ornl.gov/wp-content/uploads/2020/09/FDS-WP.pdf

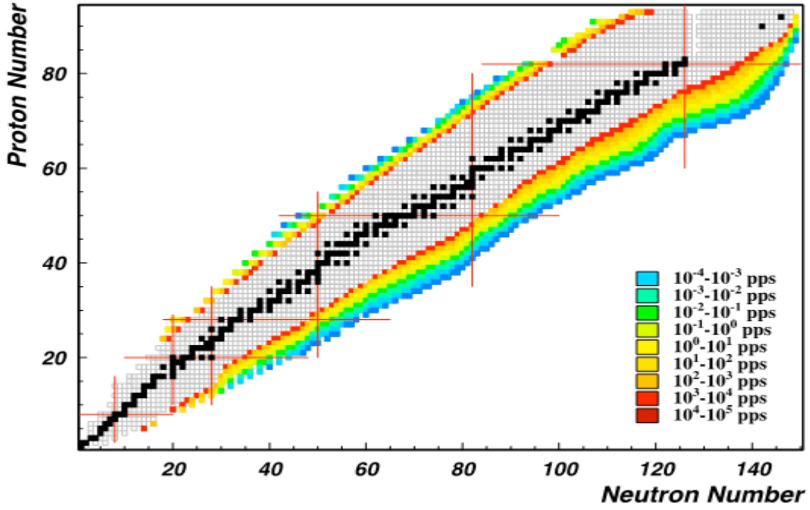
Next generation array for decay spectroscopy!

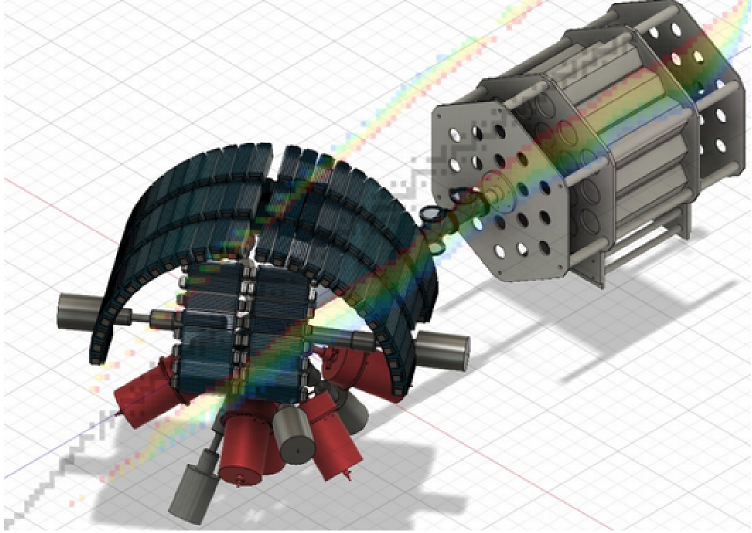
FRIB: access the nuclei very far from stability

FDS enable discovery science and complete spectroscopy with two-focal plane detection system.

Maximize solid angle and detection efficiency.



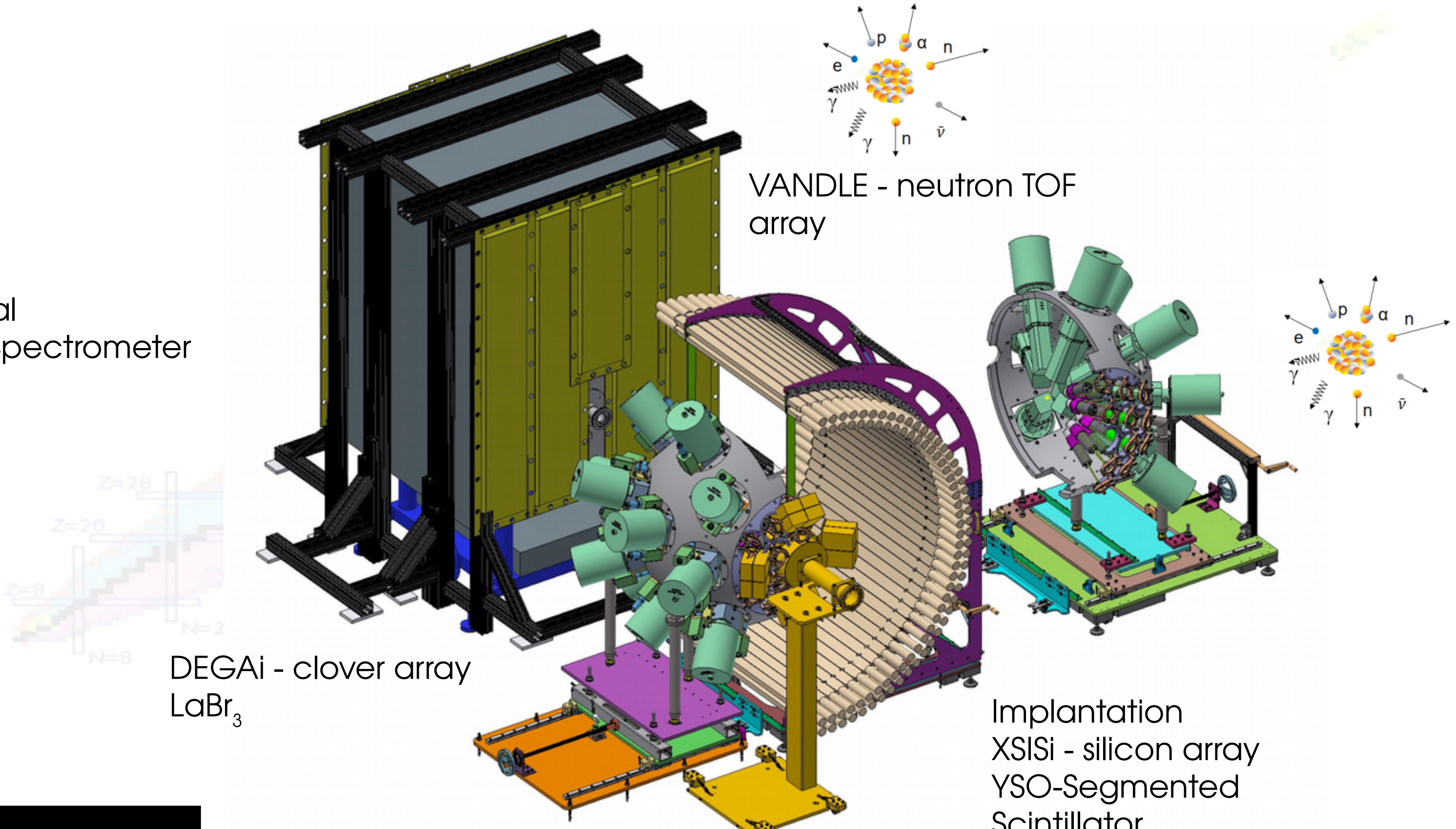




FDS initiator

Demonstrating the FDS concept with collection of the community detectors.

https://fds.ornl.gov/initiator/



VANDLE - neutron TOF array

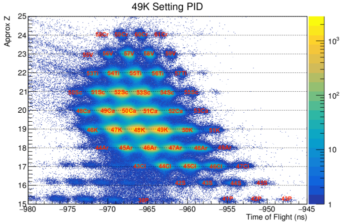
Modular Total Absorption Spectrometer

DEGAi - clover array
$LaBr_3$

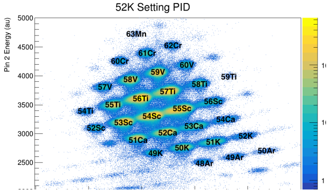
Implantation
XSISi - silicon array
YSO-Segmented Scintillator

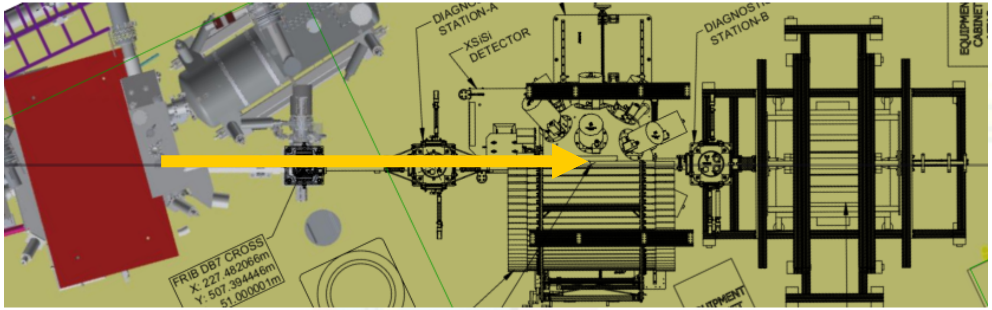
Two separator settings and two focal planes

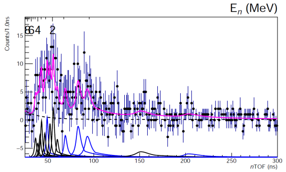
^{49}K

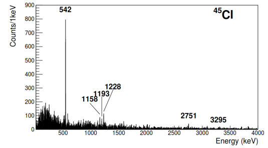


^{52}K

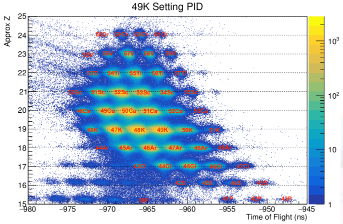




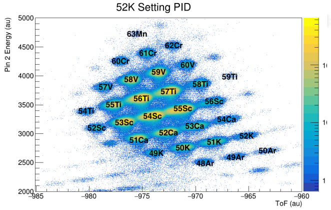


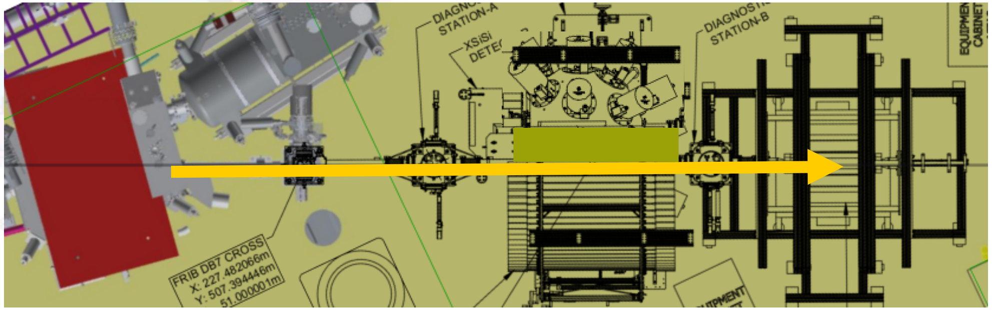


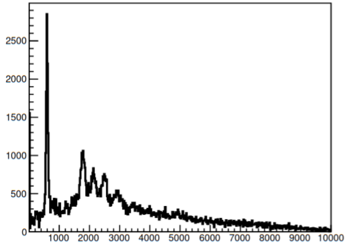
^{49}K



^{52}K



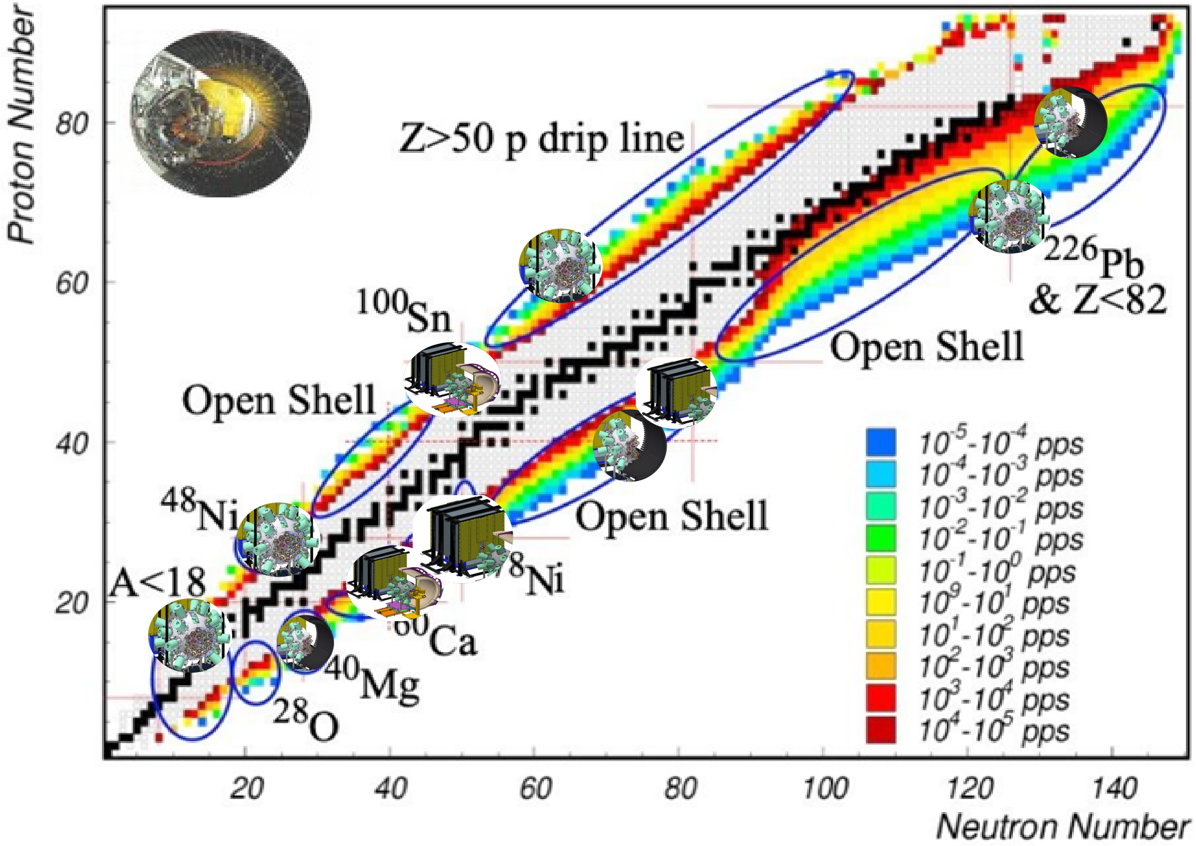




FDSi PAC1+PAC2 proposals (FRIB 10kW)

FDSi science program:

- Gamow-Teller quenching in ^{100}Sn
- Shape transitions and r-process
- in neutron rich A~100
- Shell-evolution near closed shells
- ^{60}Ca, ^{78}Ni, ^{226}Pb
- Island of inversion N~28
- Astrophysical resonances ^{20}Mg
- Gamma-strength function
  for the r-process near ^{132}Sn
- Decay near proton drip-line Z>50
- 2p correlation near ^{48}Ni

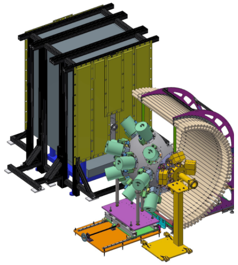


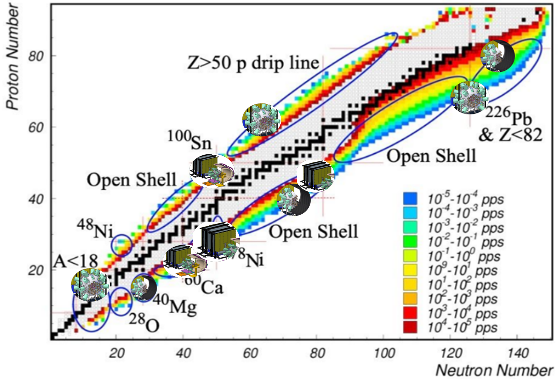
FDSi Science program – PAC approved proposals

PAC 1 (2021)
1 - "Correlation of Triaxial Deformation with Inertial Dynamics, Masses and r-Process Nucleosynthesis". J.M. Allmond (ORNL)
2 - "Decoding the doubly magic stronghold - decay spectroscopy of 78Ni ". Krzysztof Rykaczewski (ORNL)
3 - "Complete decay spectroscopy of 100Sn and its neighbors". Robert Grzywacz (UTK)
4 - "Decay spectroscopy of the N=35 nuclei 55Ca,54K and 53Ar and the search for dripline nucleus 50S". Wei Jia Ong (LLNL)
5 - "Decay Spectroscopy Near N=28: Shell Structure, Shapes and Weak Binding". Heather Crawford (LBNL)
6 - "Strength of the key 15O(a,g)19Ne resonance in X-ray bursts". Christopher Wrede (FRIB-MSU).
7 - "Constraining neutron capture rates for the r-process ". Artemis Spyrou (FRIB-MSU)
8 - "Decay spectroscopy in the vicinity of the N=126 shell closure". Jin Wu (ANL)

PAC 2 (2023)
1."Seniority Isomers and Single-Particle Evolution in 218-222 Pb Region: New Isotopes, Isomers, and Half Lives" - J.M. Allmond (ORNL)
2. "Intersections of nuclear structure and statistical model in βn-decays of cobalt isotopes and isomers" - R. Grzywacz (UTK, ORNL)
3. "The Study of Proton-Rich Isotopes Along the Proton Drip-Line above 100 Sn" - D. Seweryniak (ANL)
4. "Decay Spectroscopy Near N = 40: toward the N = 50 island of inversion near 78 Ni" - B. Crider (Mississippi State University)
5. Is there a NiCu Cycle in X-ray Bursts?" - C. Wrede (FRIB)
(6). Beta-delayed neutron spectroscopy of 24O (R. Grzywacz UTK/ORNL)

Proton-proton momentum correlations in two-proton radioactivity of 54Zn (M. Pfutzner)
Proton-proton momentum correlations in two-proton radioactivity (M. Pfutzner)
Study of the beta-decays of 22Al and 26P (H. Fynbo)





Beta decay - lifetimes, decay strength

The strength distribution within Q_β determines decay properties.

