Beta-delayed neutron emission - a new beginning

THE UNIVERSITY OF TENNESSEE KNOXVILLE

Robert Grzywacz

University of Tennessee/ORNL

OAK RIDGE National Laboratory

Physics needs:

r-process, nuclear structure, reactor anti-neutrino, reactor physics (decay heat)

Access:

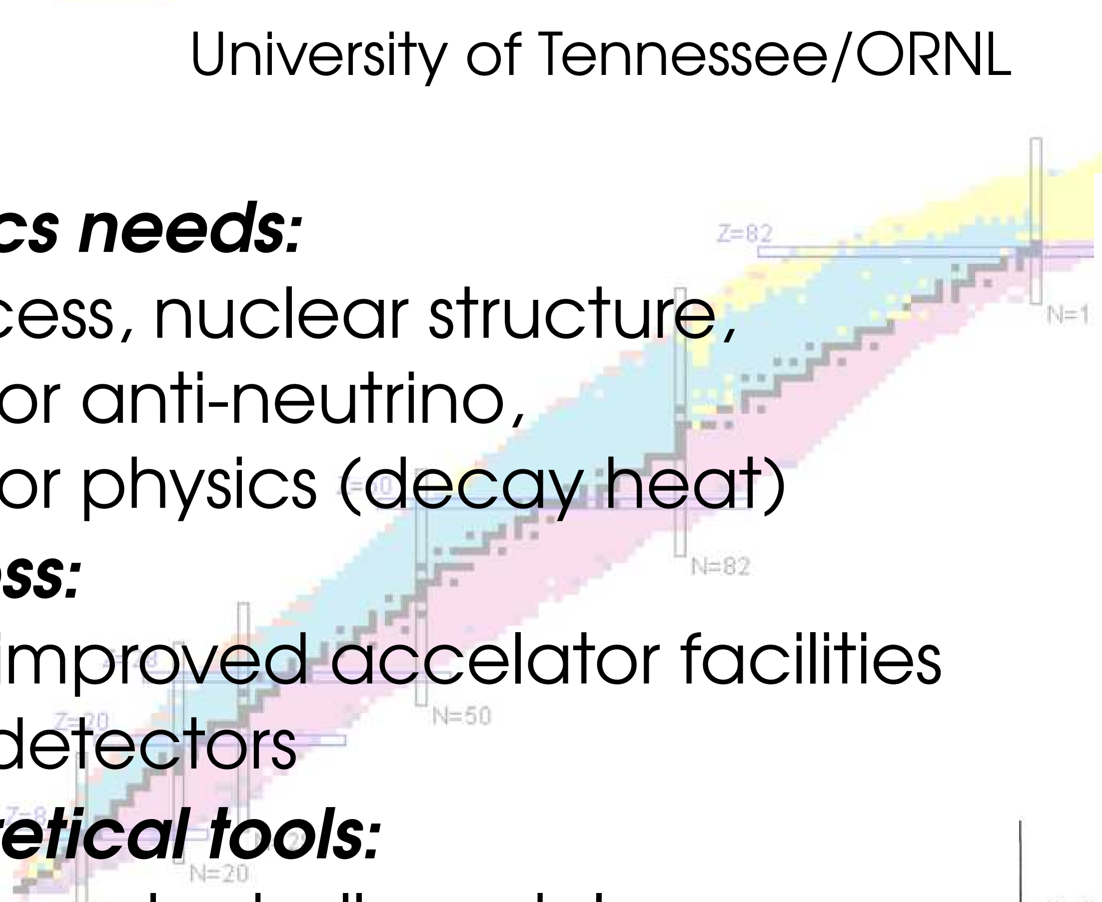
new/improved accelator facilities

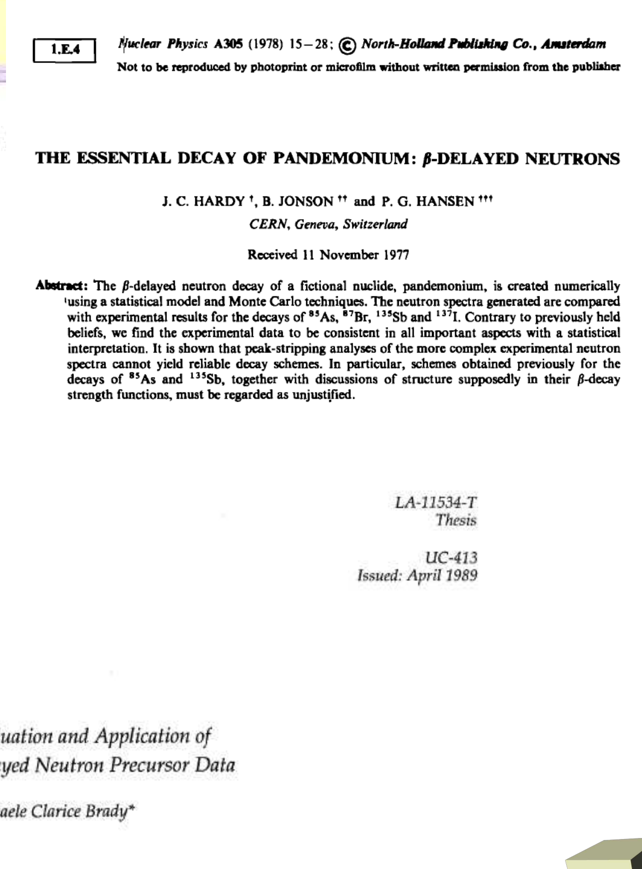
new detectors

Theoretical tools:

Large scale shell-model,

QRPA





1.E.4 Nuclear Physics A305 (1978) 15–28; © North-Holland Publishing Co., Amsterdam

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THE ESSENTIAL DECAY OF PANDEMONIUM: β-DELAYED NEUTRONS

J. C. HARDY †, B. JONSON †† and P. G. HANSEN †††

CERN, Geneva, Switzerland

Received 11 November 1977

Abstract: The β-delayed neutron decay of a fictional nuclide, pandemonium, is created numerically using a statistical model and Monte Carlo techniques. The neutron spectra generated are compared with experimental results for the decays of ^{85}As, ^{87}Br, ^{135}Sb and ^{137}I. Contrary to previously held beliefs, we find the experimental data to be consistent in all important aspects with a statistical interpretation. It is shown that peak-stripping analyses of the more complex experimental neutron spectra cannot yield reliable decay schemes. In particular, schemes obtained previously for the decays of ^{85}As and ^{135}Sb, together with discussions of structure supposedly in their β-decay strength functions, must be regarded as unjustified.

LA-11534-T
Thesis

UC-413
Issued: April 1989

Evaluation and Application of Delayed Neutron Precursor Data

Michaele Clarice Brady*

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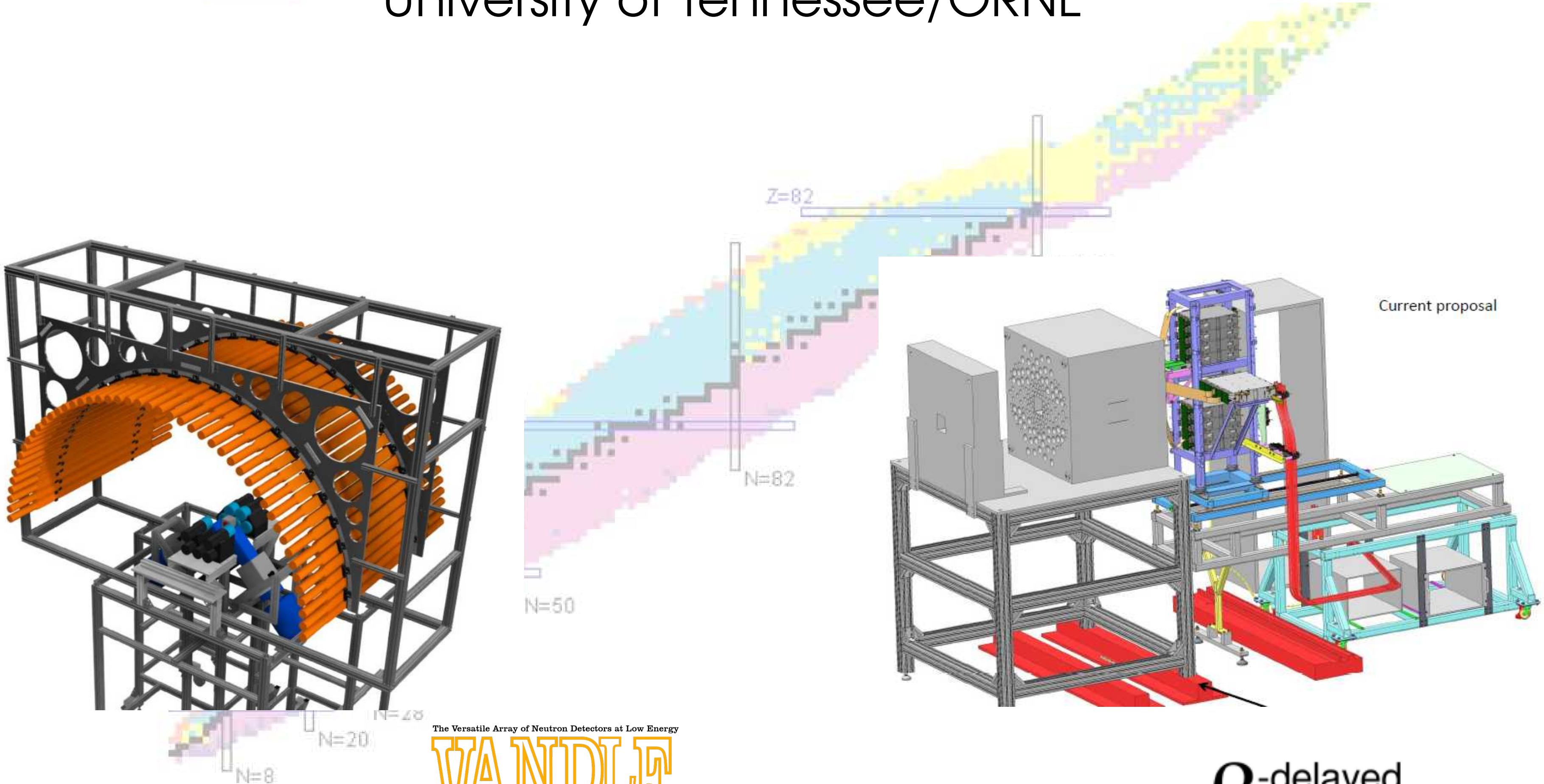
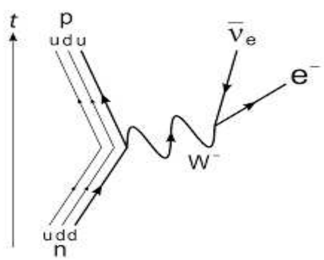
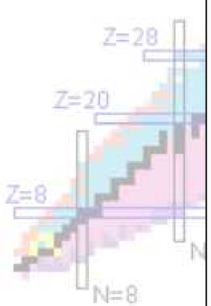