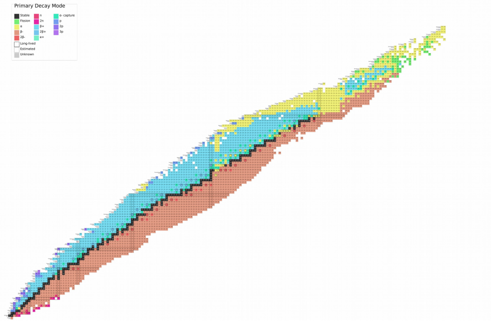
$$\frac{1}{T_{1/2}} = \sum_{E_i \ge 0}^{E_i \le Q_\beta} S_\beta(E_i) \times f(Z, Q_\beta - E_i)$$

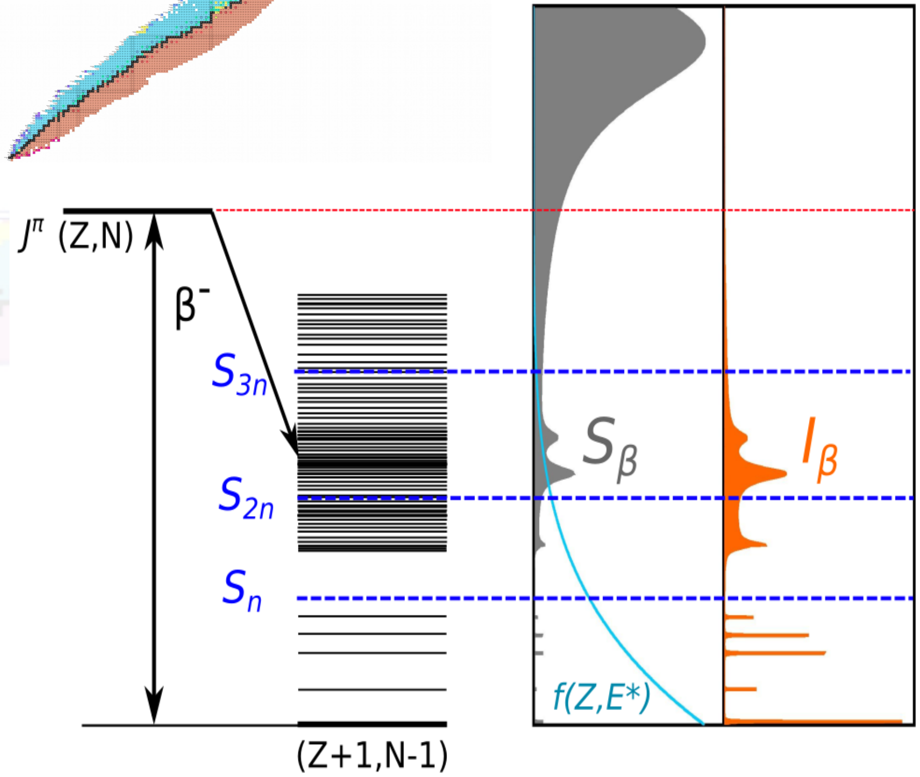
Connects strong and weak interactions
Requires the knowledge of the structure of parent and daughter.

$$S_\beta(E_i) = \langle \psi_f | \hat{O}_\beta | \psi_{mother} \rangle$$

Lifetime measurements provide ambiguous feedback into nuclear models due to the distributed nature of the decay strength.

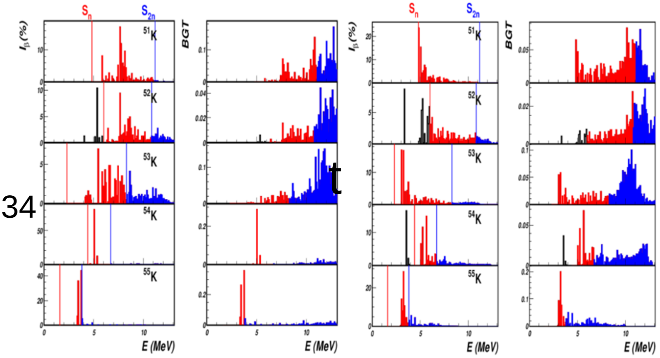
Relevance/Frontiers:
Nuclear astrophysics – r-process modeling
Reactor anti-neutrino problem, double-beta decay
Reactor physics – decay heat
Fundamental interactions - test of standard model





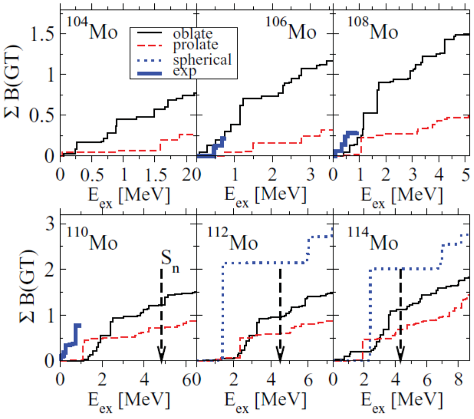
Beta-decay strength and nuclear structure

Shell-evolution



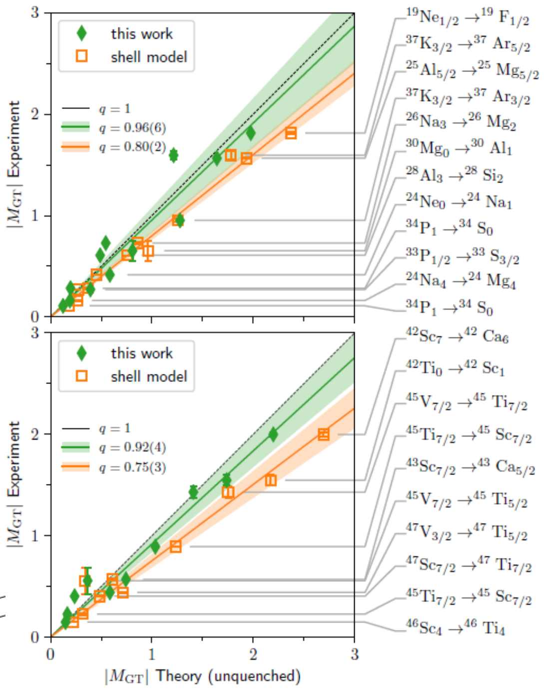
N=34

Shape



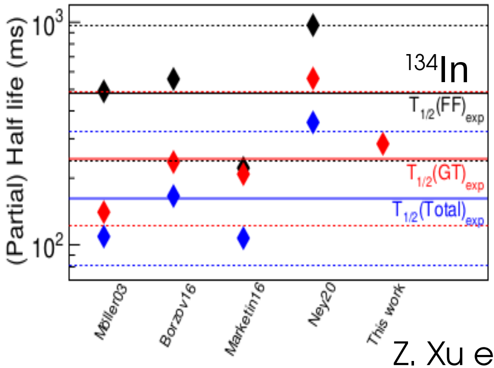
PR C 95, 024308 (2017)

GT quenching

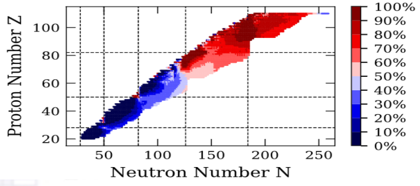


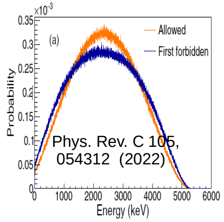
Nature Physics 15, 428–431 (2019)

Allowed vs. forbidden



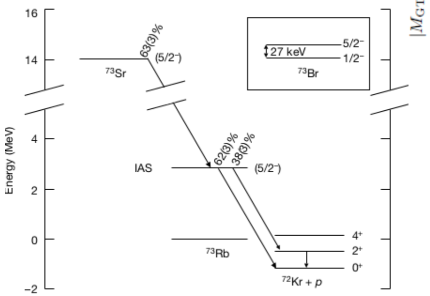
Z. Xu et al.





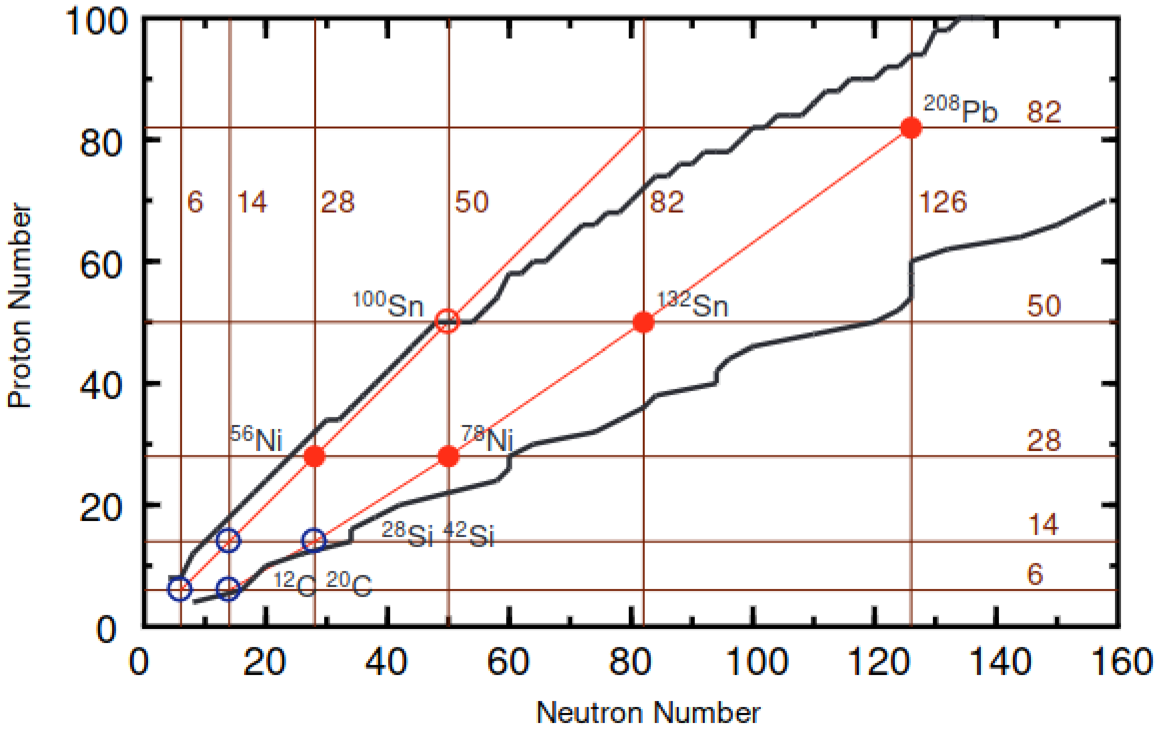
Phys. Rev. C 105, 054312 (2022)

Isospin mixing
Mirror symmetry breaking



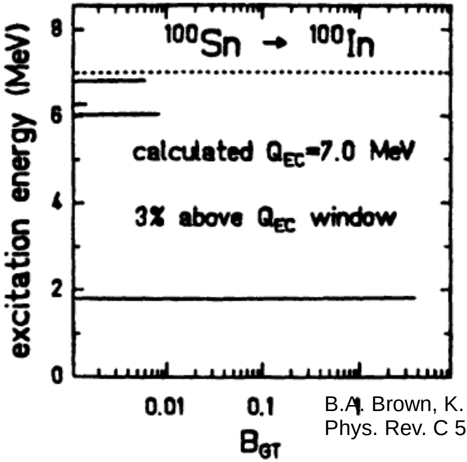
Nature 580 (2019).

Strength measurement near doubly magic nuclei

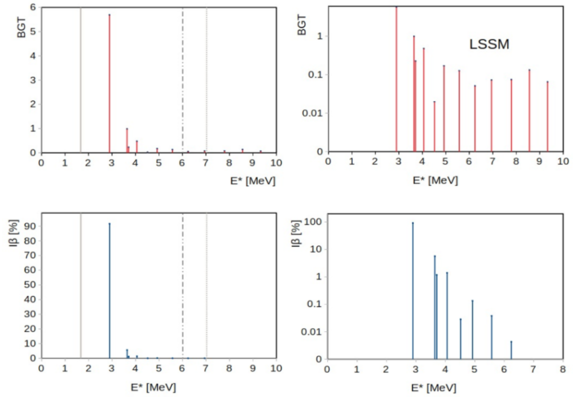


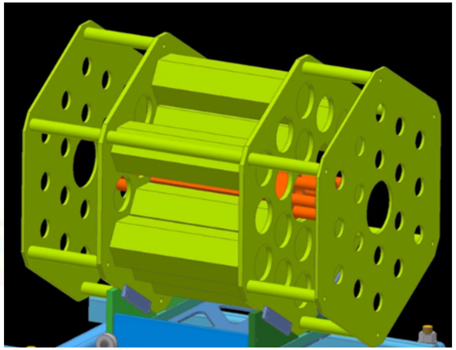
Decay of ^{100}Sn

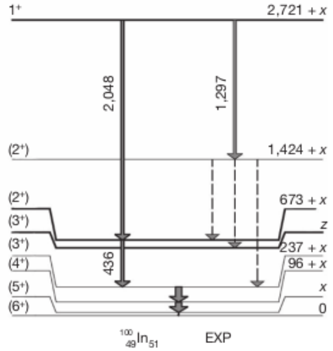
"Complete decay spectroscopy of 100Sn and its neighbors". RG et al. (UTK/ORNL)

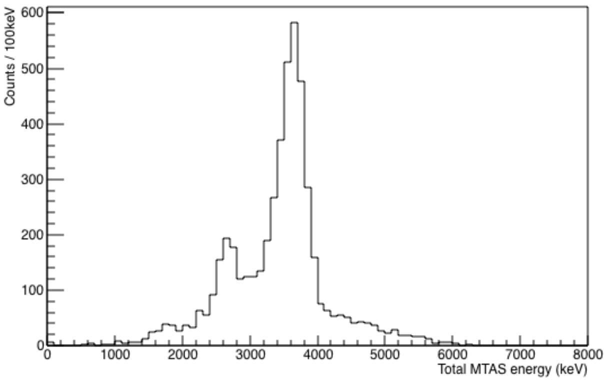


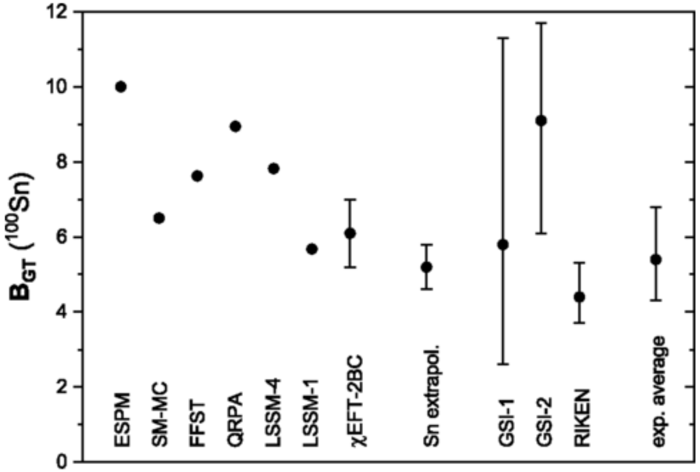
B.A. Brown, K. Rykaczewski,
Phys. Rev. C 50, R 2270 (1994).