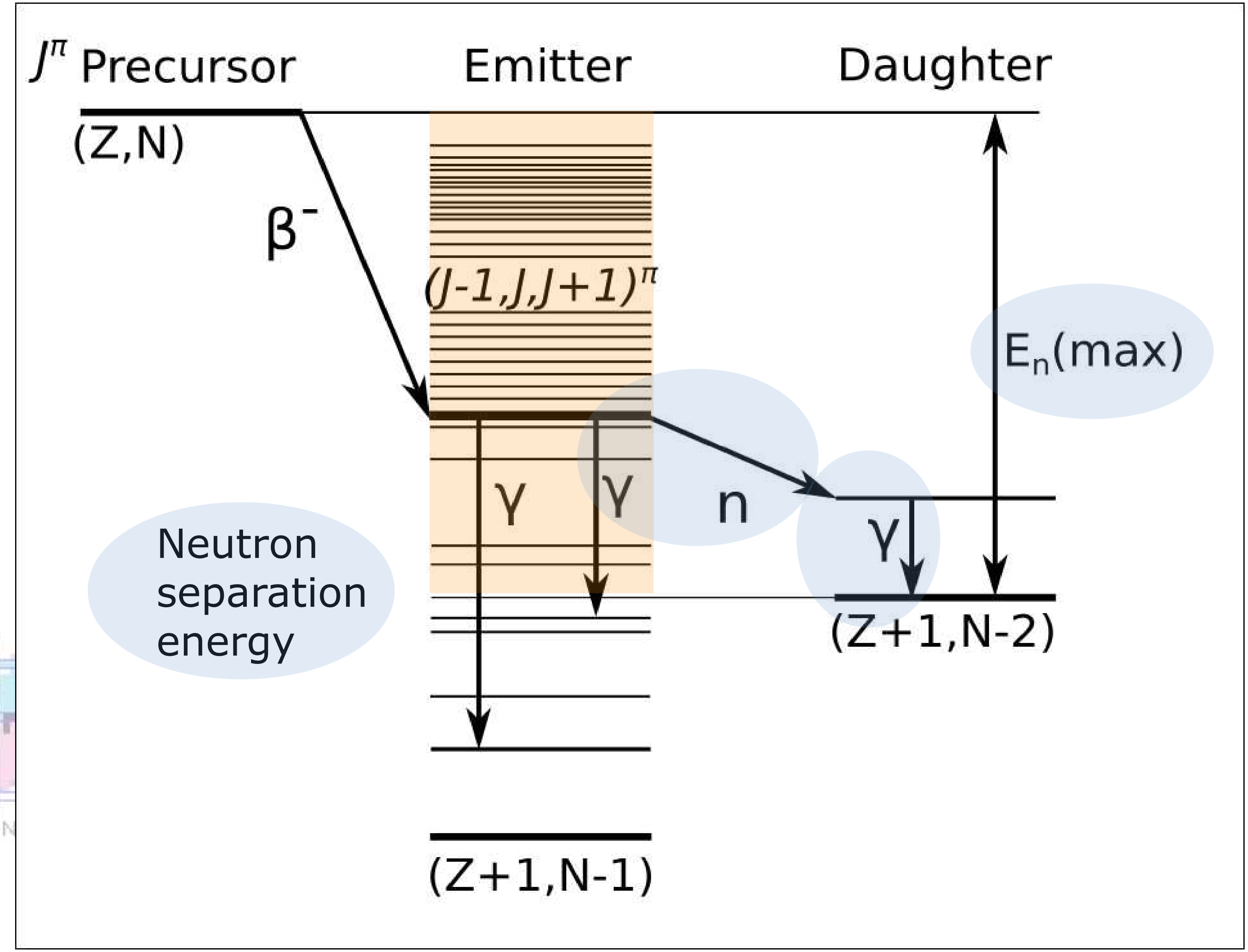
The Versatile Array of Neutron Detectors at Low Energy
VANDLE

β-delayed neutrons at RIKEN

Beta-delayed neutron emission relevant observables







Beta-delayed neutron detection

The Versatile Array of Neutron Detectors at Low Energy

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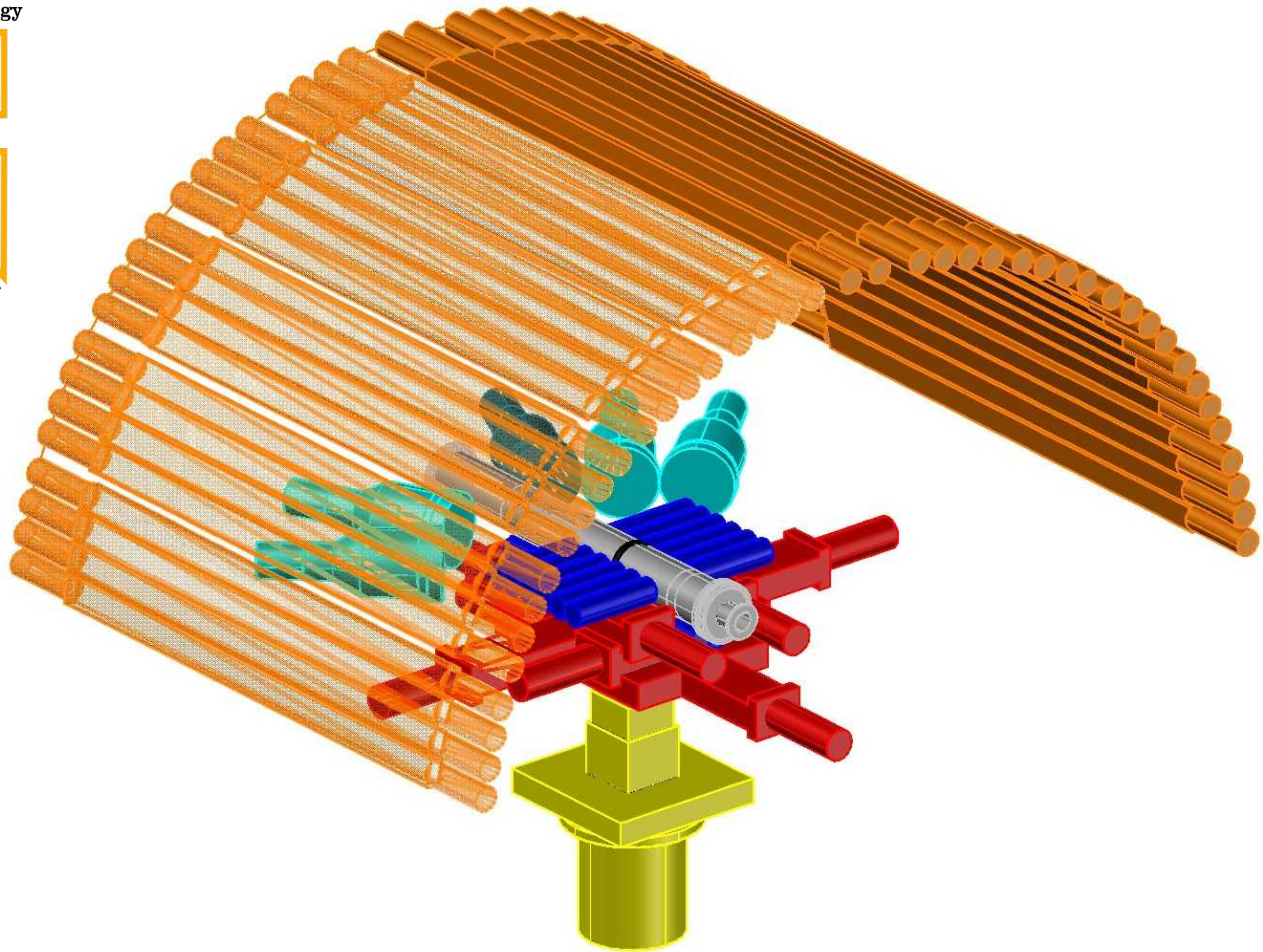
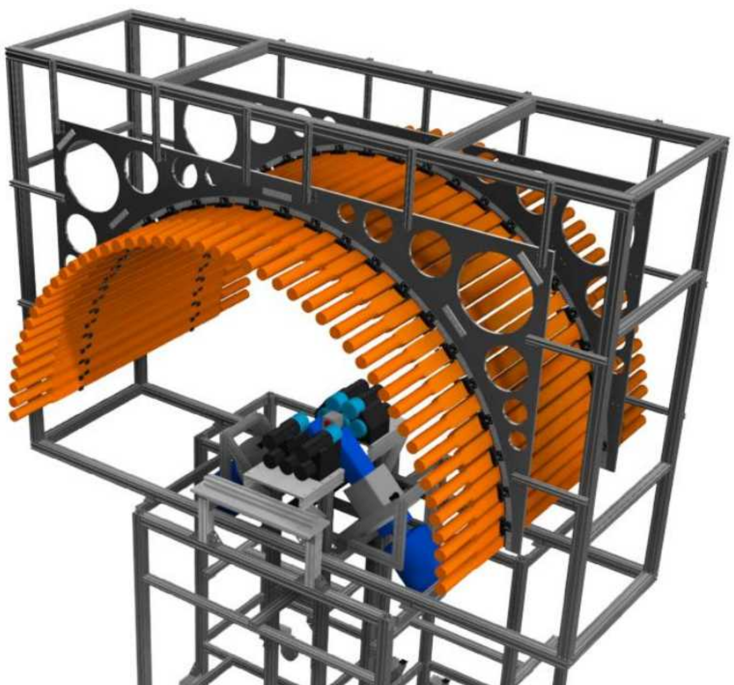
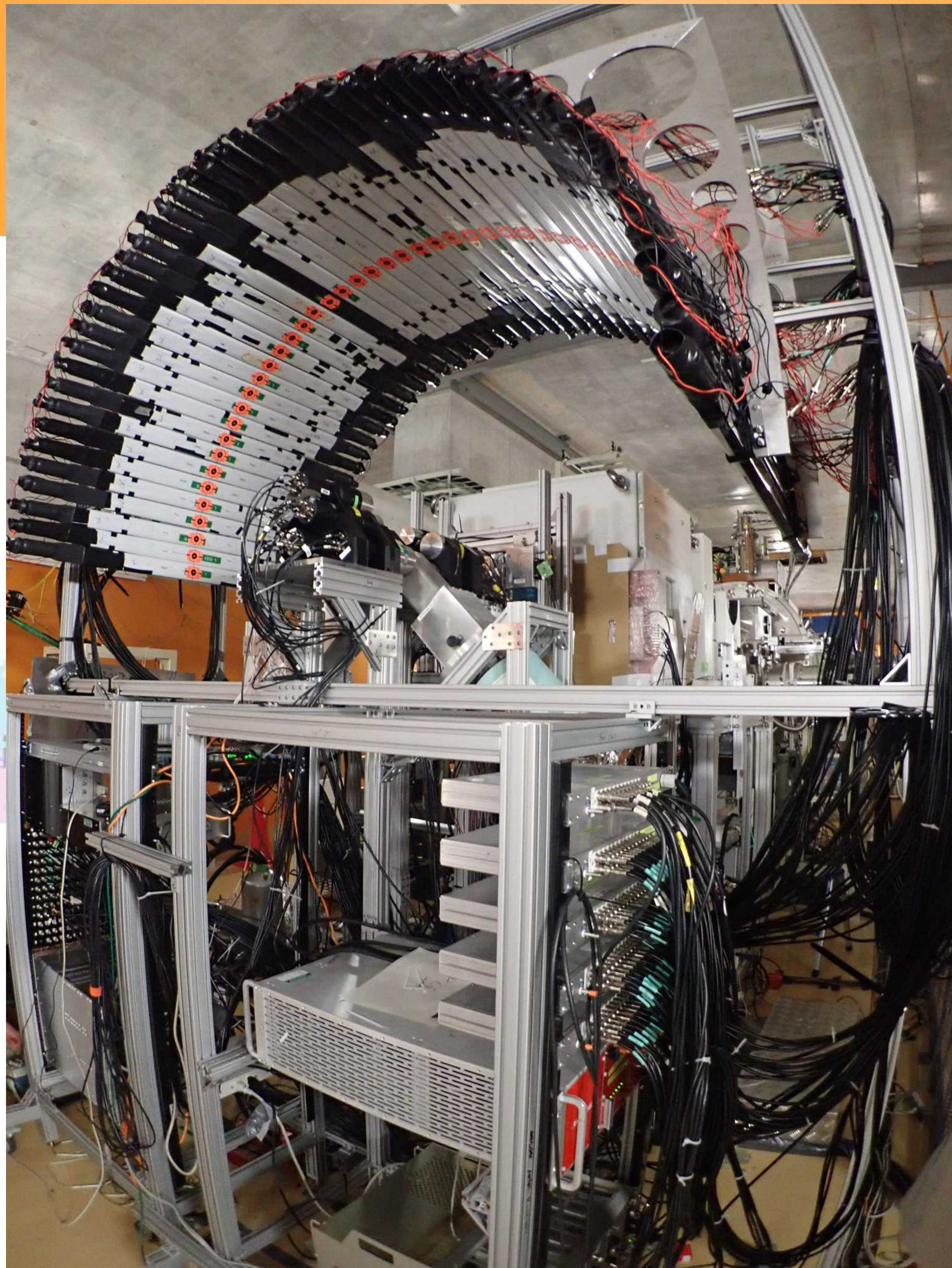