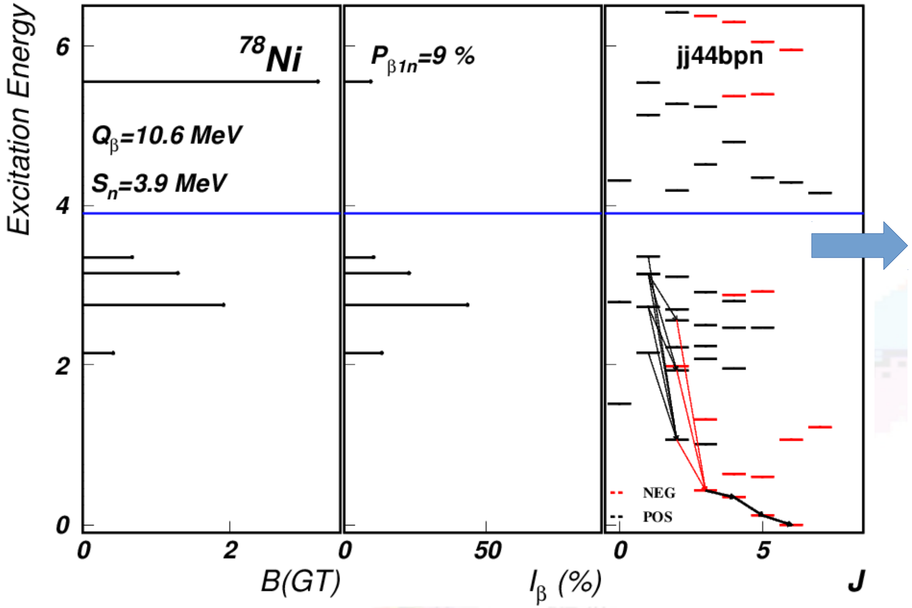


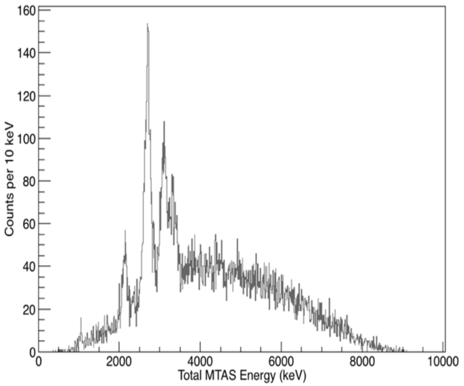

Expected 100Sn decay in MTAS

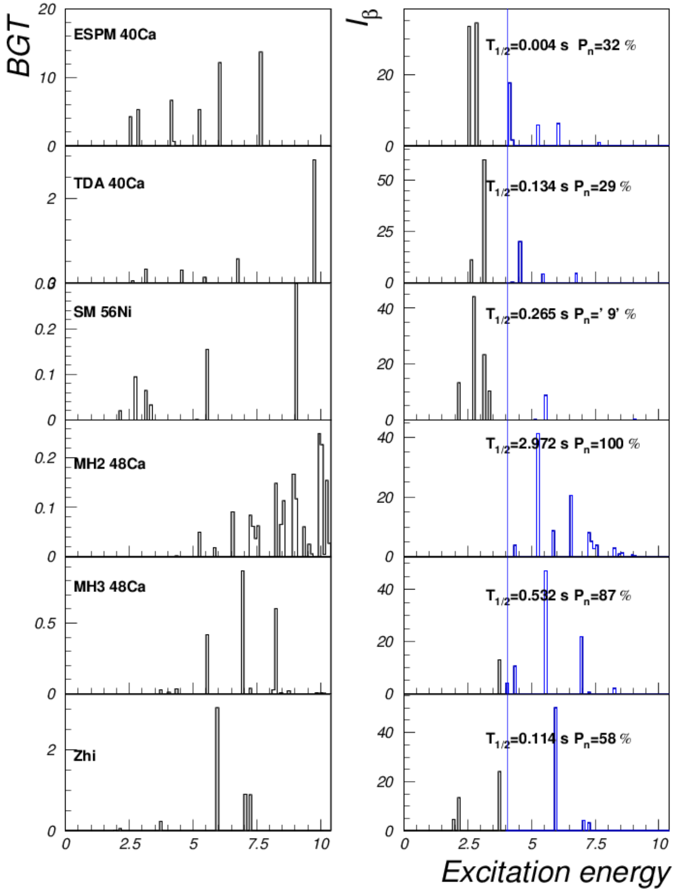


Decay of ^{78}Ni – strength distribution

"Decoding the doubly magic stronghold - decay spectroscopy of 78Ni ".
Krzysztof Rykaczewski (ORNL)



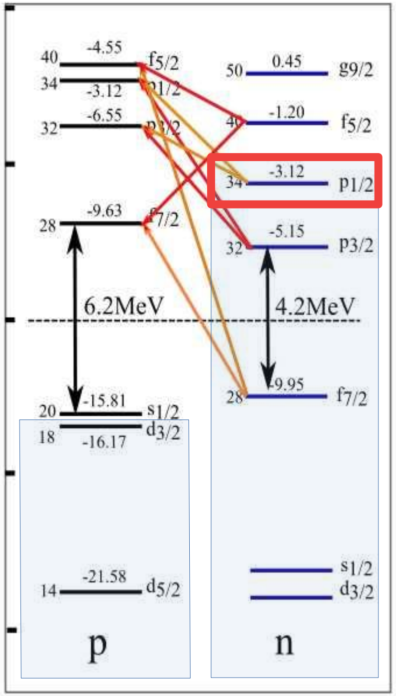




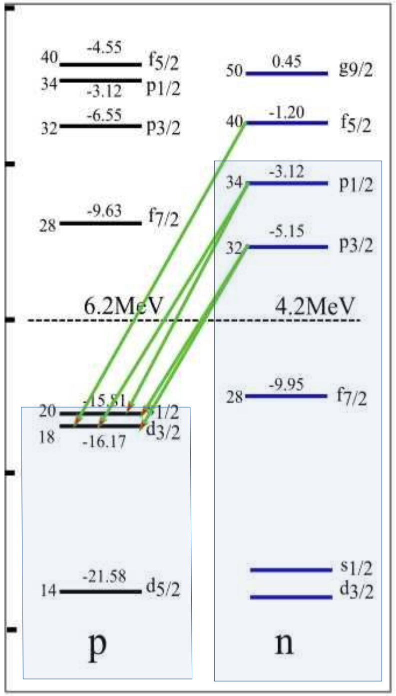
^{54}K decay - shell model picture

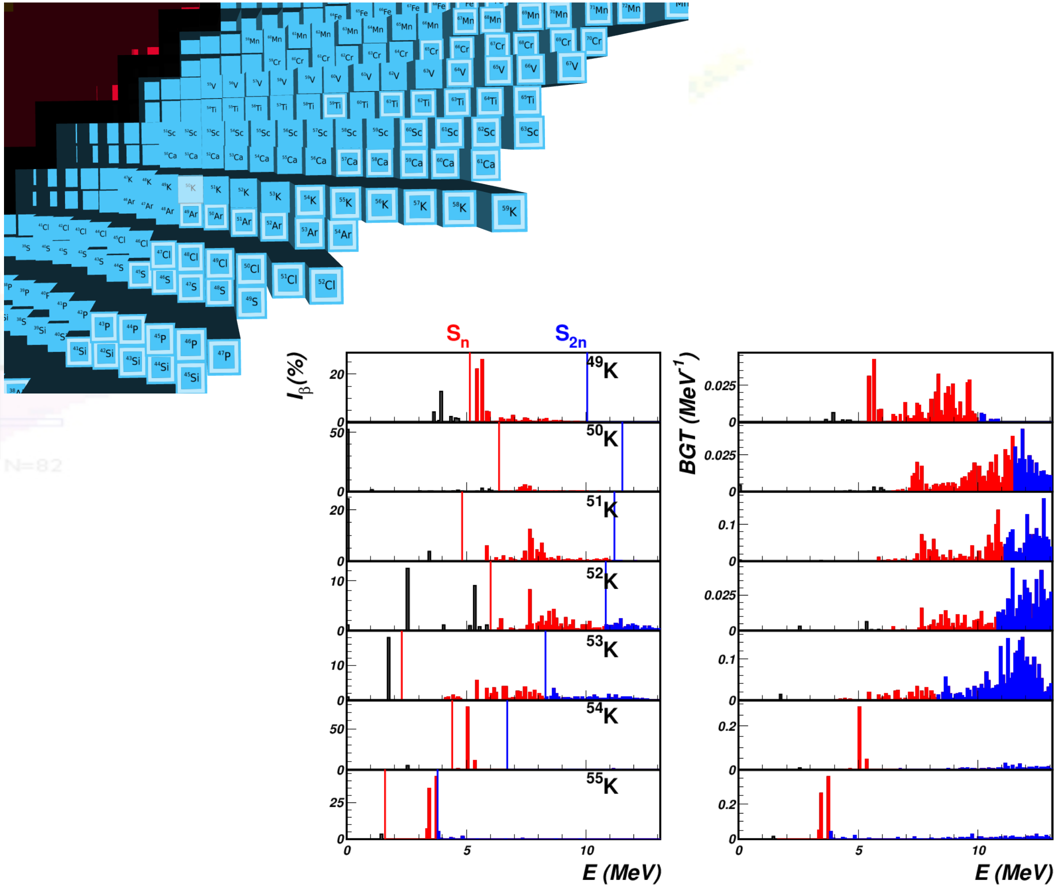
"Decay spectroscopy of the N=35 nuclei 55Ca,54K and 53Ar and the search for dripline nucleus 50S". Wei Jia Ong (LLNL)

Gamow-Teller

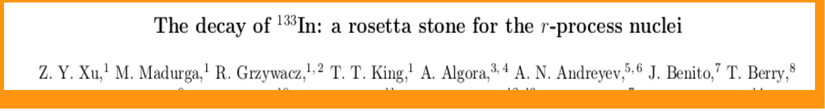


First-forbidden





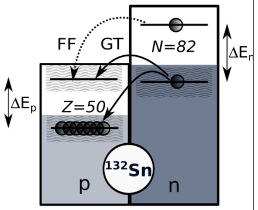
The decay of ^{133}In at IDS

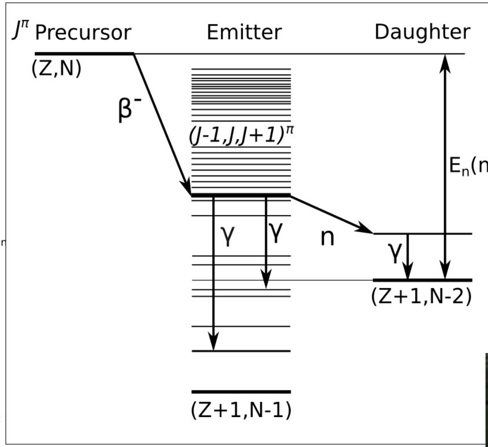


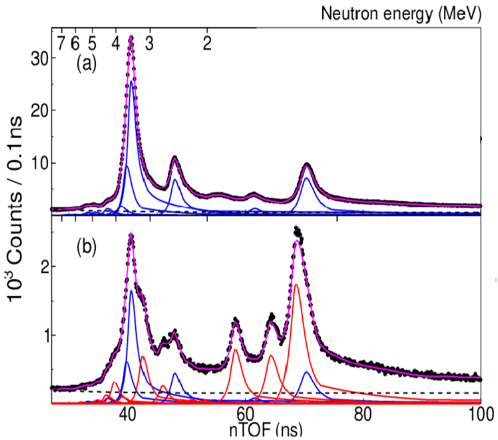
The decay of ^{133}In: a rosetta stone for the r-process nuclei

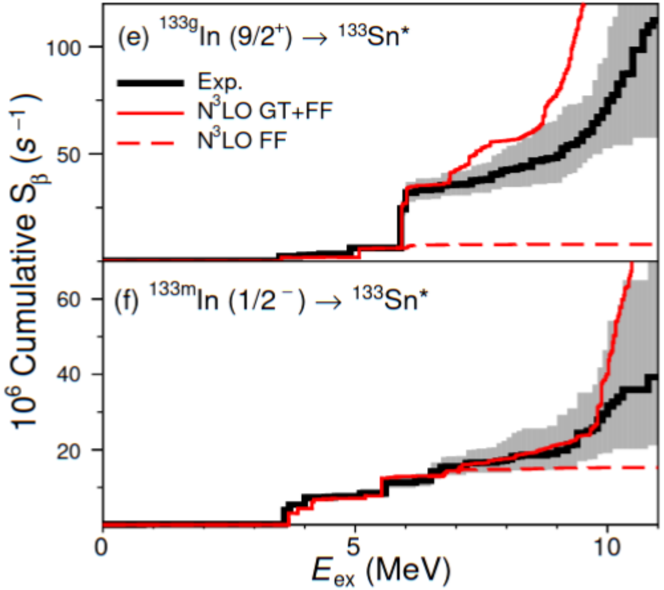
Z. Y. Xu,[1] M. Madurga,[1] R. Grzywacz,[1,2] T. T. King,[1] A. Algora,[3,4] A. N. Andreyev,[5,6] J. Benito,[7] T. Berry,[8]

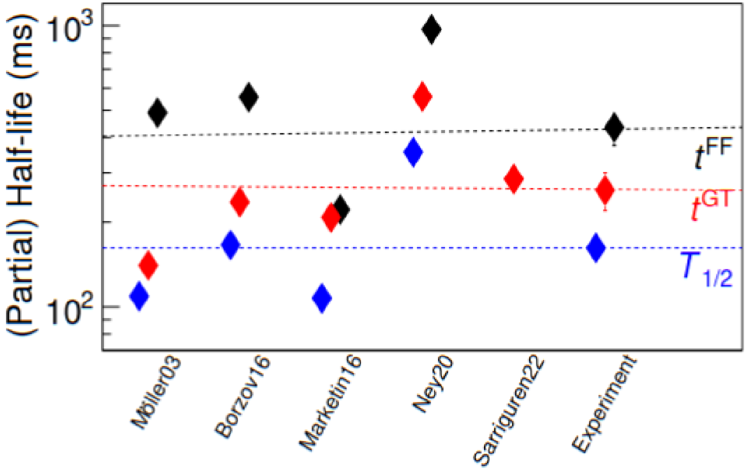
- Model for the neutron spectroscopy
- Discrete neutron spectrum
- Quantified role of "elementary" GT and FF transitions
- Role of single particle transitions
- Measure neutron-gamma competition
  (Experiment at Isolde Decay Station, CERN)



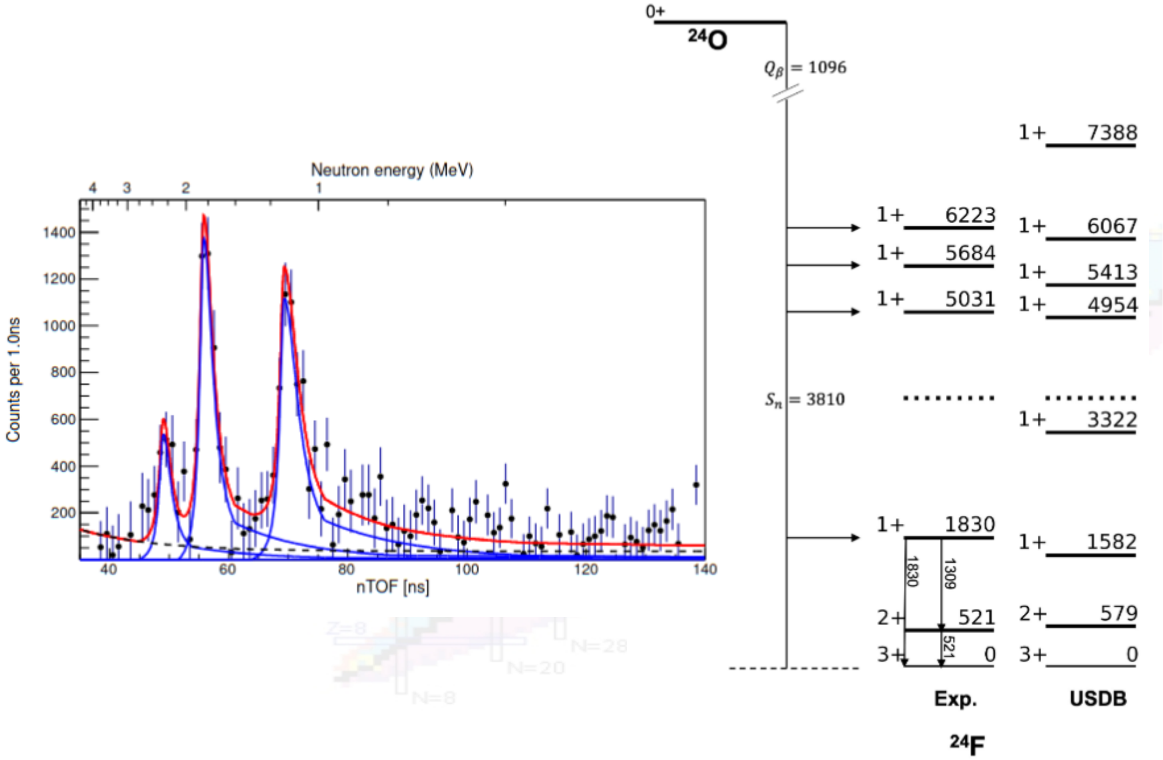


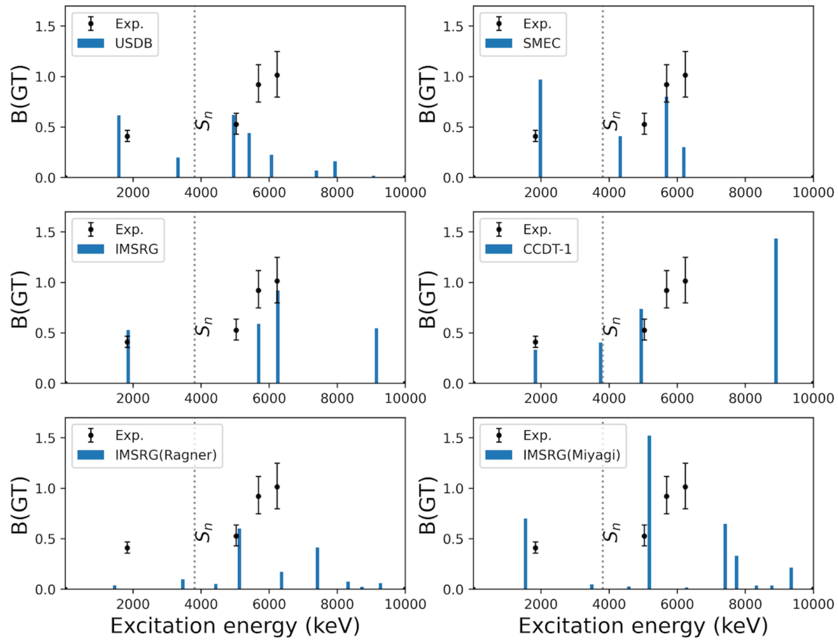




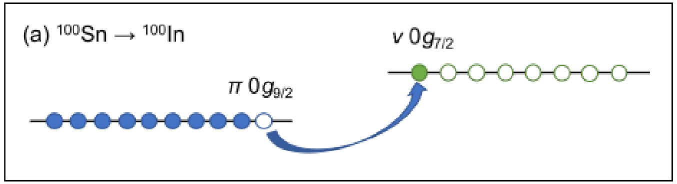


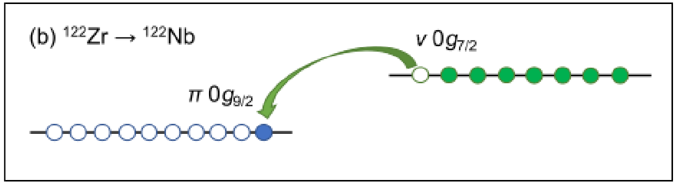
Delayed neutron emission ^{24}O

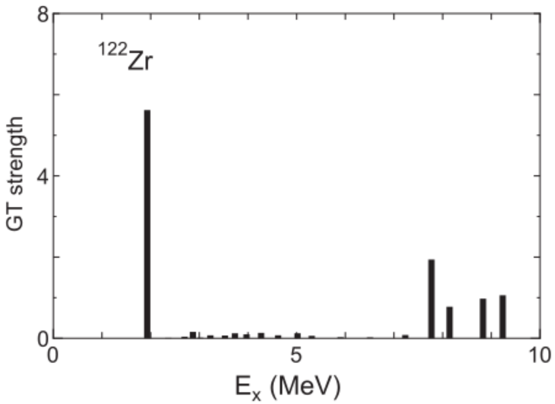




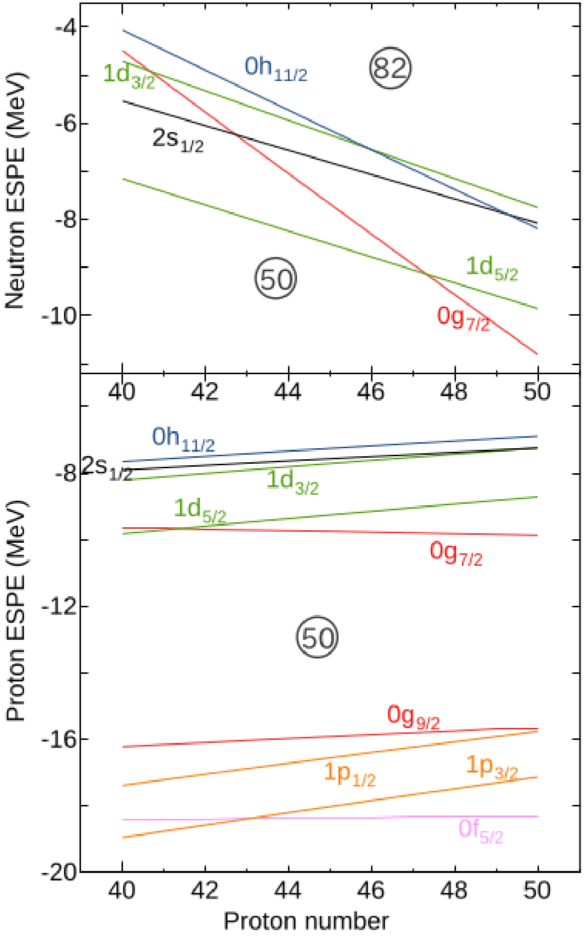
(Very) Long term goal - superallowed decay of ^{122}Zr

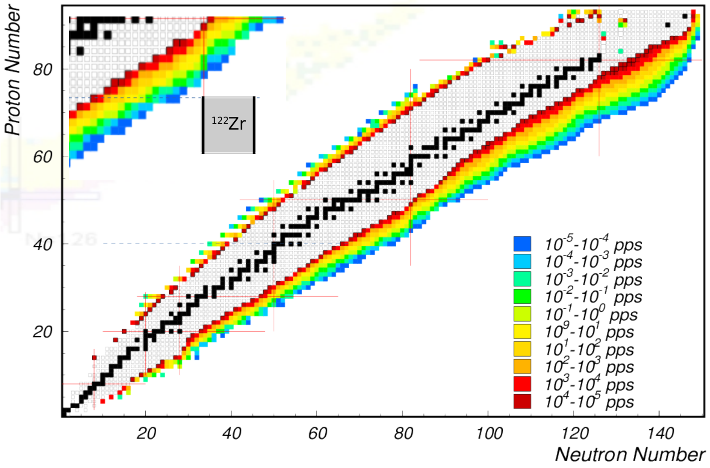






Shimizu et al.



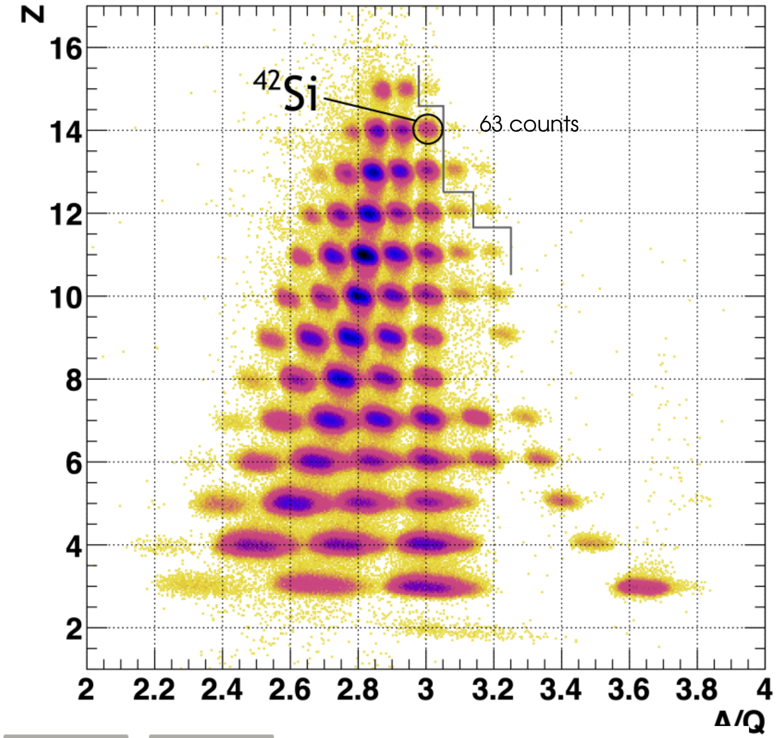


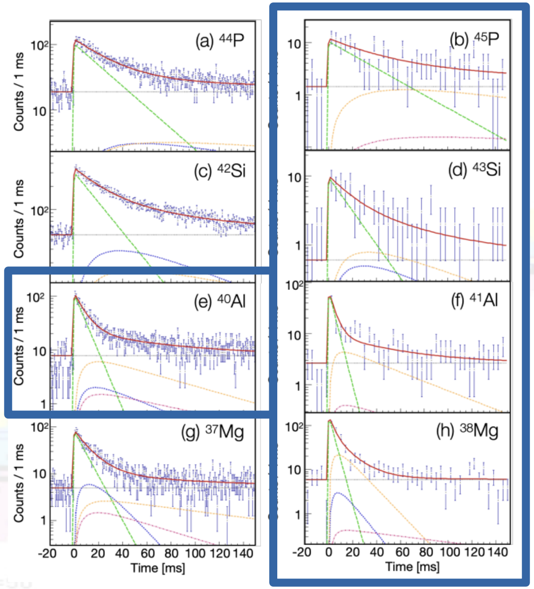
Rate < 10^{-5} pps

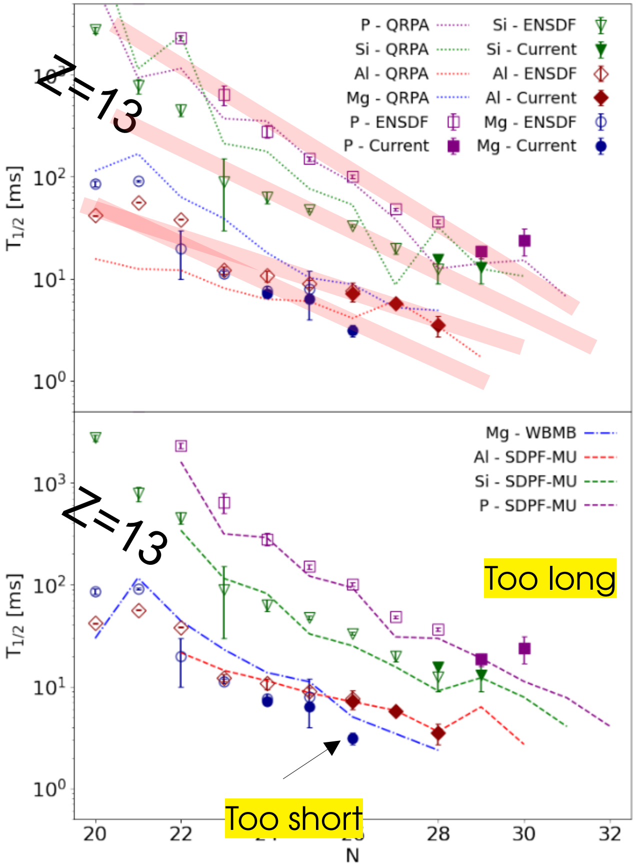
Even at 400 kW FRIB

FDSi and FRIB first experiment

Five new half-lives in the N=28 Island of Inversion.







Too long

Too short

Featured in Physics

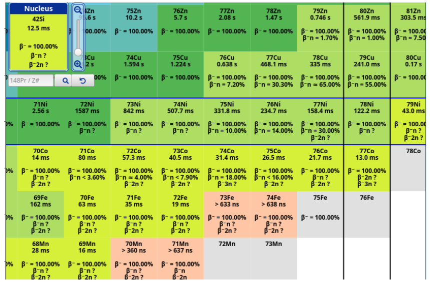
Editors' Suggestion

Crossing $N = 28$ Toward the Neutron Drip Line: First Measurement of Half-Lives at FRIB

H. L. Crawford *et al.*

Phys. Rev. Lett. **129**, 212501 – Published 14 November 2022

Physics See Viewpoint: Probing the Limits of Nuclear Existence

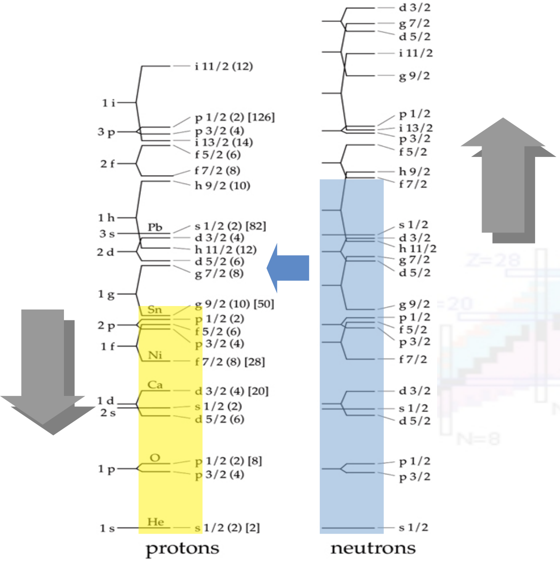


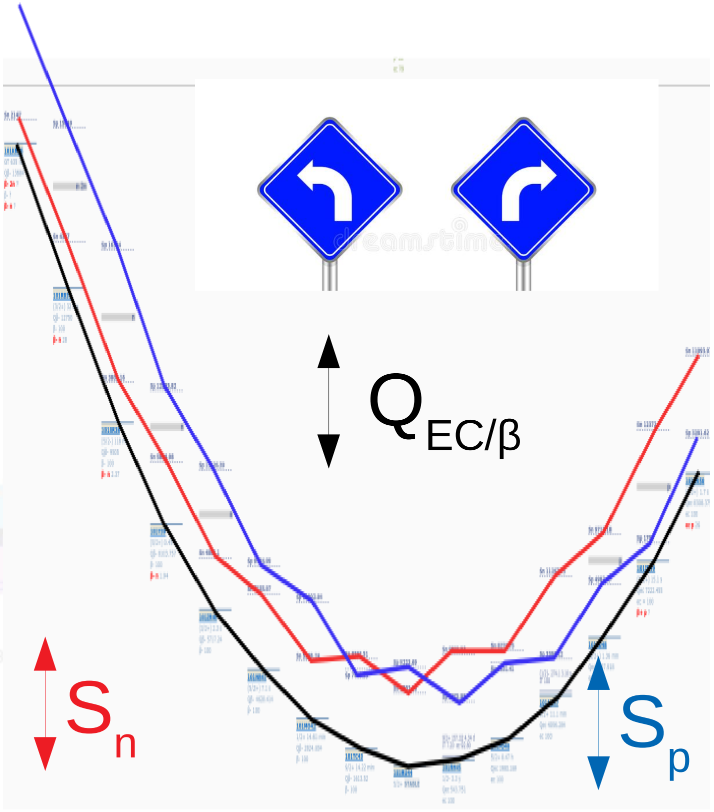
Beta decay, shell structure – βxn and βxp

Beta decay “heats” the nucleus.

Allowed GT
forbidden (mostly FF)
N > Z

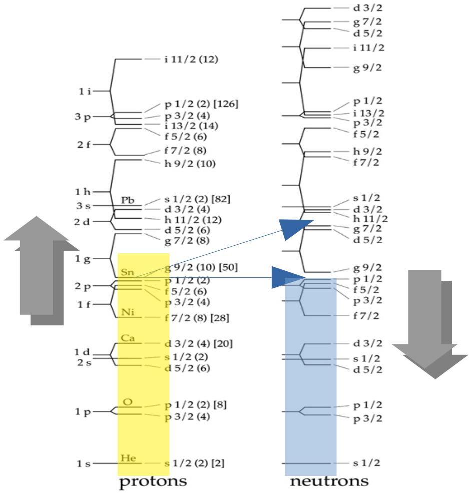
^{132}Sn





Allowed GT, FF and
Fermi decays to IAS
N ≤ Z

^{100}Sn



Particle emission in beta-decays

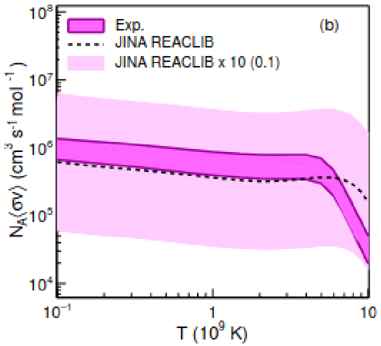
Compound nucleus

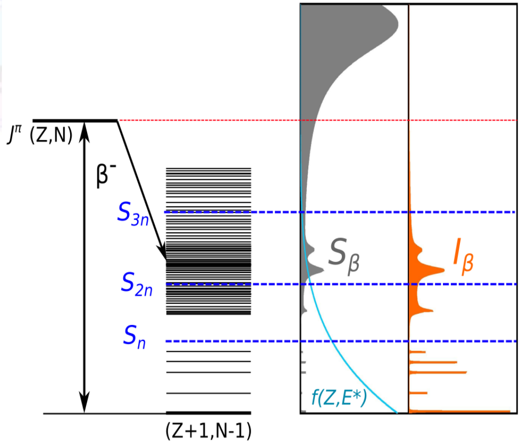
YES

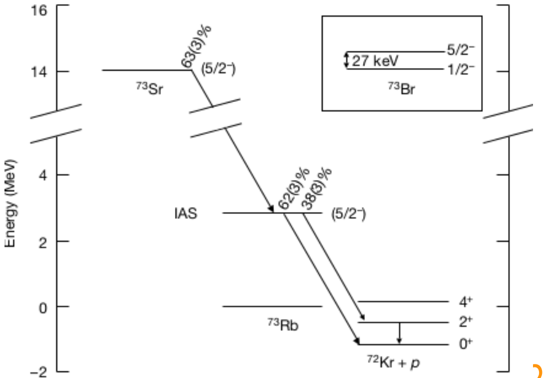
- emission depends only on spin,parity, decay energy (Hauser-Feshbach)
- explore broad range of excitation modes,
- sequential decays only
- constrain spin and parties
- can be used to extract level-densities and gamma-ray strength for astrophysics (beta-Oslo method)

NO

- selective population of excited states
- additional selectivity,
- correlated decays (2n, 2p) ?
- sensitive to details of nuclear structure, (deformation, single particle orbitals...)
- complex astrophysical consequences