S. Paulauskas et al. NIM A737,22(2014)
W.A. Peters et al. NIM A836, 122 (2016)
K. Smith et al NIM B 414 (2017).

VANDLE+ HAGRID at RIBF (11/2018)

VANDLE
48 neutron bars at 100 cm
HAGRID
2 HPGE clovers
10x 3″x3″ +2x 2″x2″ LaBr3





The Versatile Array of Neutron Detectors at Low Energy
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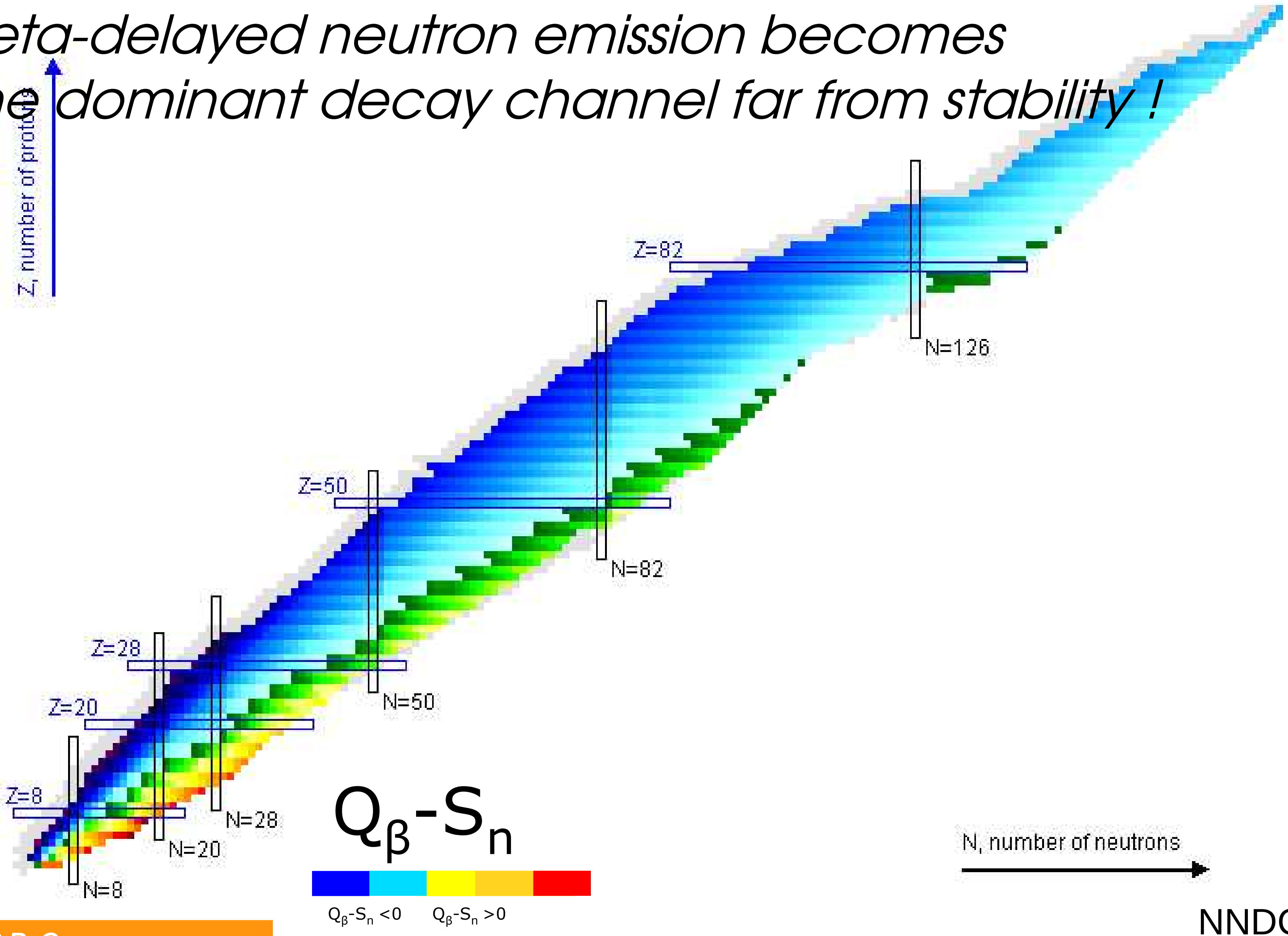
@
RIBF