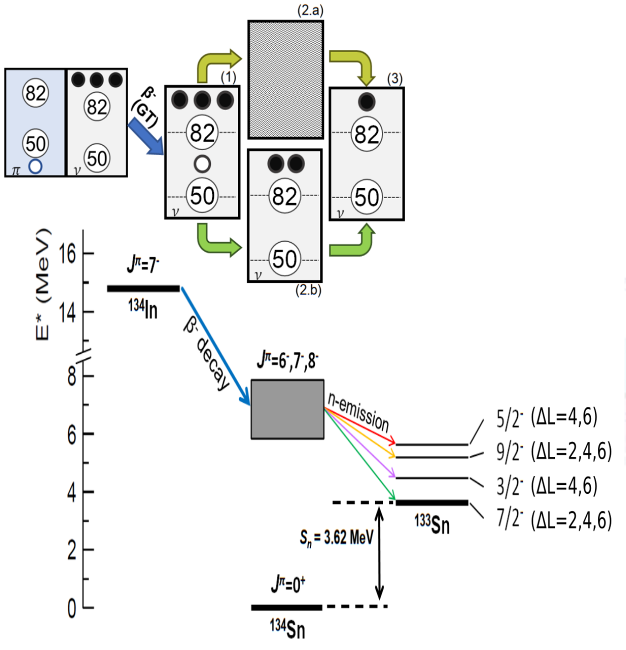


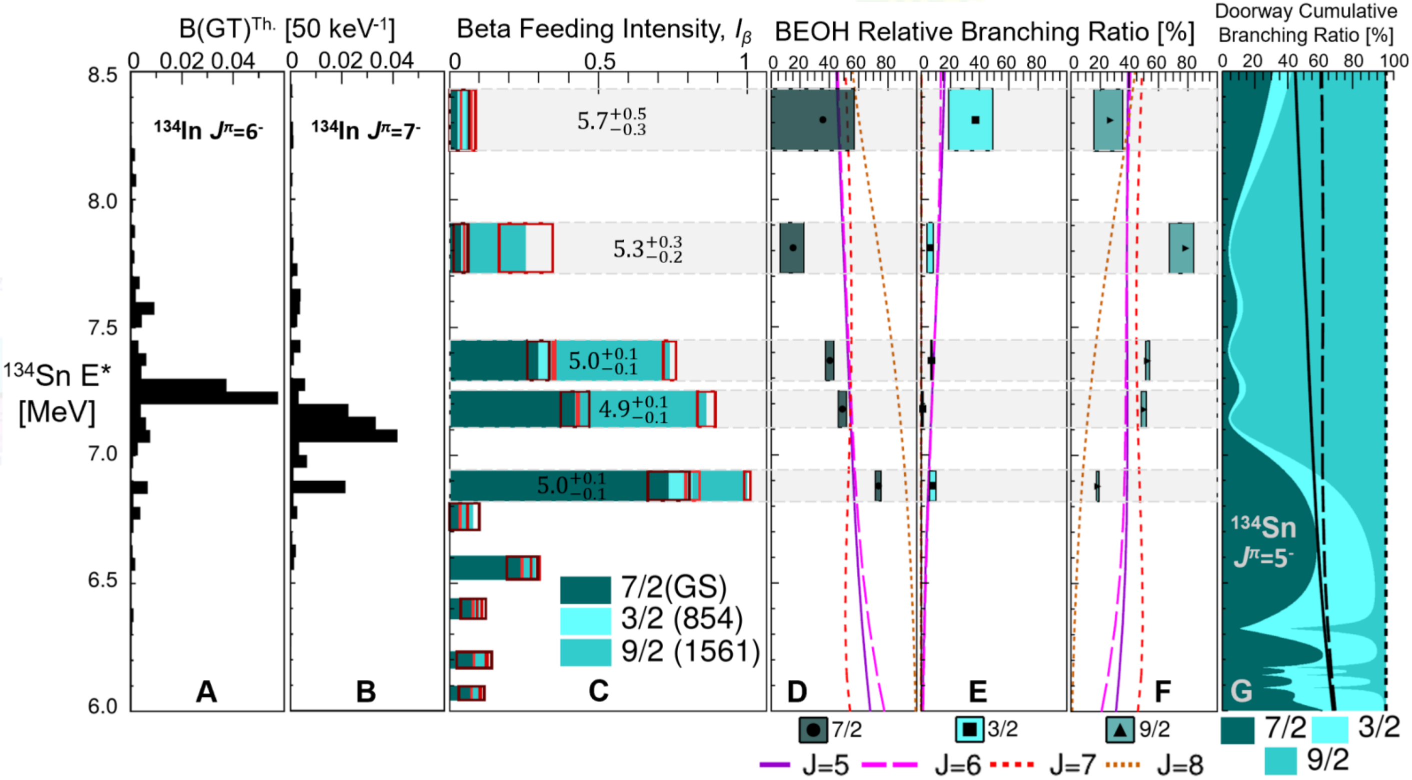
Non-statistical neutron emission from ^{134}In beta-n
Doorway states decay hypothesis for βn

J. Heideman et al.

Neutron emission to excited states in 133Sn not consistent with the Hauser-Feshbach model predictions.

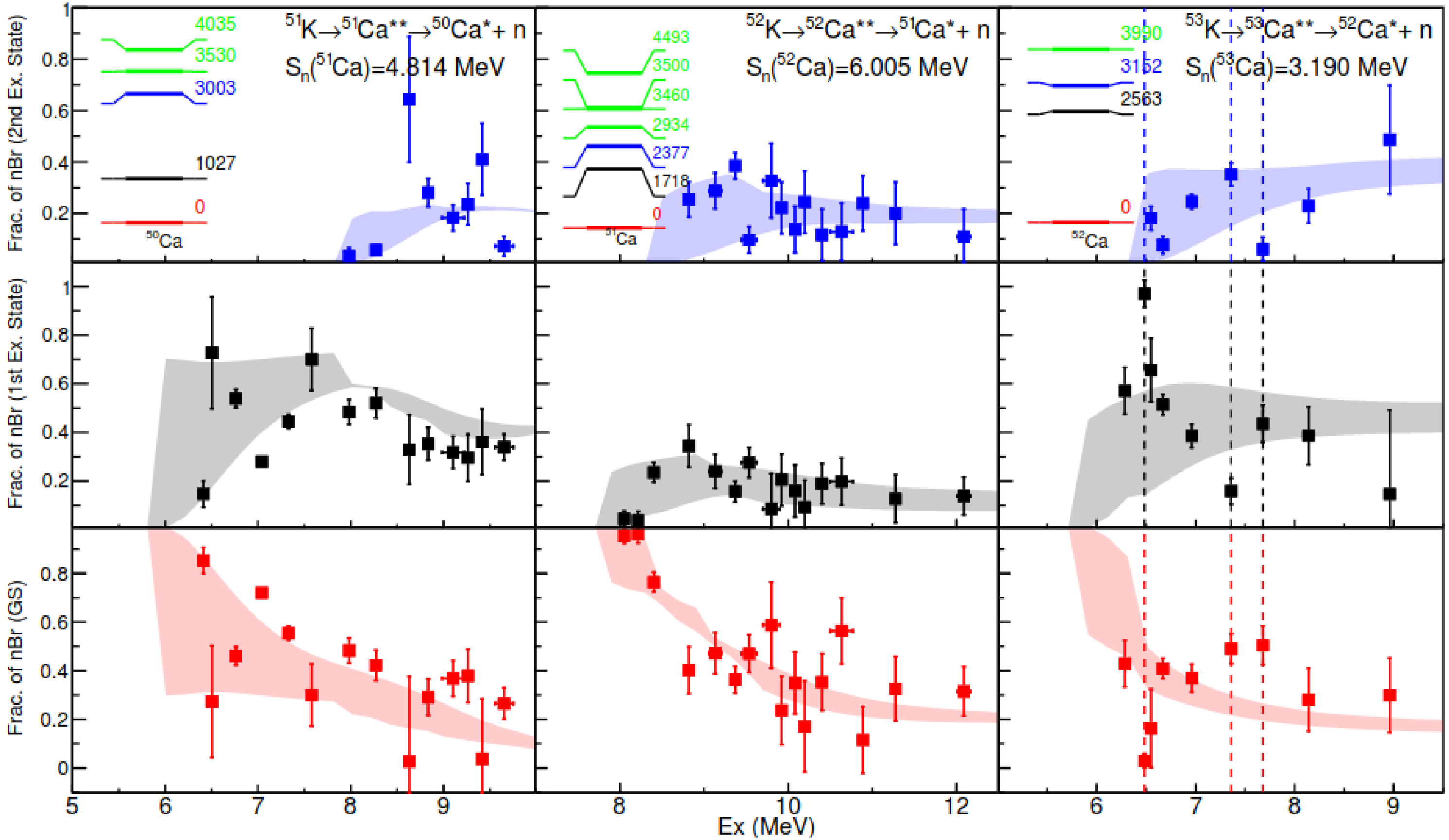
Neutron emission - coupling to $0i_{13/2}$ (L=6) and $1g_{9/2}$ (L=4) configurations

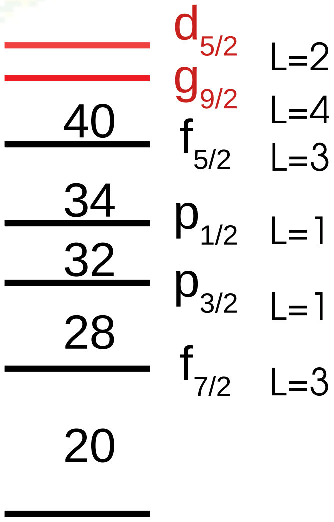




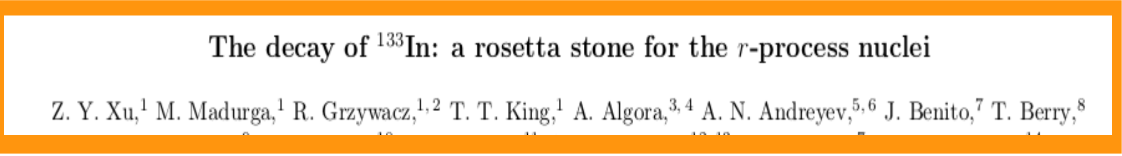
$^{51-53}$K decays – statistical emission

(Z. Xu et al. In preparation)





The decay of ^{133}In at IDS

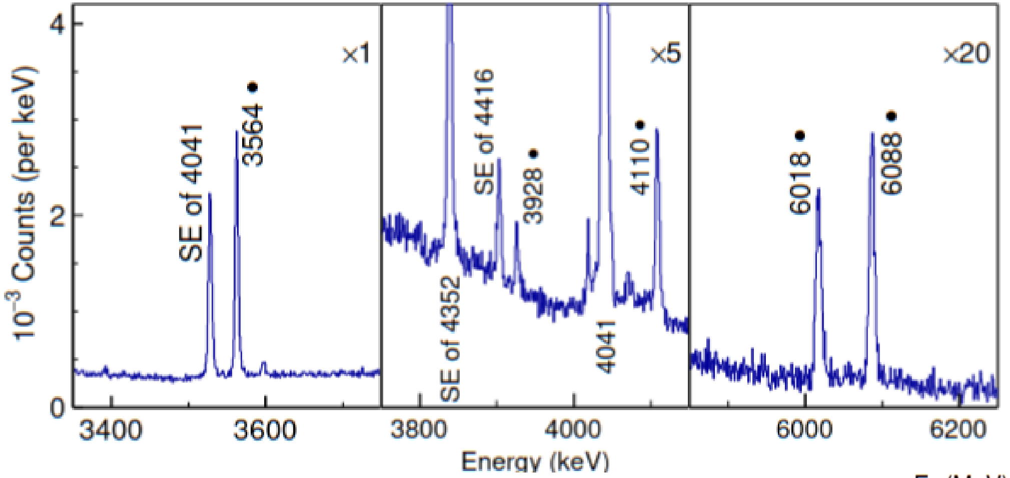


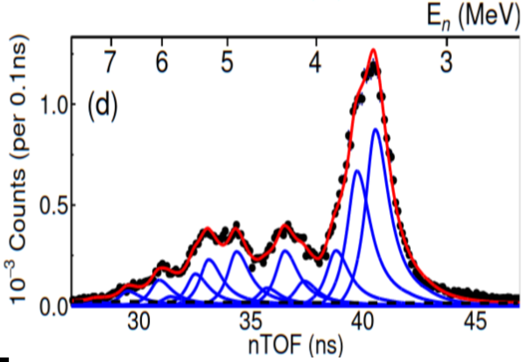
The decay of ^{133}In: a rosetta stone for the r-process nuclei

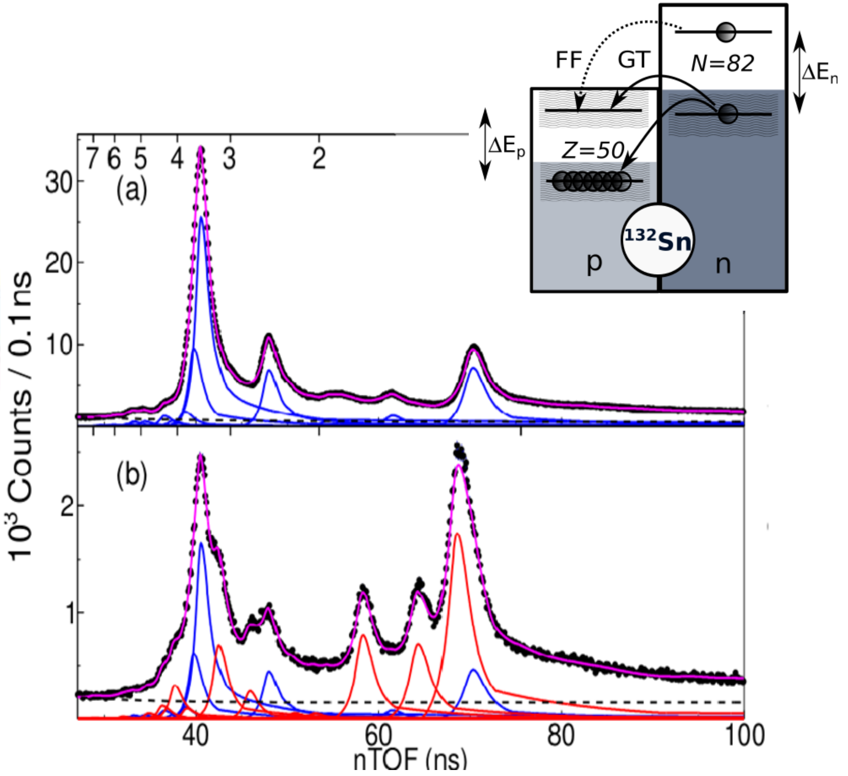
Z. Y. Xu,[1] M. Madurga,[1] R. Grzywacz,[1,2] T. T. King,[1] A. Algora,[3,4] A. N. Andreyev,[5,6] J. Benito,[7] T. Berry,[8]

Evidence for Neutron-gamma competition

Neutron emitting states ~ 1 keV

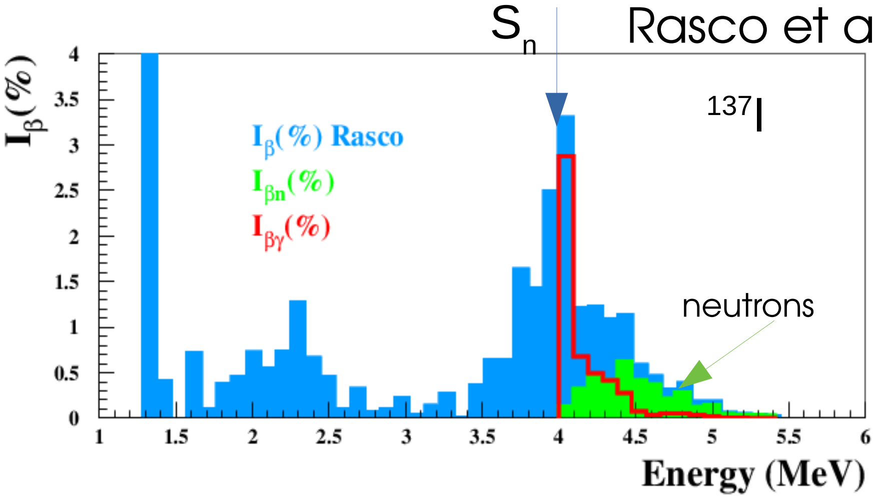


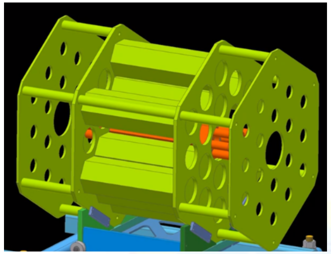




Neutron-gamma competition with total absorption spectroscopy

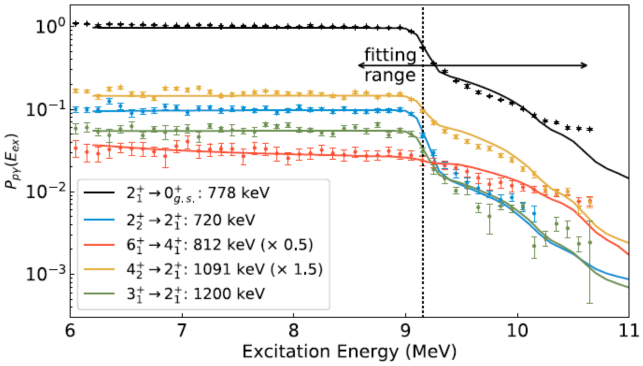
Rasco et al.