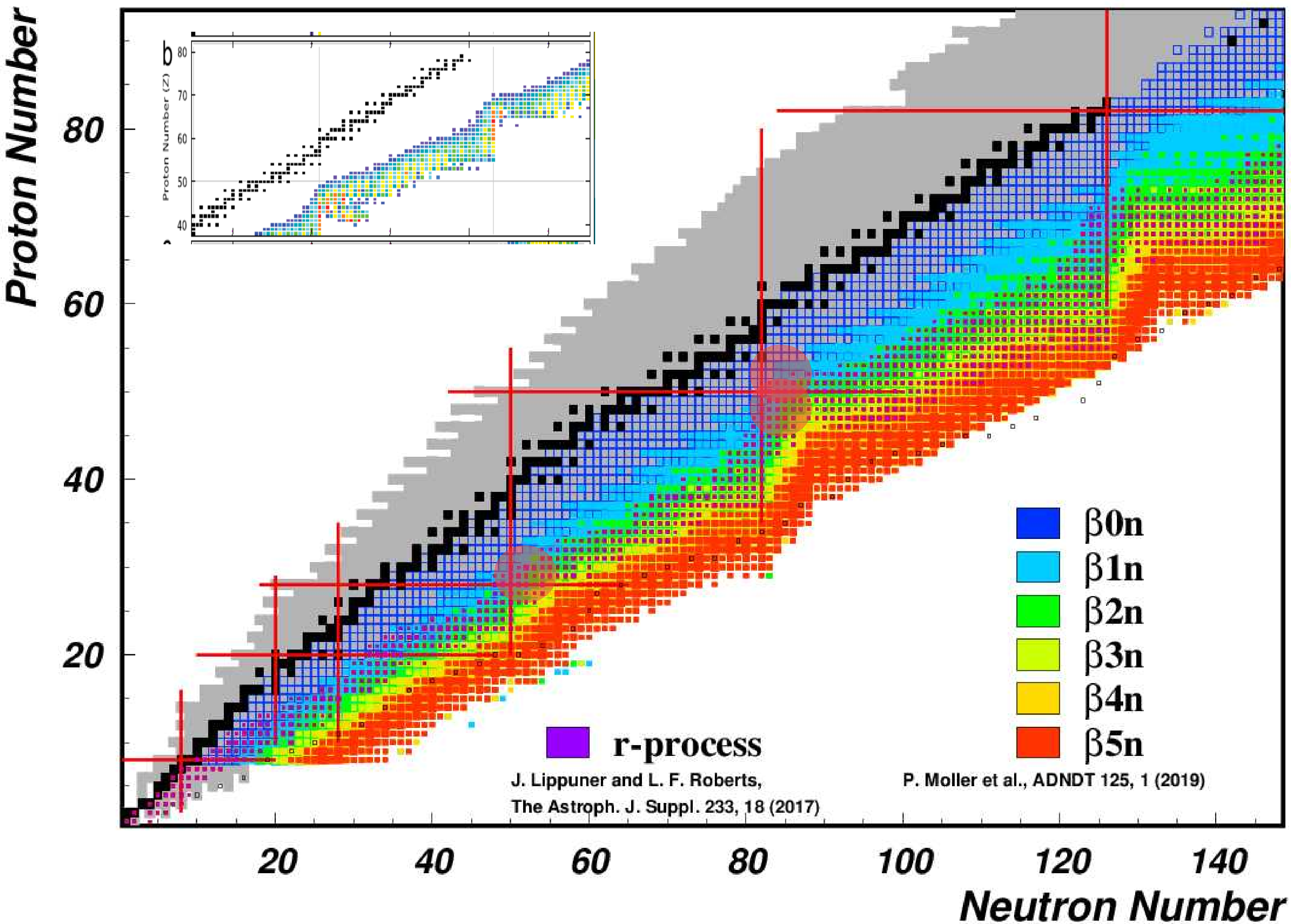
Energy window for beta-delayed neutron emission

Beta-delayed neutron emission becomes the dominant decay channel far from stability !

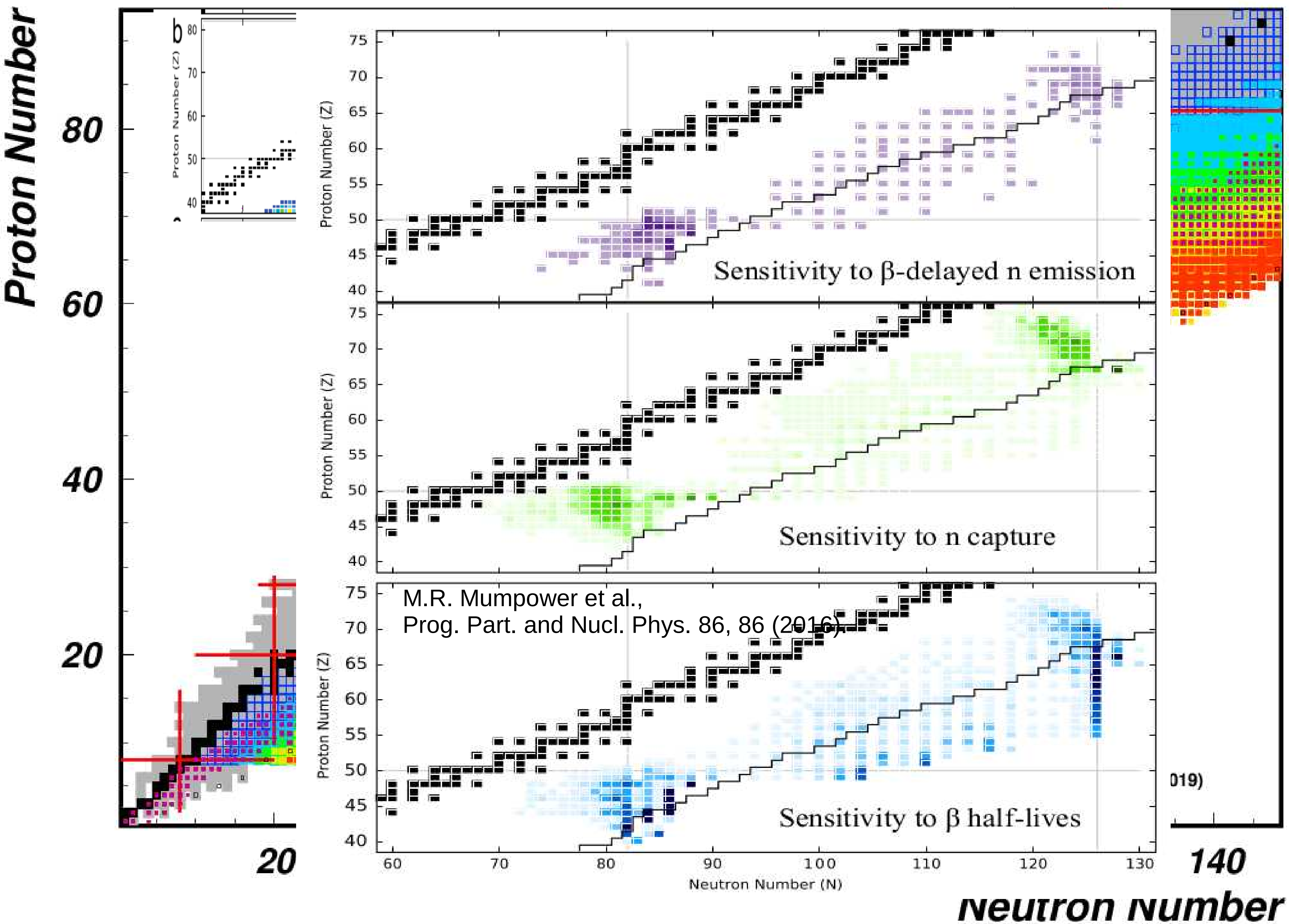


NNDC

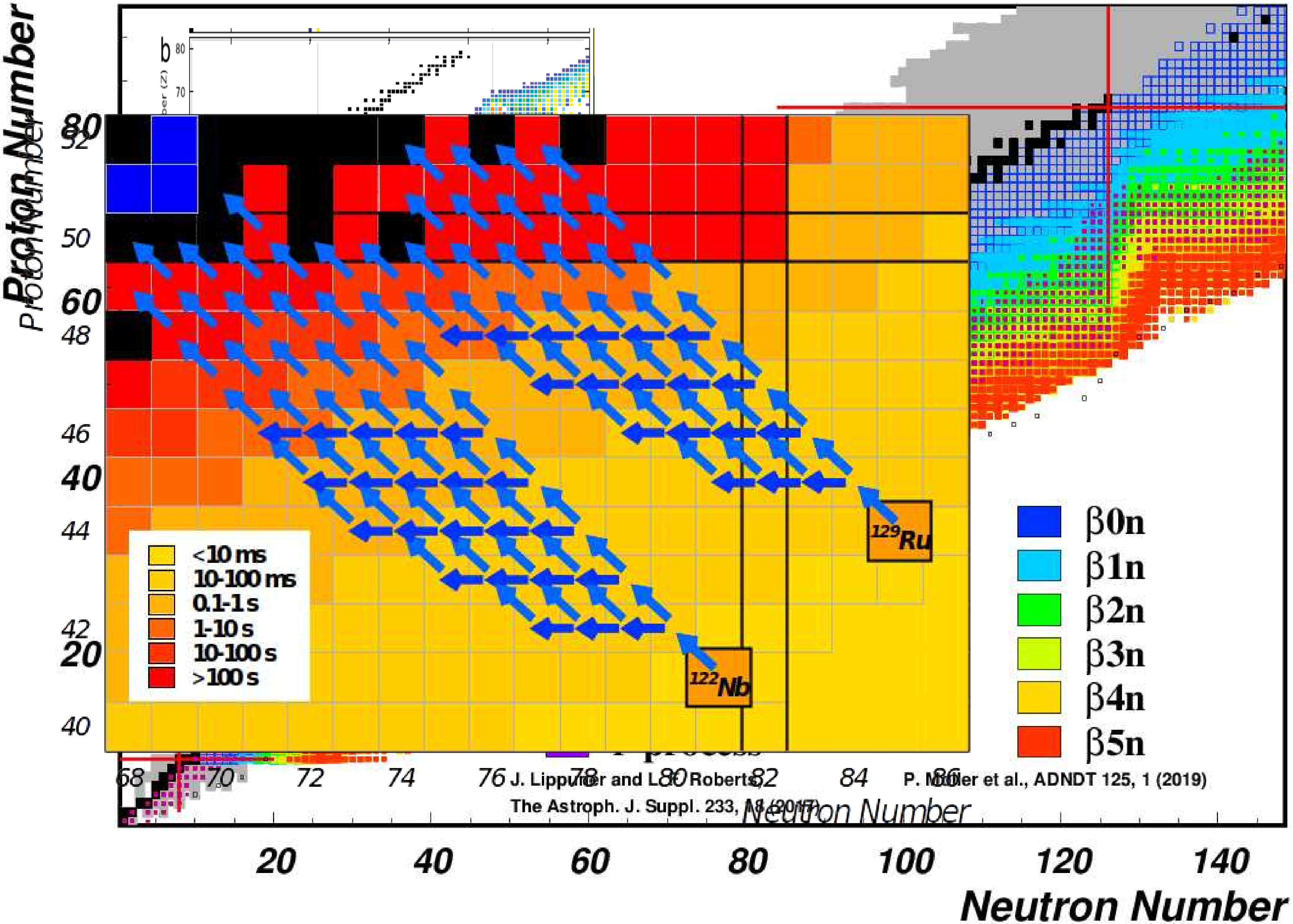
Beta delayed neutron emitters
βxn and the r-process