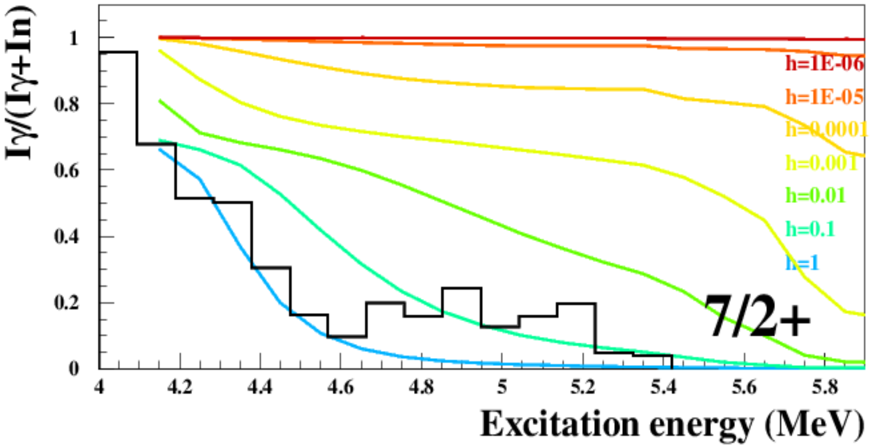


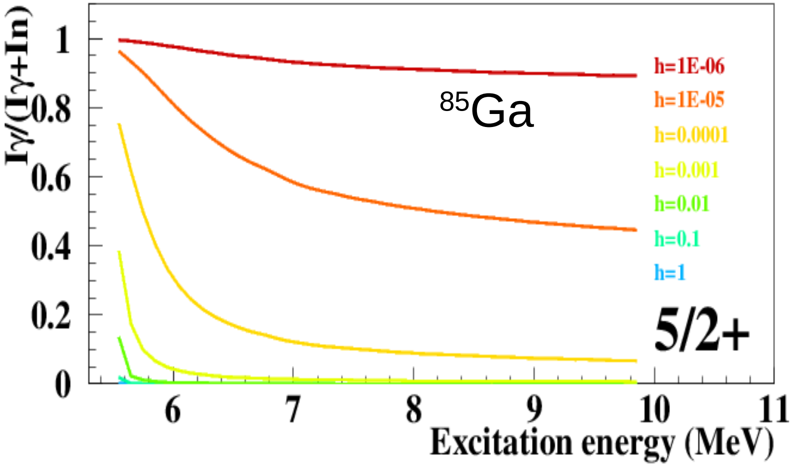


95Mo(d,p)

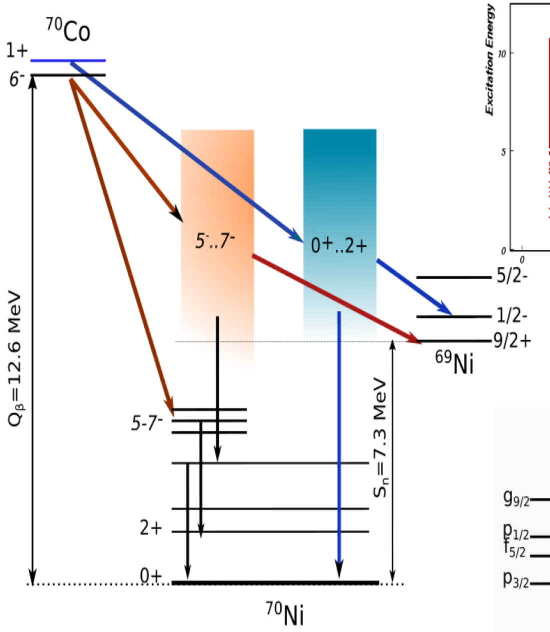
Ratkiewicz et al.

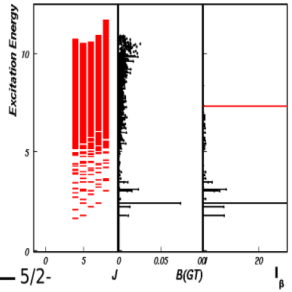


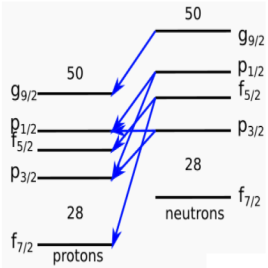


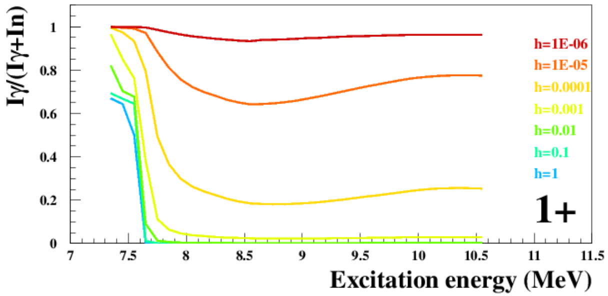


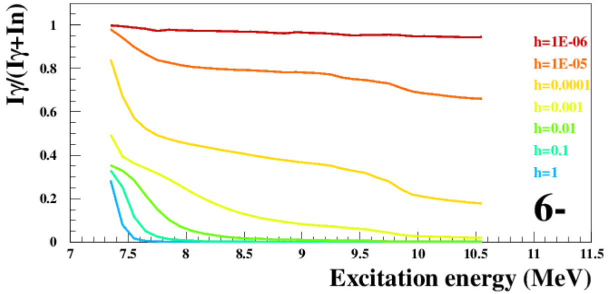
Intersections of nuclear structure and statistical model in βn-decays of cobalt isotopes and isomers (R. G. et al. PAC2 proposal)

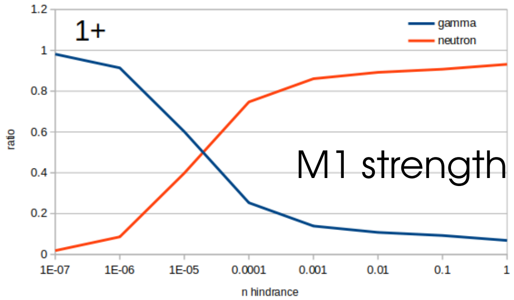


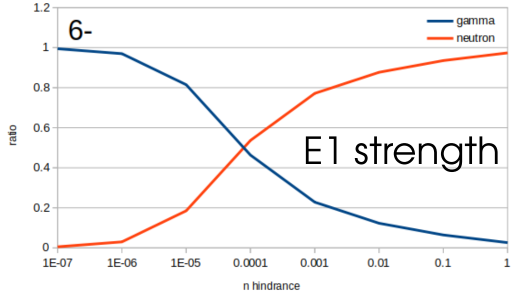












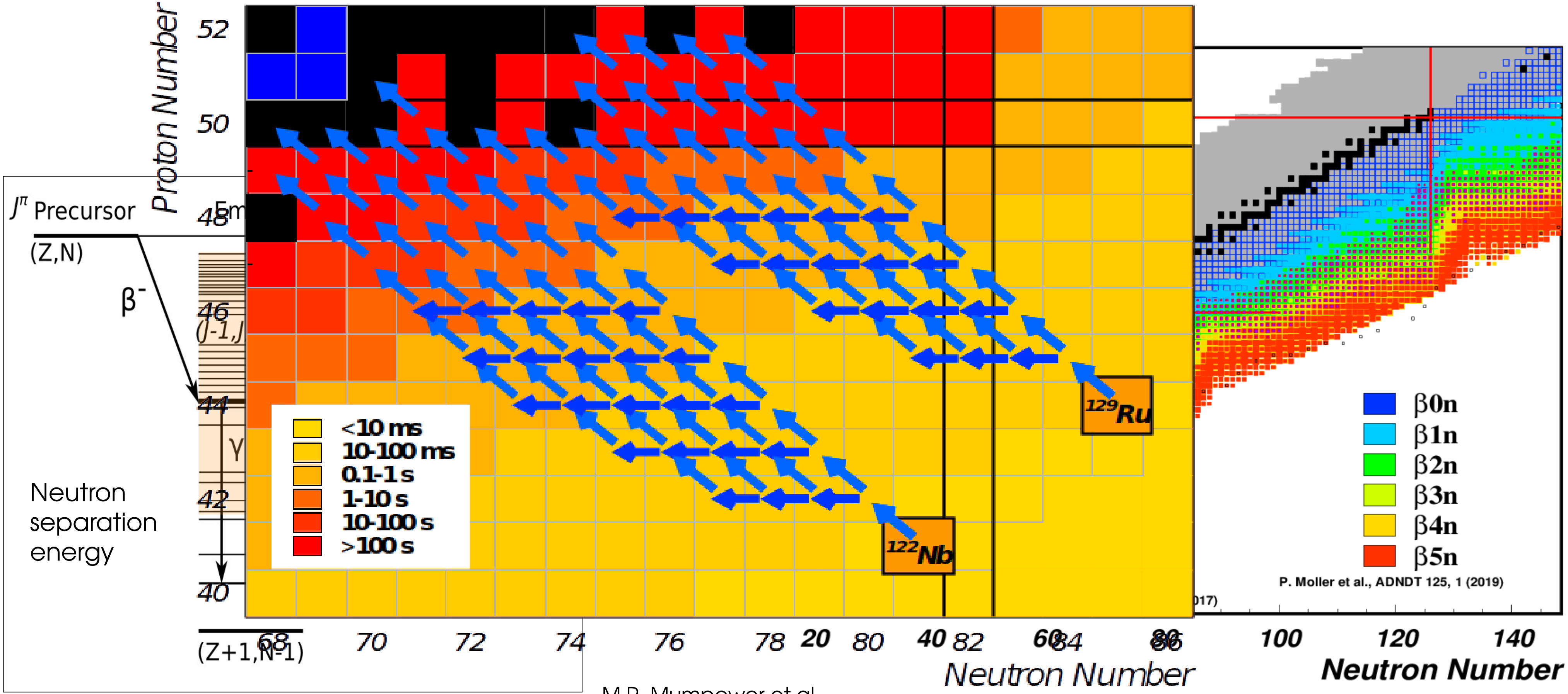
Rates >10^3 pps

	Q_β (MeV)	S_n	Q_β-S_n (MeV)	Optimized for	hours to $2x10^6$	Meas. time (h)	Re-tune time	grow/ decay [s]	cycles /h	Shifts request	Grow/ Decay	Decays Pos. 1 VANDLE	Decays Pos. 2 VANDLE	Decays Pos. 3 MTAS	P_n	emitted neutrons	neutrons in VANDLE	neutrons in MTAS
71Co	**11**	**4.26**	6.74	g.s.	13.6	8*		1.0/1.0	545	1.0	7.6	4.76E+6	4.76E+6	4.76E+6	0.15	7.15E+5	1.00E+5	3.50E+4
70Co	**12.6**	**7.3**	5.3	g.s.	40.6	62.1	2	1.0/1.0	545	5.3	5.1	1.22E+7	1.22E+7	1.22E+7	0.15	1.83E+6	2.56E+5	8.97E+4
70Co				isomer	21.5			1.5/2.5	286	2.7	1.46	4.92E+6	4.92E+6	4.92E+6	0.15	7.38E+5	1.03E+5	3.62E+4
69Co	**9.59**	**4.58**	5.01	g.s.	8.6	14.4	2	1.0/2.0	375	1.3	3	8.00E+6	8.00E+6	8.00E+6	0.10	8.00E+5	1.12E+5	3.92E+4
69Co				isomer	5.8			2.5/4.5	167	0.7	1.85	5.70E+6	5.70E+6	5.70E+6	0.10	5.70E+5	7.98E+4	2.79E+4
68Co	**11.8**	**7.8**	4	g.s.	10.4	13.1	2	1.0/1.0	545	1.6	6.01	1.40E+7	1.40E+7	1.40E+7	0.03	4.21E+5	5.89E+4	2.06E+4
68Co				isomer	2.7			3.0/5.0	146	0.3	1.84	5.68E+6	5.68E+6	5.68E+6	0.03	1.70E+5	2.39E+4	8.35E+3
Total										**13**								

Continuation of: Spyrou et al.
Phys. Rev. Lett. 117, 142701

TA 2023 R. Grzywacz

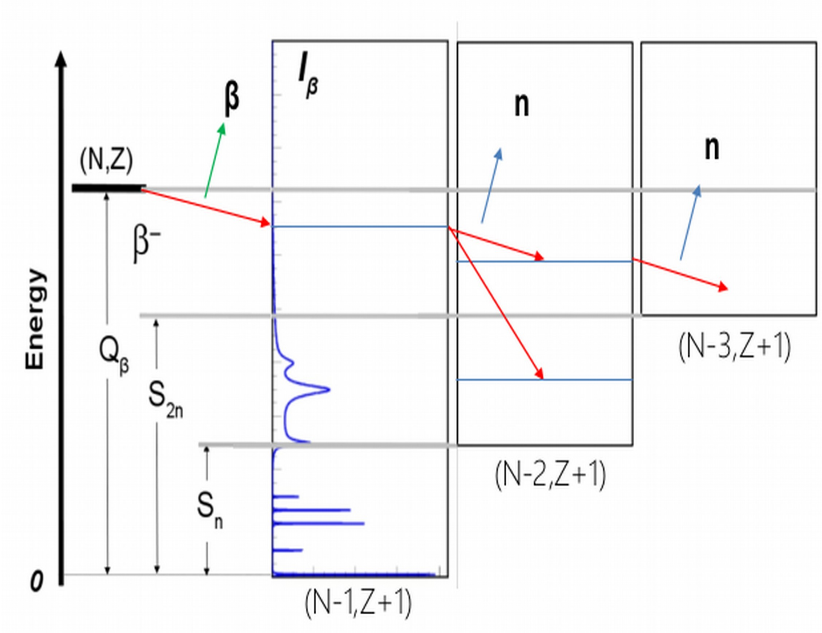
Beta-Delayed multi-neutron emission

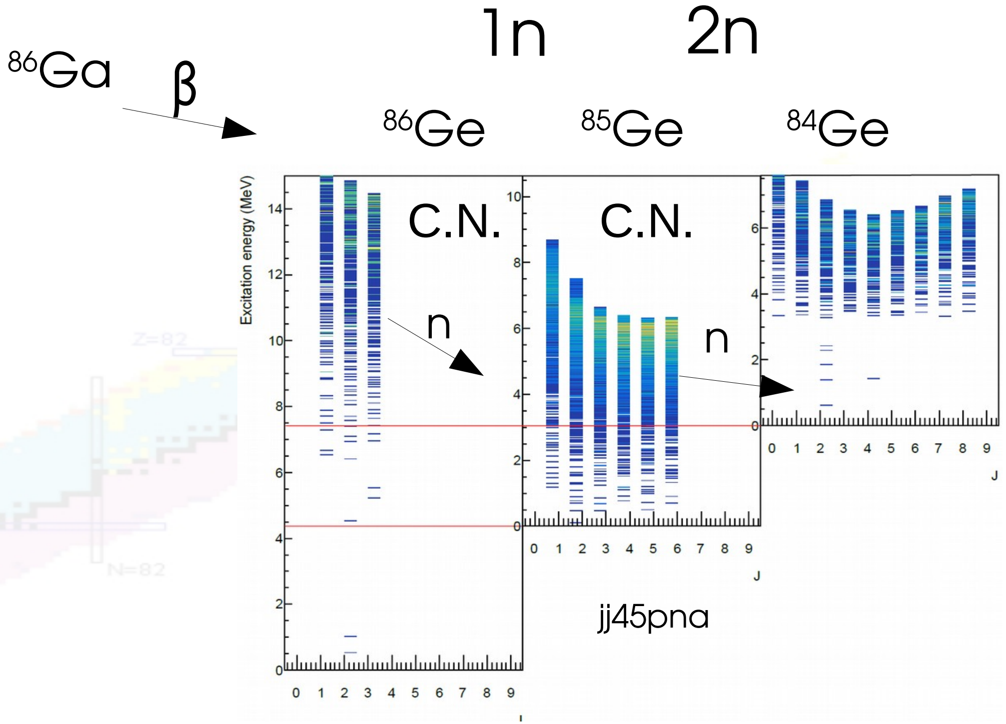


P. Moller et al., ADNDT 125, 1 (2019)

M.R. Mumpower et al.,
Prog. Part. and Nucl. Phys. 86, 86 (2016).

Beta-delayed neutrons and particle emission model





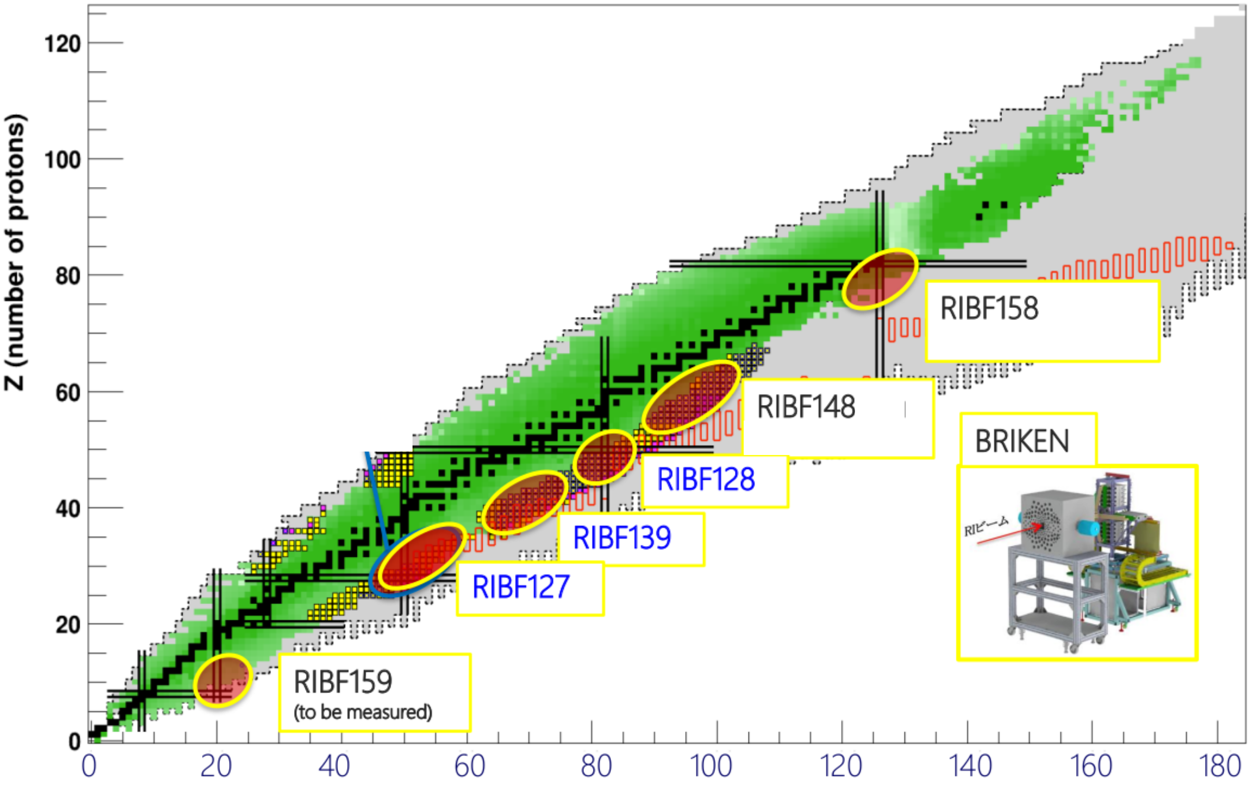
BeoH code

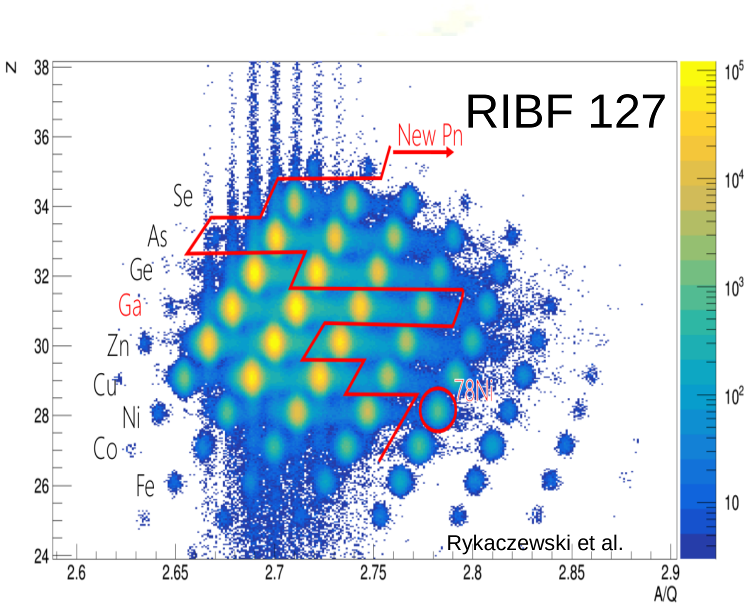
(Hauser Feshbach, Gilbert Cameron formula for the level densities)
S. Okumura, ***T. Kawano,*** Journal of Nuclear Science and Technology 55, 1009 (2018).