Beta delayed neutron emitters βxn and the r-process

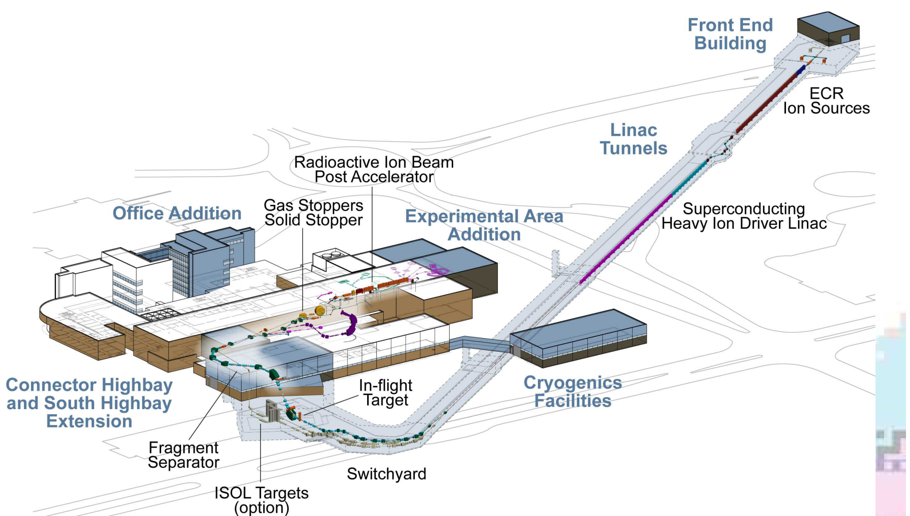


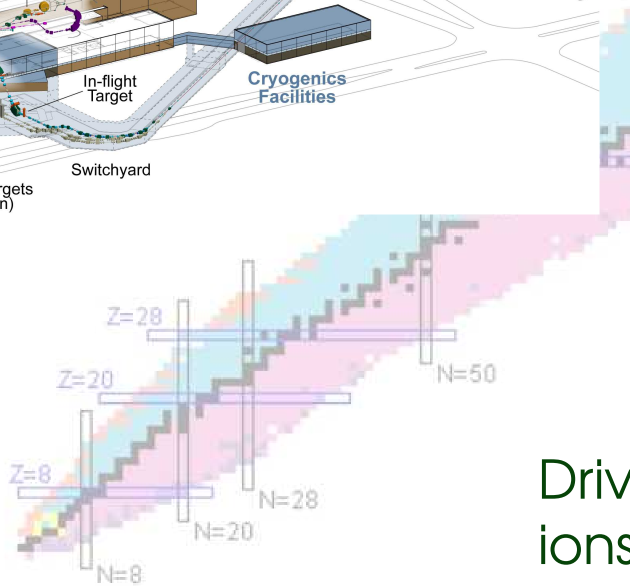
Beta delayed neutron emitters
βxn and the r-process

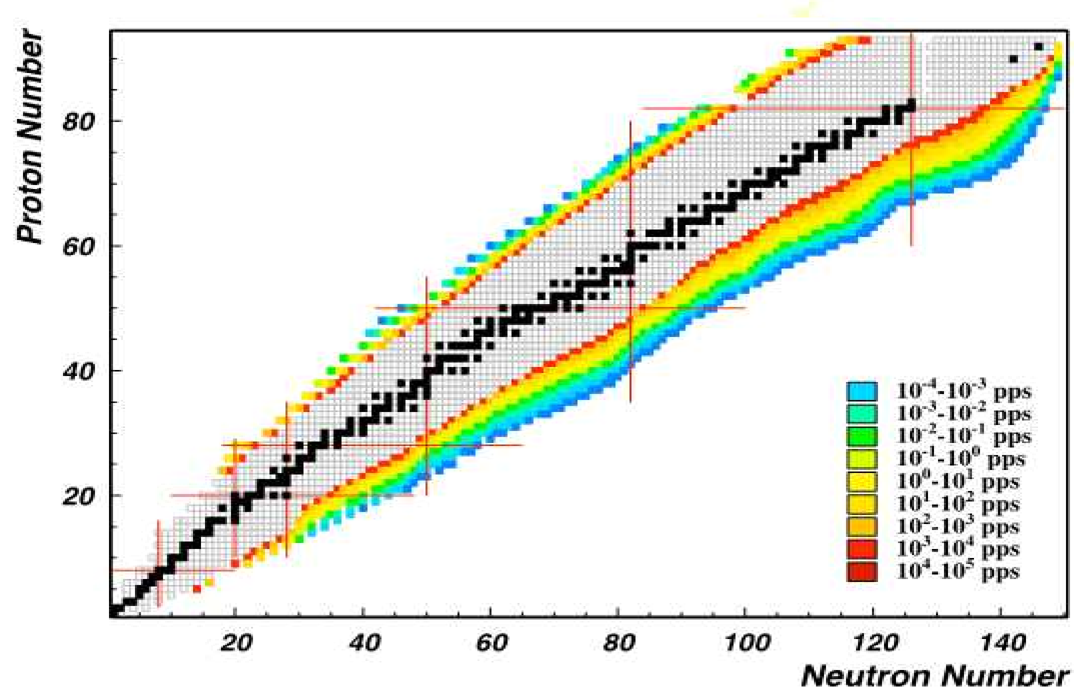


New facilities - bonanza for βxn studies
Survival of the "conventional" shell-structure ?

Facility for Rare Isotope Beams,







Driver linac capable of E/A ~ 200 MeV for all ions, $P_{beam} \geq 400$ kW

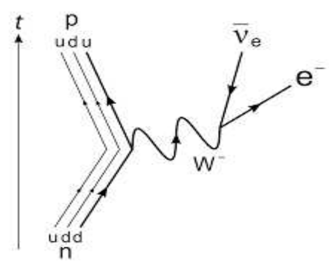
Experimental capabilities for reaccelerated, stopped and in-flight beams

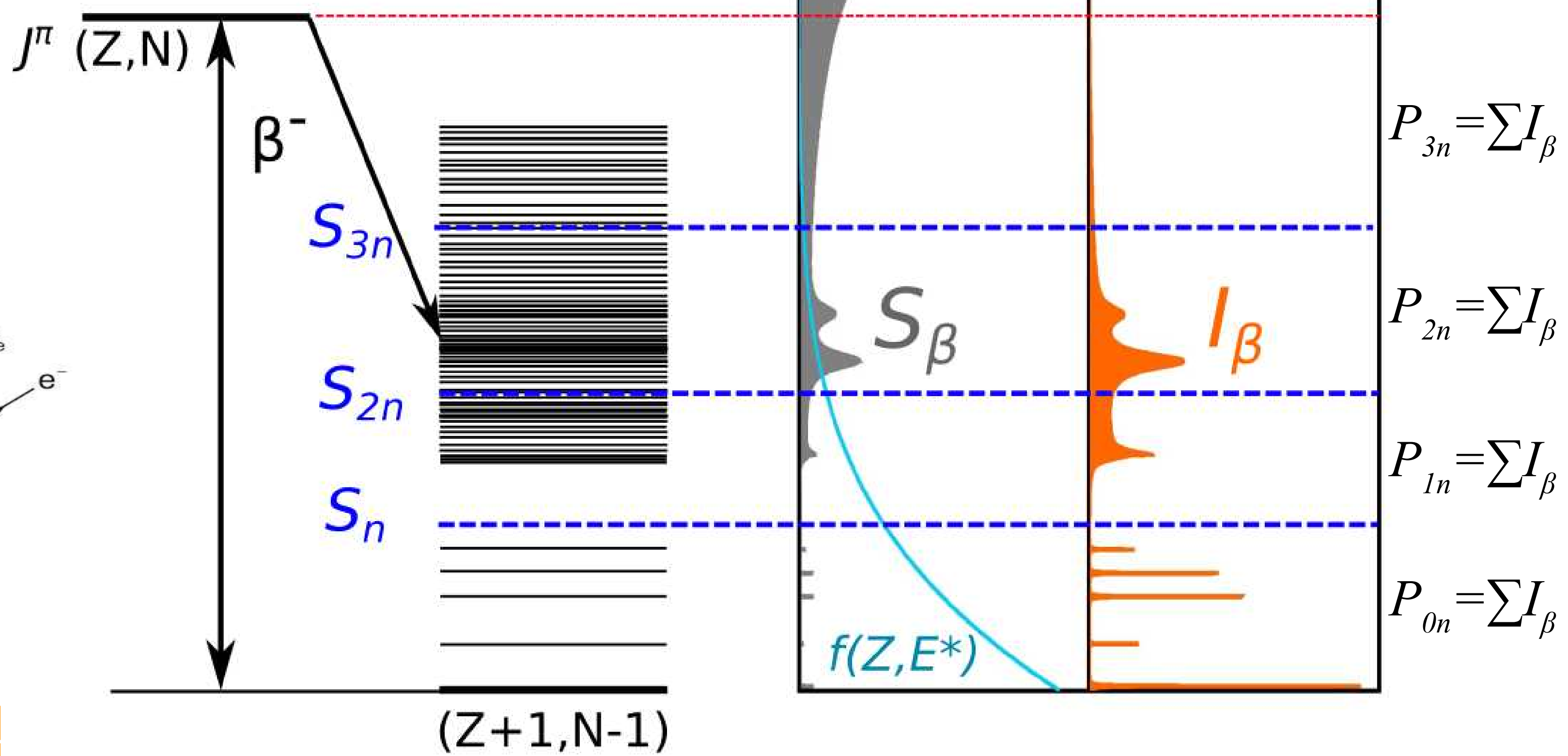
Beta delayed multi-neutron emitters

$$\frac{1}{T_{1/2}} = \sum_{E_i \geq 0}^{E_i \leq Q_\beta} S_\beta(E_i) \times f(Z, Q_\beta - E_i) \qquad S_\beta(E_i) = \langle \psi_f | \hat{O}_\beta | \psi_{mother} \rangle$$

only nuclear degrees of freedom

P_{xn} proportional to the integrated β-feeding in the respective energy window (?)

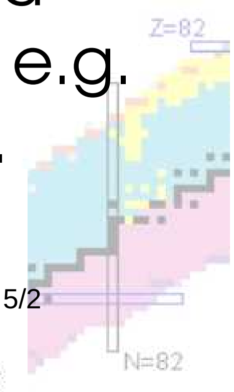


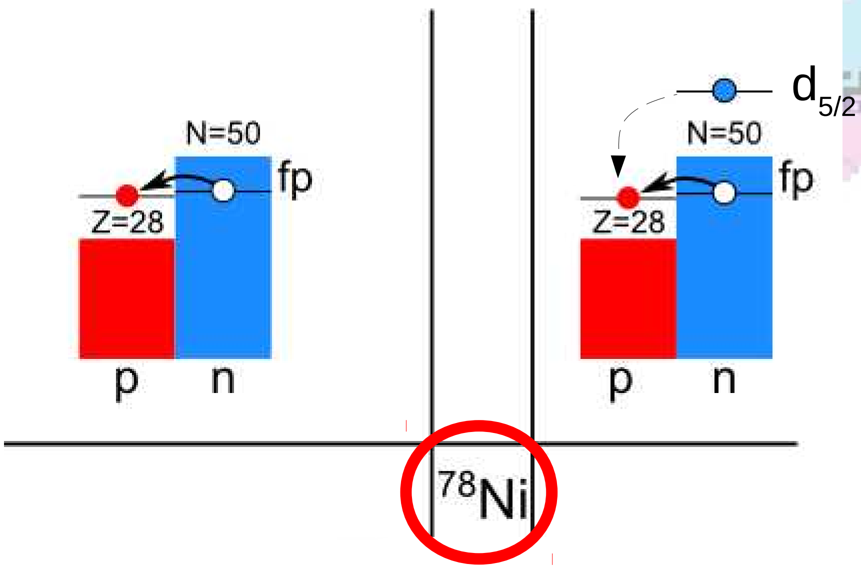


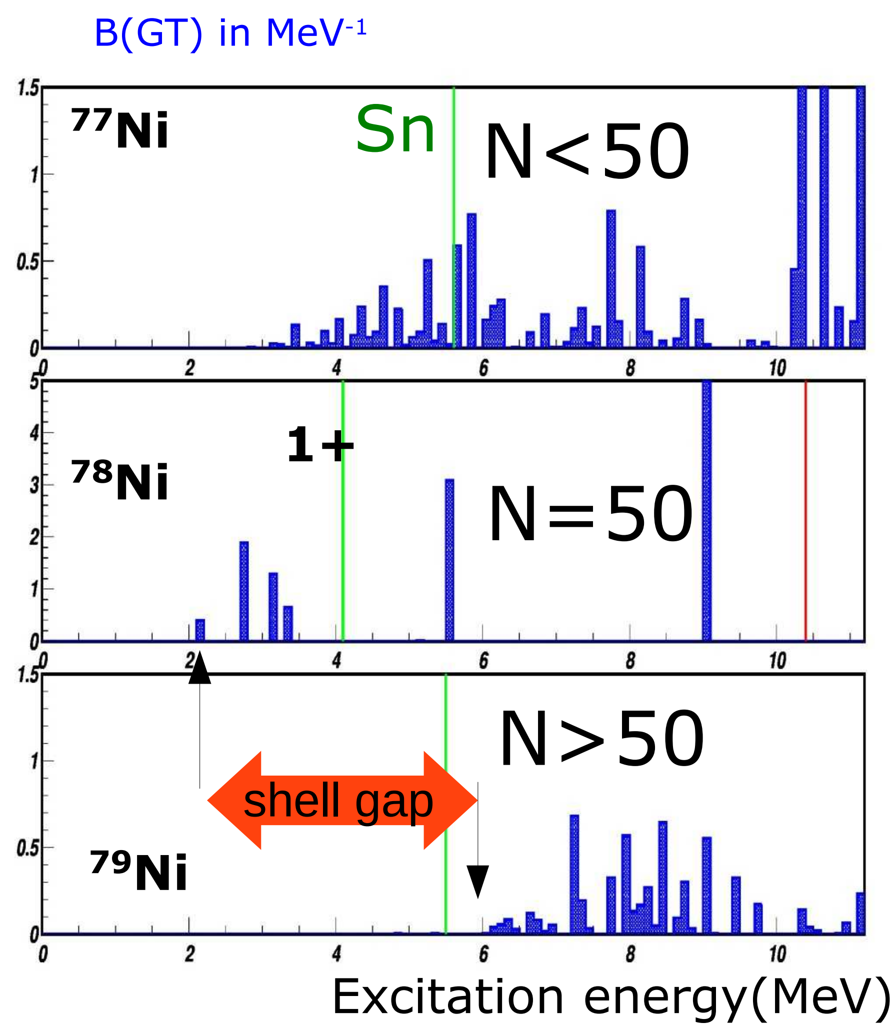
Effects of the shell gap on the decay of isotopes with N>50

Nuclear structure constraints on beta decay:
Gamow-Teller (↑↑) operator connects spin-orbit partner orbitals.

This mechanism drives beta delayed neutron emission e.g. across the N=50 shell-gap.







B(GT) for ^{84}Ga and shell model interpretation

Observed large beta strength at high excitations compatible with GT-decay of ^{78}Ni core states

Dominant: $\nu p_{1/2} \longrightarrow \pi p_{3/2}$ transformations

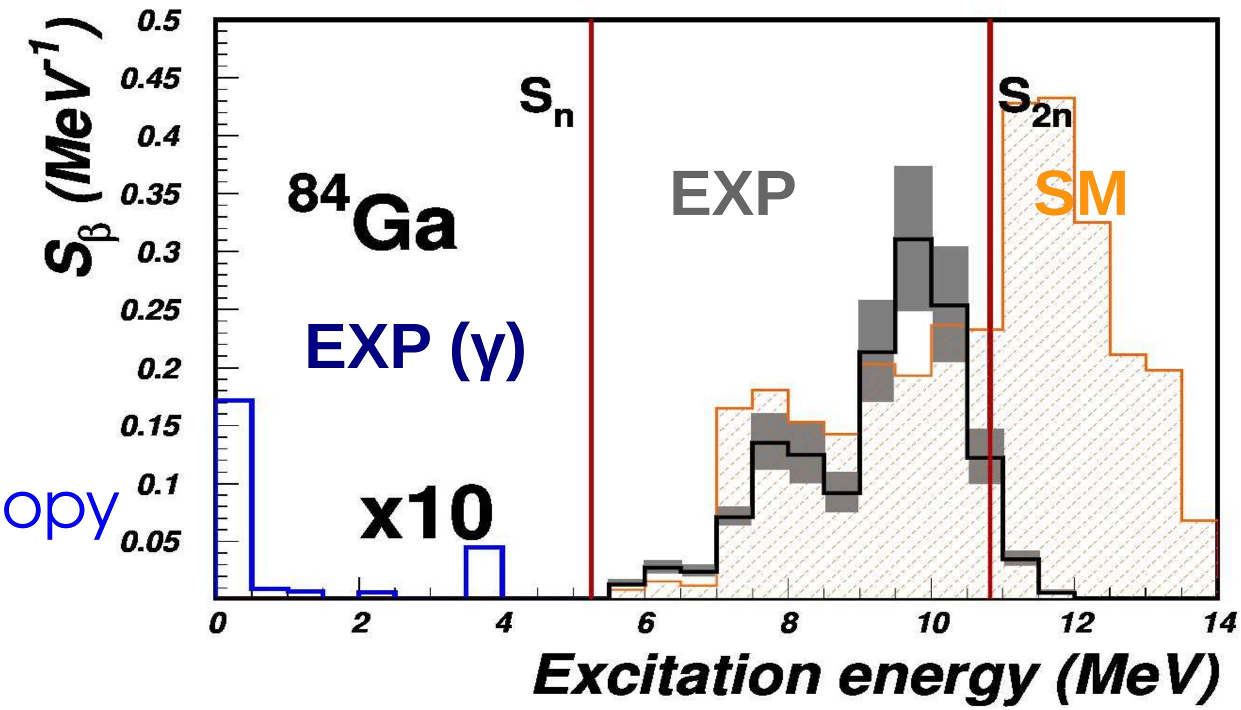
The Versatile Array of Neutron Detectors at Low Energy

VANDLE @ HRIBF

Strength below S_n from gamma spectroscopy

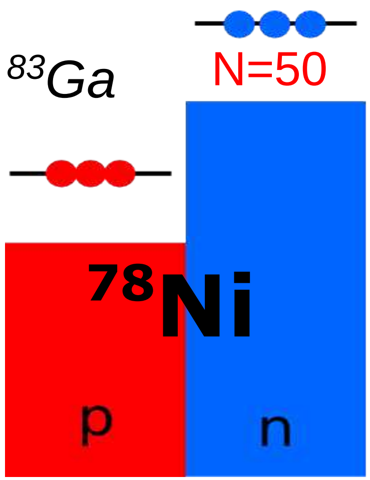
Kolos et al Phys. Rev. C 88, 047301 (2013)