T. Kawano, P. Talou, I. Stetcu, and M. B. Chadwick, Nuclear Physics A 913, 51 (2013).
M. R. Mumpower, T. Kawano, and P. Möller, Physical Review C 94, 064317 (2016).

Statistical model combined with shell-model predictions.

P_{2n}/P_{1n} measurements with BRIKEN array

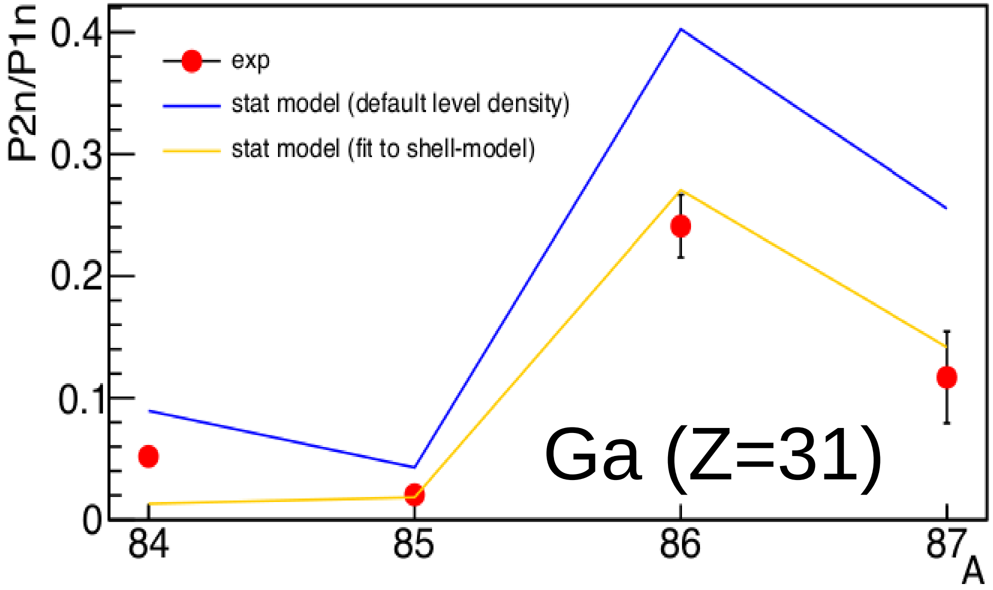


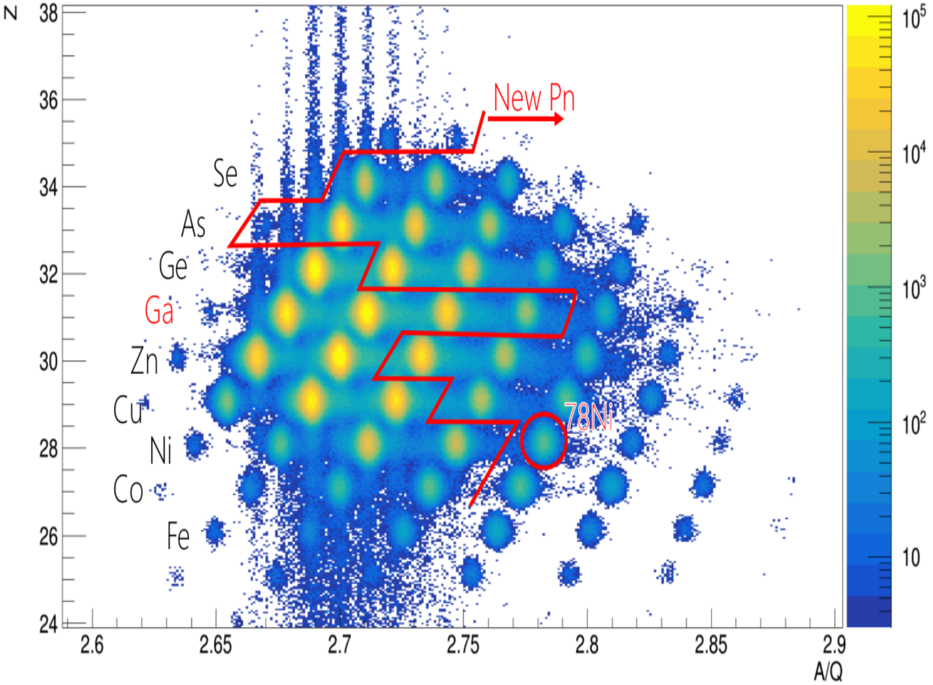


Rykaczewski et al.

Beta-Delayed multi-Neutron emission

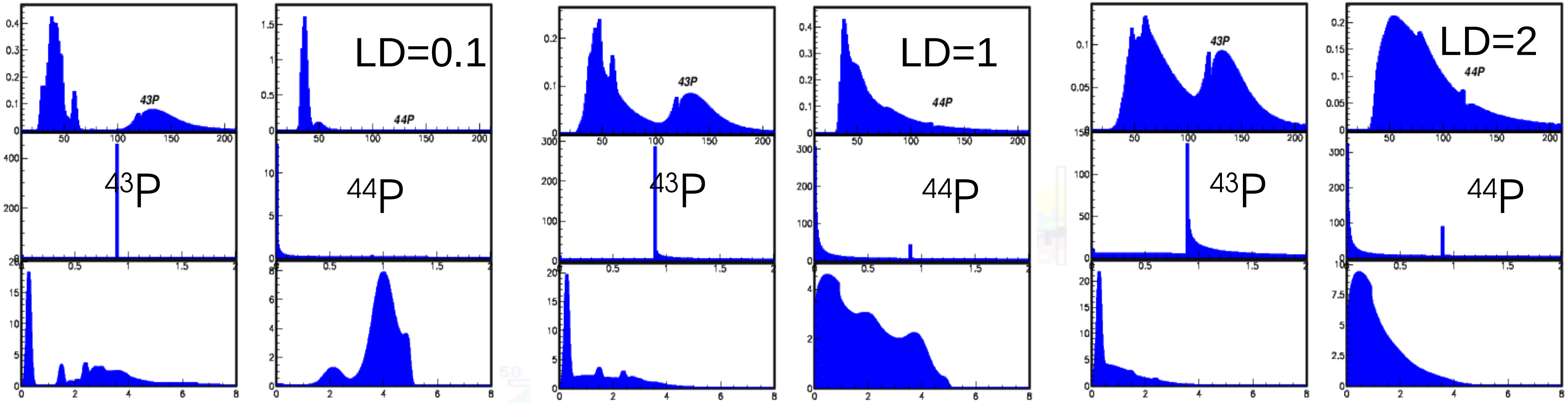
Larger level density in β1n daughter (A-1) enhances 2n emission process.

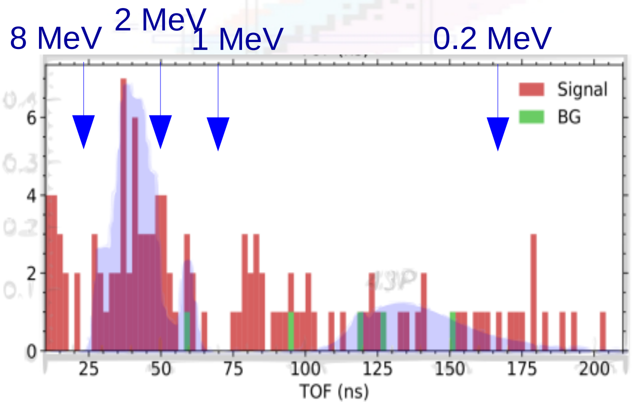


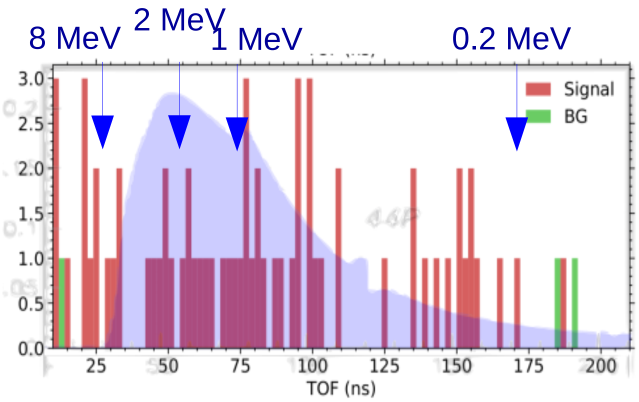


First βn and β2n spectroscopy of ^{43}P and ^{44}P

Predicted neutron spectra sensitive to level densities.







Single step particle radioactivity

- Alpha decay

Precise Q_α and $T_{1/2}$ measurement,

Discovery ***tool*** for heavy and SHE nuclei

Alpha preformation

Superallowed alpha decay near ^{100}Sn.

Microscopic mechanism of alpha decay

Revisit the Gamow-Model ?

- Proton emission

“Spectroscopic factors” - nuclear structure at the drip-line.

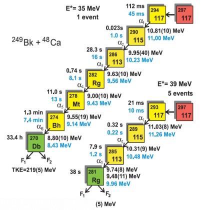
3D barrier tunneling for deformed proton emitters.

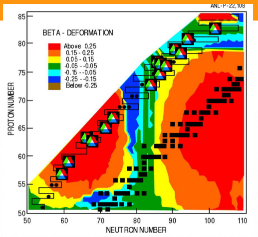
- Two-proton emission:

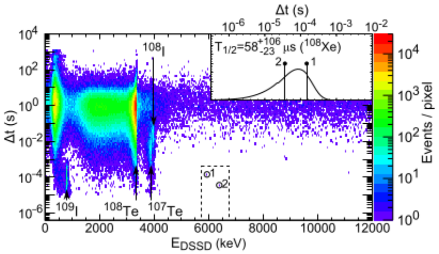
“***nucleon-nucleon correlations***“ and links to nuclear structure

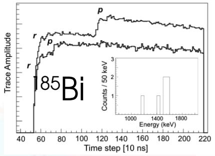
- Discovery of 3p emission (^{31}K $T_{1/2}$<10 ps) PRL 123, 092502 (2019)

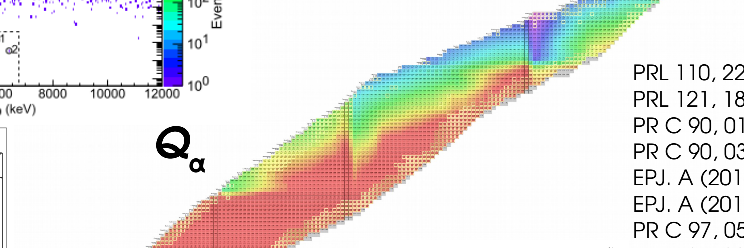
Can we observe ***neutron or two-neutron*** radioactivity?



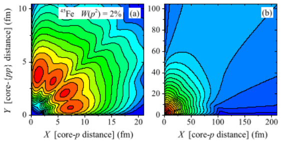


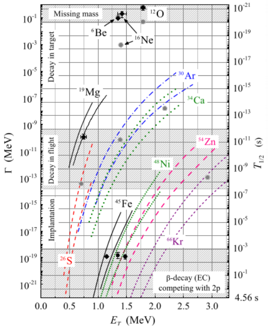


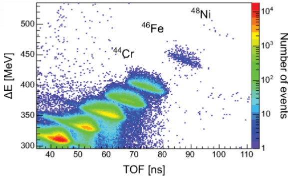


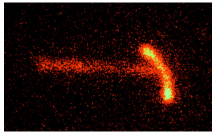


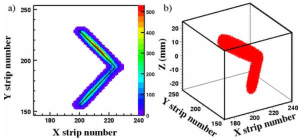
PRL 110, 222501 (2013).
PRL 121, 182501 (2018)
PR C 90, 014311 (2014)
PR C 90, 034317 (2014)
EPJ. A (2016) 52: 89
EPJ. A (2015) 51
PR C 97, 051301(R) (2018)
PRL 127, 202501 (2021)
PRL 128, 112501 (2022)
Rev.Mod.Phys., 84, (2012)







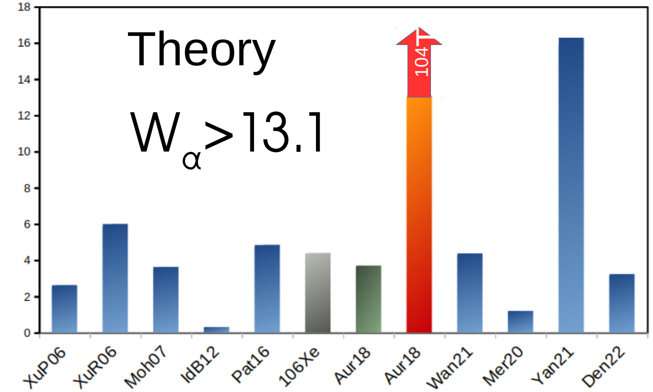




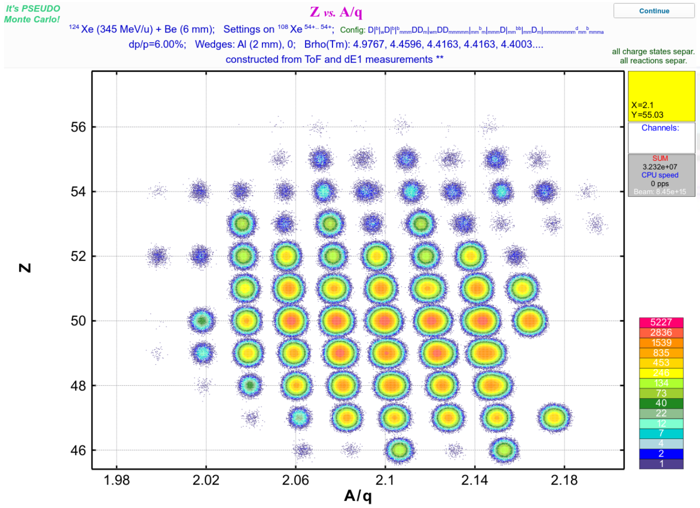
^{45}Fe, ^{48}Ni, ^{54}Zn, ^{67}Kr

Study of "superallowed" decay of lightest alpha emitters near doubly-magic ^{100}Sn

(RIKEN)NP 1812 – RIBF168R1



K. Auranen et al. Phys. Rev. Lett. 121, 182501 (2018).


It's PSEUDO Monte Carlo!

Z vs. A/q

^{124}Xe (345 MeV/u) + Be (6 mm); Settings on ^{108}Xe $^{54+..54+}$; Config: D|b|wD|b|b mmmDDm|wmDDmmmmm|mm b m|mmmD|mm bb|mmDm|mmmmmmmmm d mm b mmma

dp/p=6.00%; Wedges: Al (2 mm), 0; Brho(Tm): 4.9767, 4.4596, 4.4163, 4.4163, 4.4003....