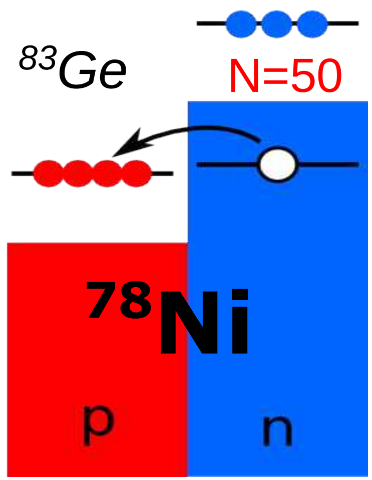
for B(GT)=0.1/MeV=> log *ft* = 4.6

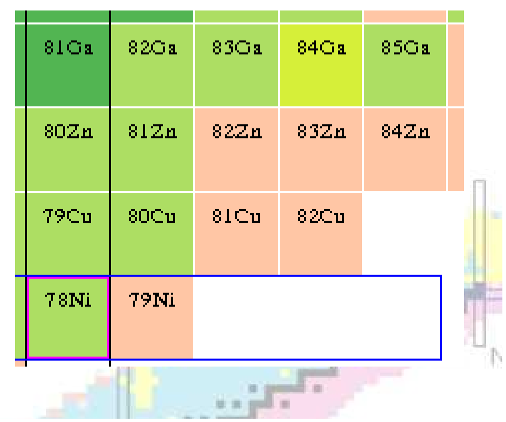


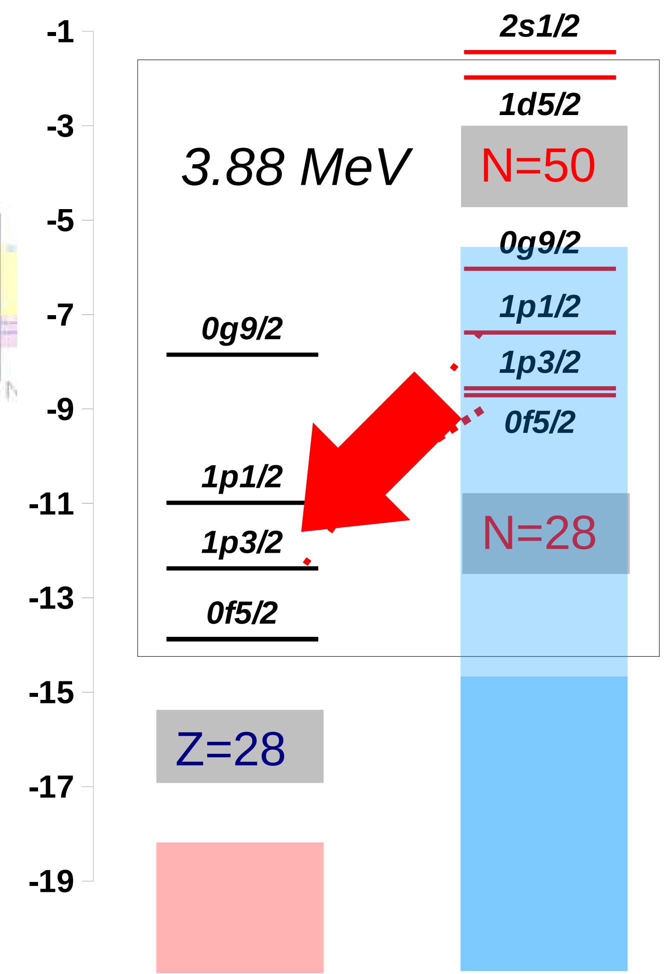
Madurga et al. Phys. Rev. Lett. 117 (2016) 092502

Shell-model interpretation "realistic" calculation of GT-strength









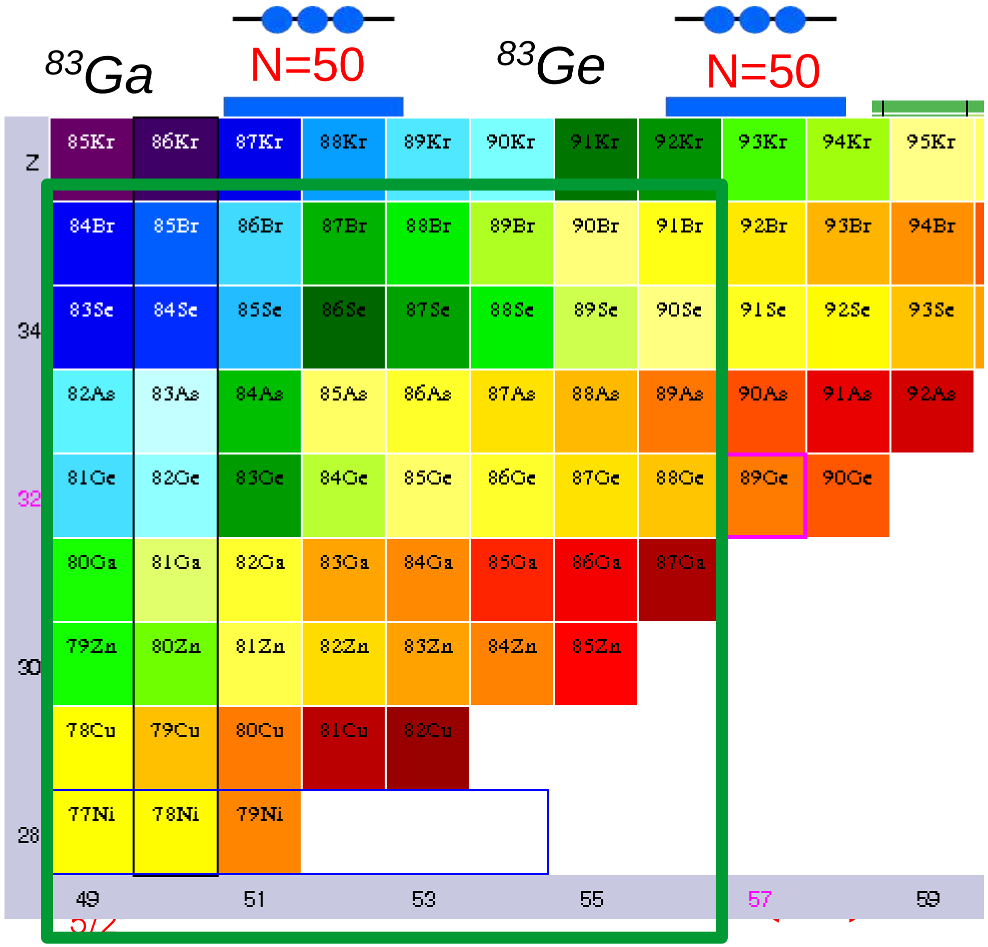
Nushellx with hybrid interactions based on: *jj44bpn* for fpg (^{56}Ni core, B.A. Brown), (GOOD DESCRIPTION OF N<50 ISOTOPES)

Hybrid interactions with matrix elements for: neutrons in $d_{5/2}$ and protons and neutrons in fpg.

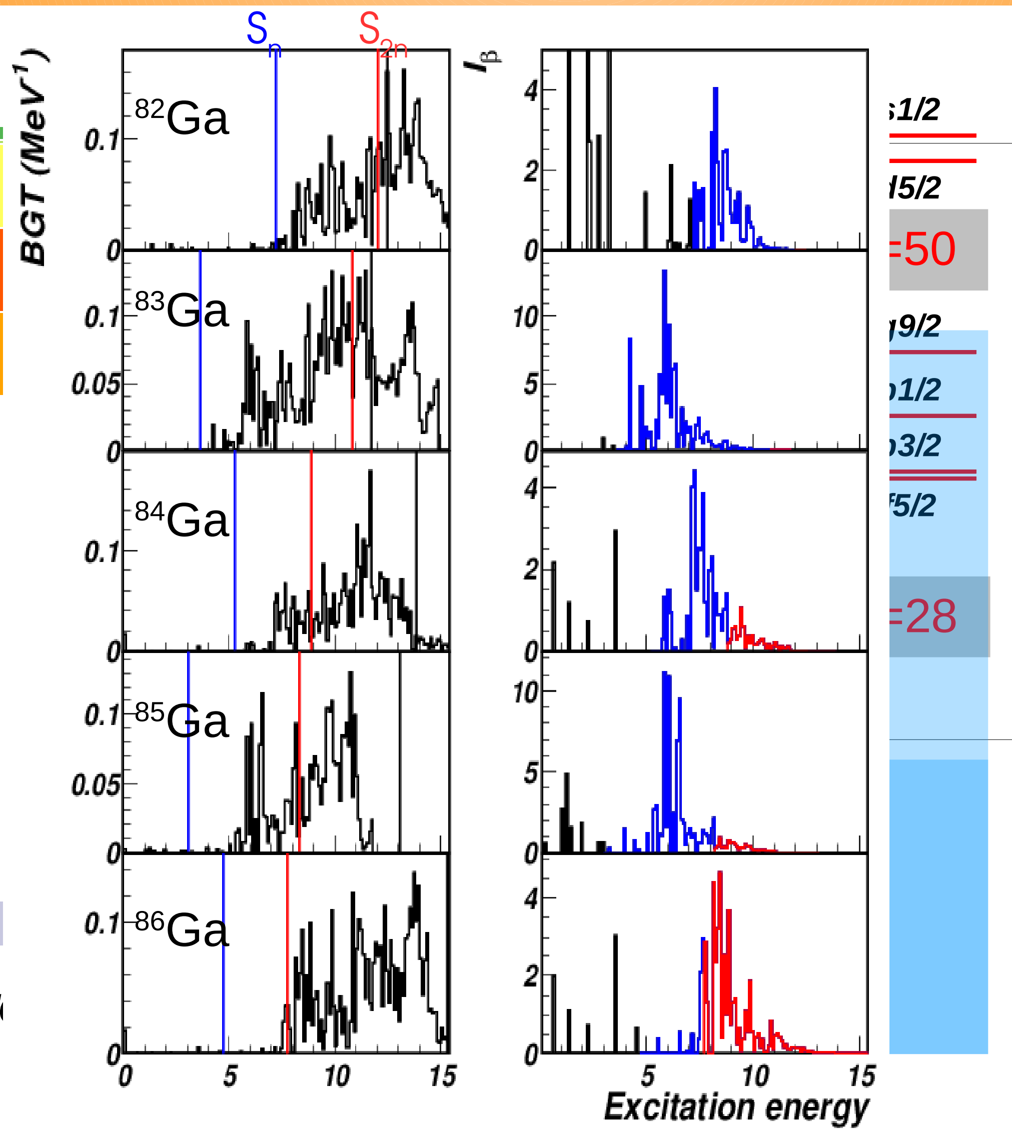
$d_{5/2}$ neutrons ***"blocked"*** for B(GT) calculations

Single Particle Energies – experimental systematic (Grawe)