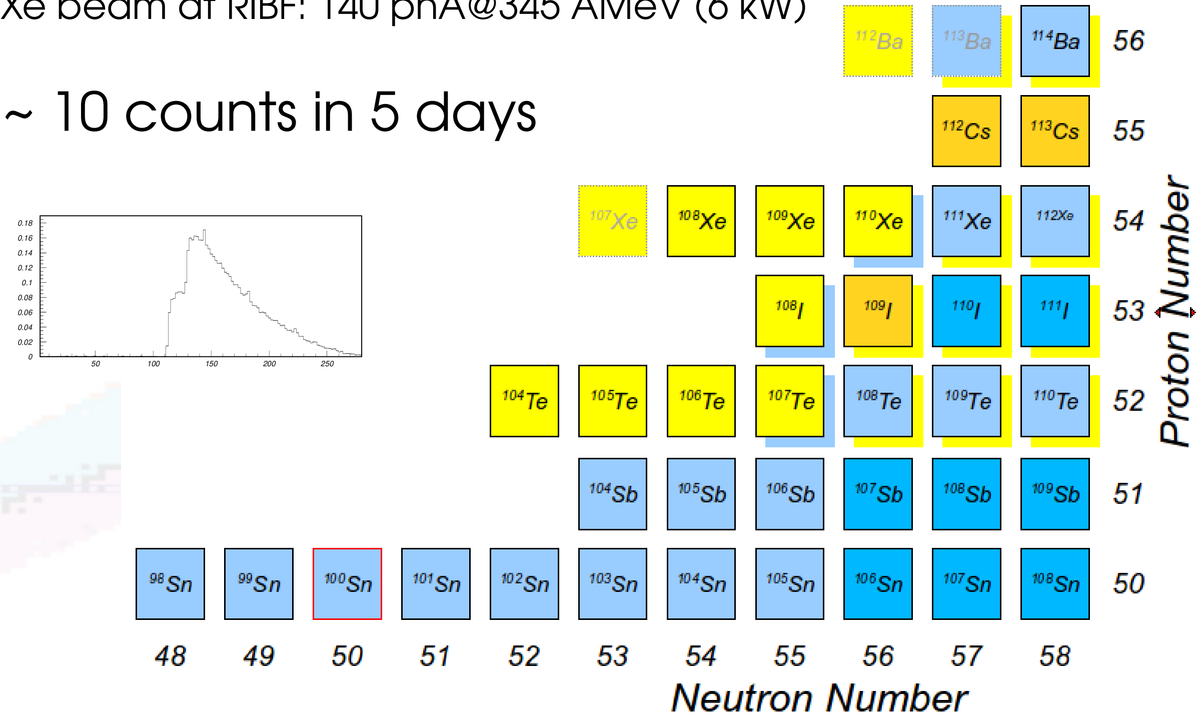
constructed from ToF and dE1 measurements **

all charge states separ.
all reactions separ.

X=2.1
Y=55.03

^{124}Xe beam at RIBF: 140 pnA@345 AMeV (6 kW)

~ 10 counts in 5 days



107Xe→103Te
2p or α
102Te ???

E. Olsen et al.
PRL 110, 222501 (2013)

The quartetting model and alpha particle pre-formation

Quartetting wave function approach (QWFA)

α-cluster can only be formed on the surface of the "core"
Inside the nucleus the α cluster dissolves and four nucleons are uncorrelated.

- Four nucleons moving in a self-consistently determined mean field, the shell model wave function determine the nuclear surface density and probability to form α-clusters.
- QWFA predicts $T_{1/2}$ for ^{212}Po and ^{104}Te cosistent with experimental results.
- The (p,p′a) experiment determined the probability of cluster formation for stable neutron rich Sn isotopes.

PHYSICAL REVIEW C **104**, 034302 (2021)

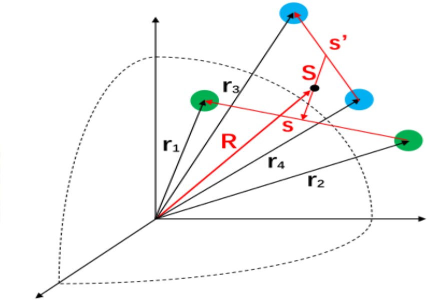
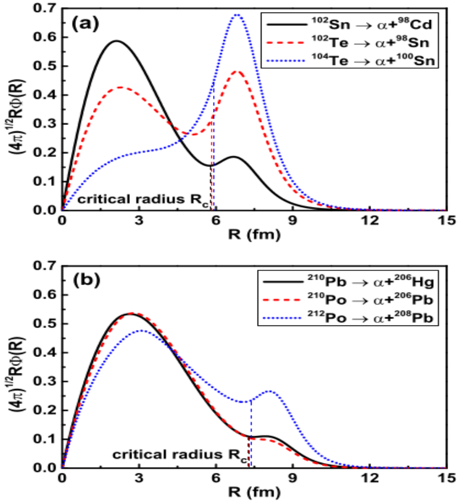
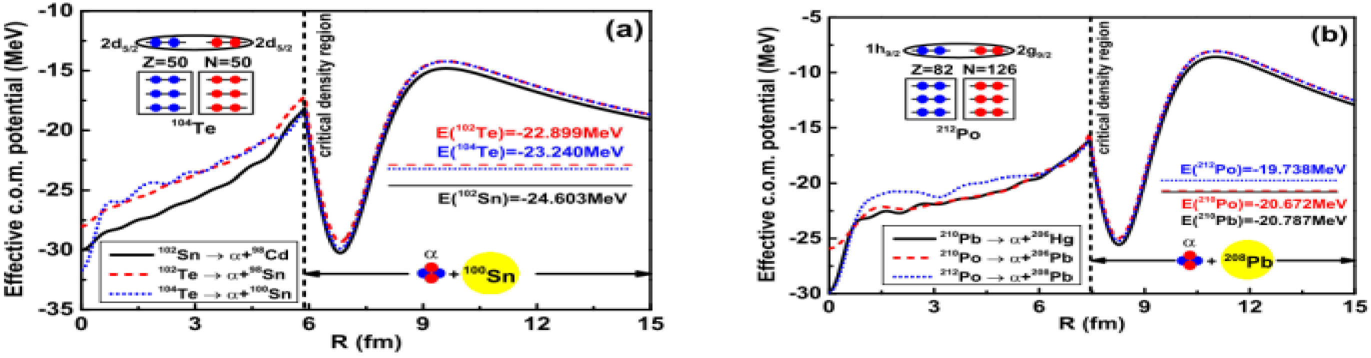


FIG. 1. A sketch of Jacobi-Moshinsky coordinates for the quartet with two protons at positions $\mathbf{r}_1 \uparrow, \mathbf{r}_2 \downarrow$ and two neutrons at positions $\mathbf{r}_3 \uparrow, \mathbf{r}_4 \downarrow$.

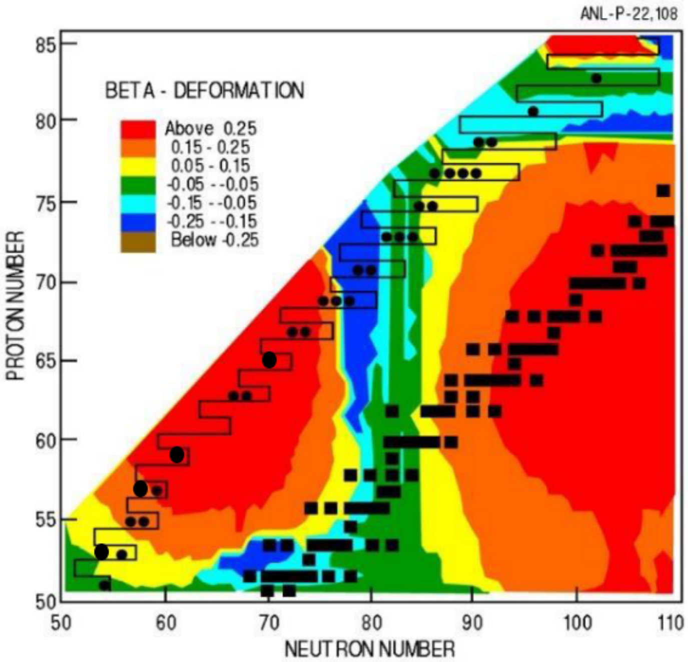
Tanaka et al., Science 371, 260–264 (2021)

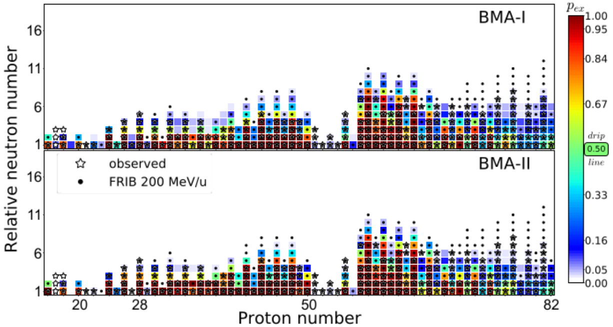


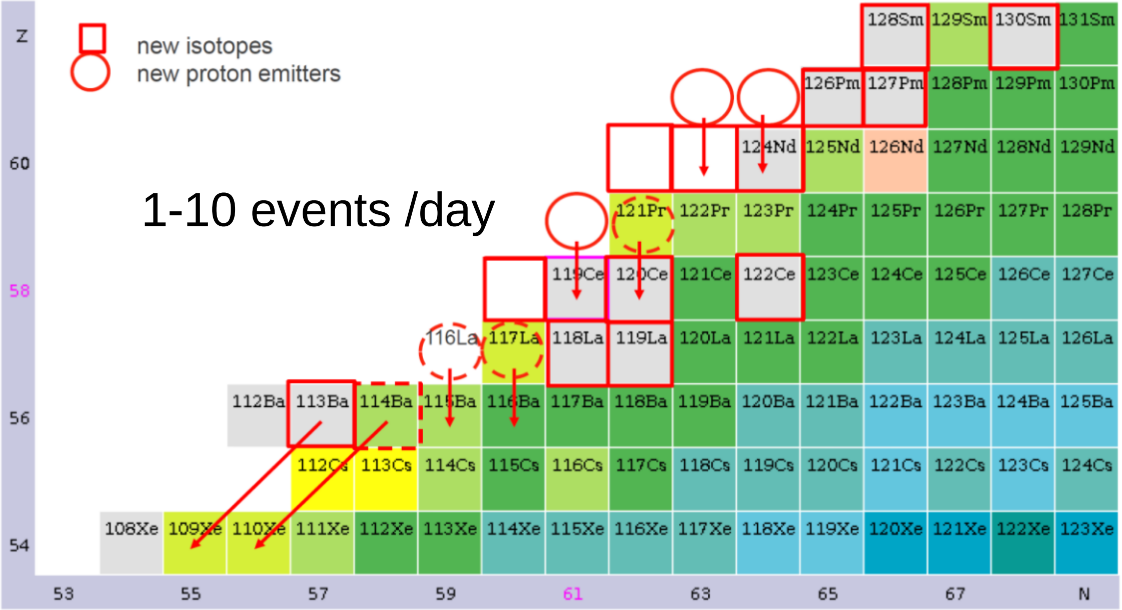


Shuo Yang et al., PHYSICAL REVIEW C 101, 024316 (2020)

"The Study of Proton-Rich Isotopes Along the Proton Drip-Line above ^{100}Sn" - D. Seweryniak (ANL) et al.







1-10 events /day

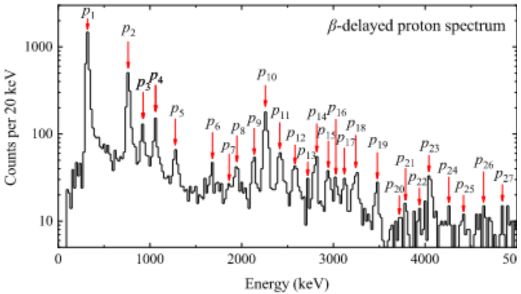
Z	53		55		57		59		61		63		65		67		N
														128Sm	129Sm	130Sm	131Sm
													126Pm	127Pm	128Pm	129Pm	130Pm
60												124Nd	125Nd	126Nd	127Nd	128Nd	129Nd
										121Pr	122Pr	123Pr	124Pr	125Pr	126Pr	127Pr	128Pr
58									119Ce	120Ce	121Ce	122Ce	123Ce	124Ce	125Ce	126Ce	127Ce
							116La	117La	118La	119La	120La	121La	122La	123La	124La	125La	126La
56				112Ba	113Ba	114Ba	115Ba	116Ba	117Ba	118Ba	119Ba	120Ba	121Ba	122Ba	123Ba	124Ba	125Ba
					112Cs	113Cs	114Cs	115Cs	116Cs	117Cs	118Cs	119Cs	120Cs	121Cs	122Cs	123Cs	124Cs
54		108Xe	109Xe	110Xe	111Xe	112Xe	113Xe	114Xe	115Xe	116Xe	117Xe	118Xe	119Xe	120Xe	121Xe	122Xe	123Xe

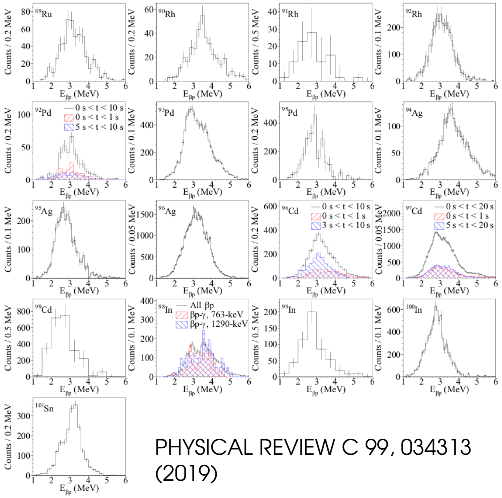
Multi-step processes - beta delayed protons

Charged particle spectroscopy
a sensitive tool for nuclear structure
Gas detectors (TPC) enable suppression
of the βp summing.

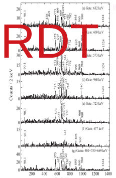
Resurgence of efforts with light nuclei
Isospin mixing, mirror symmetry
astrophysically relevant resonances
p-capture rates in novae
Proxy for reactions measurement !

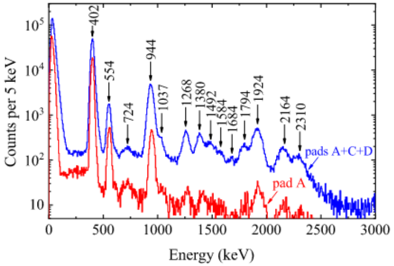
Hevy nuclei - “Pandemonium”

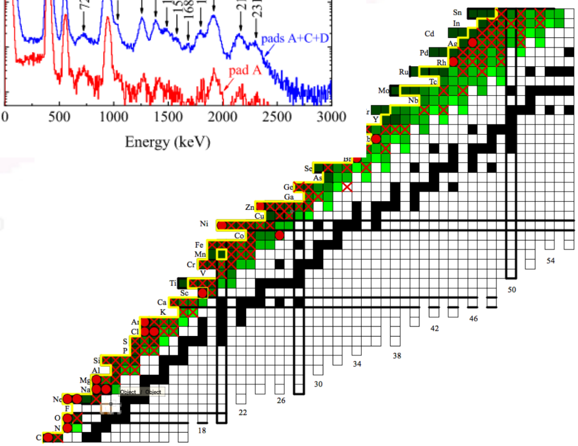




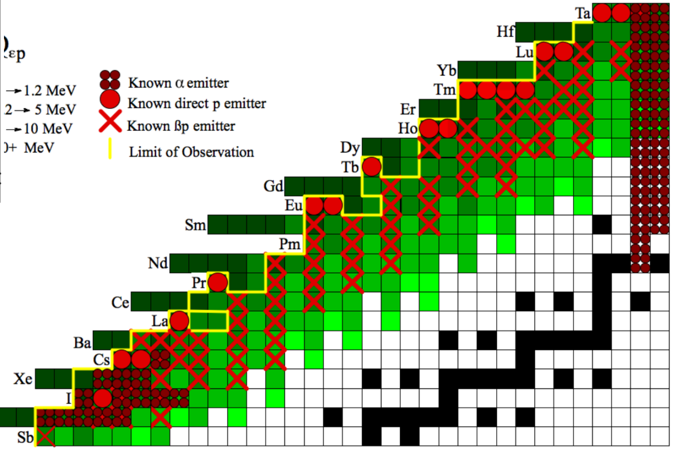
PHYSICAL REVIEW C 99, 034313 (2019)



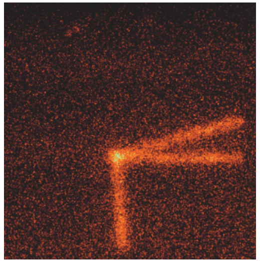


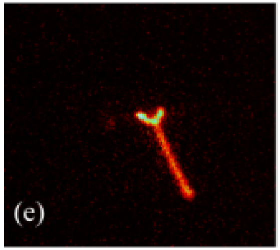


εp
→1.2 MeV
2→5 MeV
→10 MeV
)+ MeV



- Known α emitter
- Known direct p emitter
- Known βp emitter
- Limit of Observation





PR C 91, 064309 (2015)
PR C 93, 044336 (2016)
PR C 95, 034315 (2017)
PR C 93, 064320 (2016)
PR C 95, 024301 (2017)
PR C 99, 064312 (2019)
PR C 99, 065801 (2019)
PR C 102, 045810 (2020)

https://nucleardata.berkeley.edu/projects/beta_p.html
Atomic Data and Nuclear Data Tables 132 (2020) 101323

Summary

- Decay studies demonstrated to be an effective discovery tool.
- Beta decay strength distribution near doubly-magic nuclei.
- The expanded role of multi-step decay processes (βxn, βxp,βα,βf). Statistical or doorway decays ?
- βxn - branching ratios, widths, angular distributions, nn-correlations.
- Two-proton – pairing correlations – high-statistics experiments possible !
- What is the physics of alpha particle preformation ?
- Beta-gamma and isomer spectroscopy will dominate the high-Z region.

Access to exotic nuclei expands the discovery potential of decay studies.

FRIB provides opportunity to address open problems with precision experiments !