Shell-model interpretation
"realistic" calculation of GT-strength

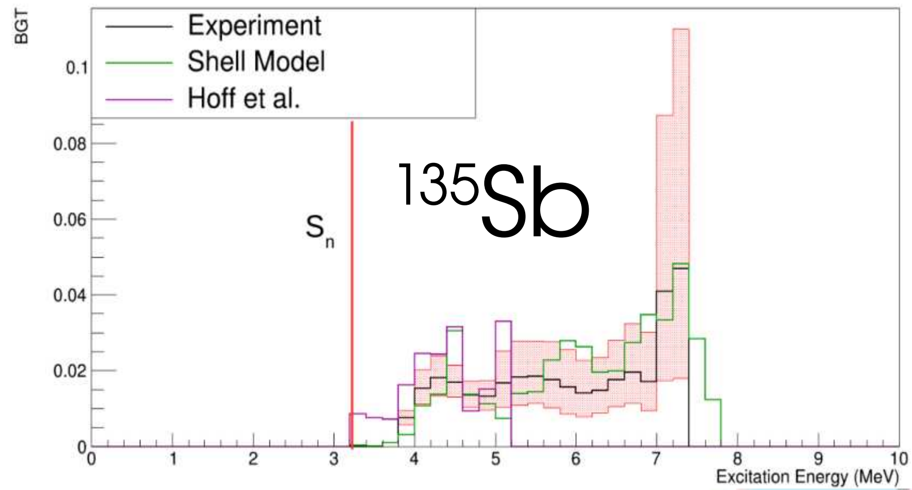


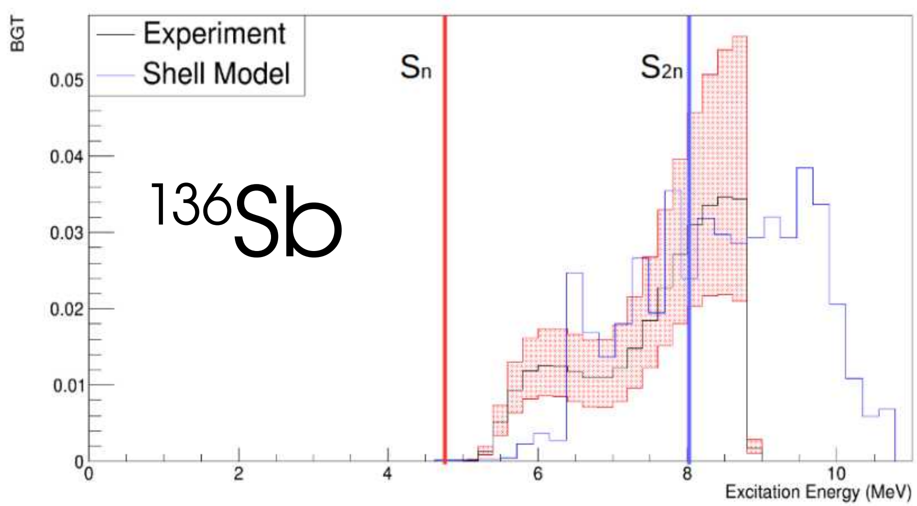
Single Particle Energies – experiment



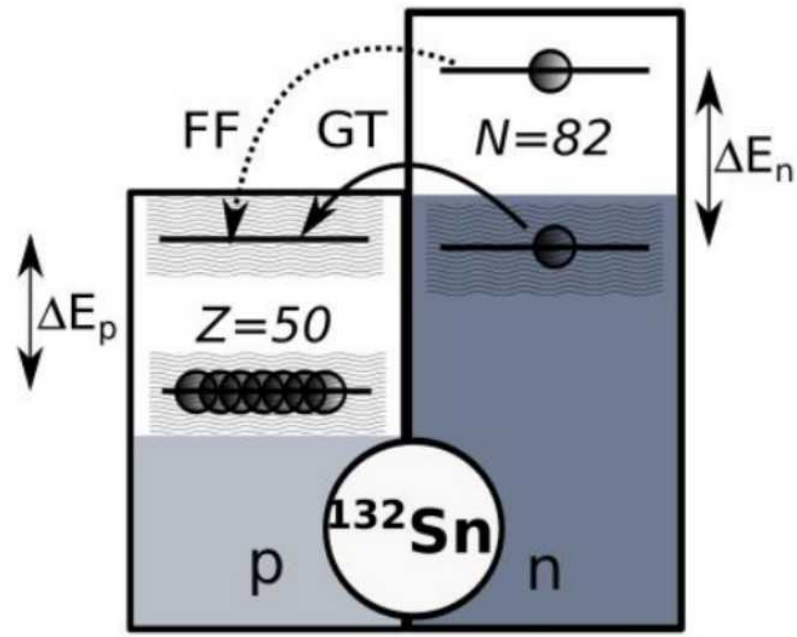
Mazzocchi et al. Phys. Rev. C C.92.054317
Alshudifat et al. Phys. Rev. C 93, 044325
Madurga et al. Phys. Rev. Lett. 117 (2016) 092502

GT selectivity in decays of ^{135,136}Sb

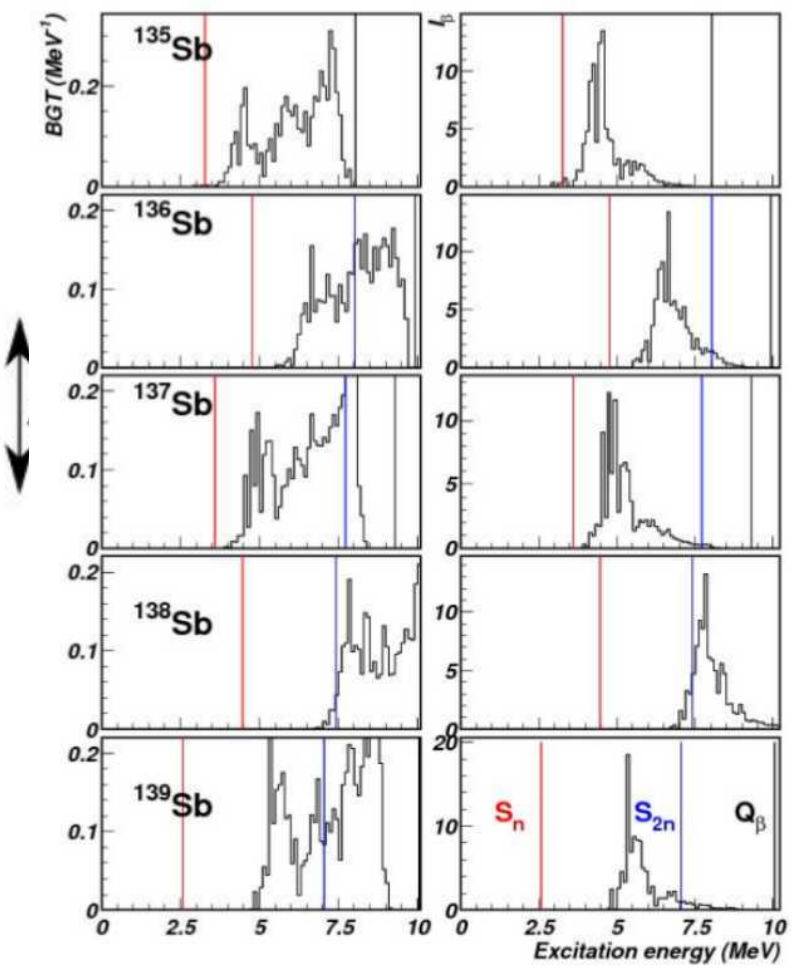


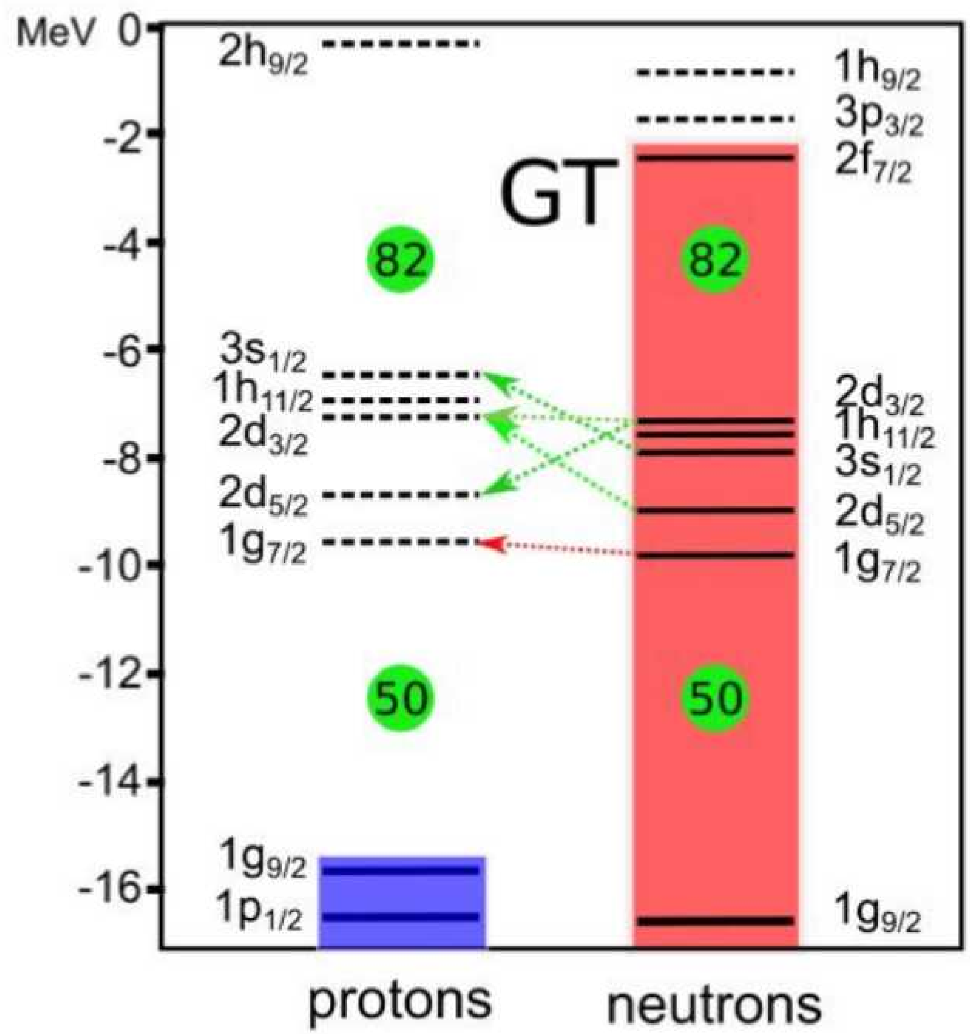


S. Z. Taylor - dissertation



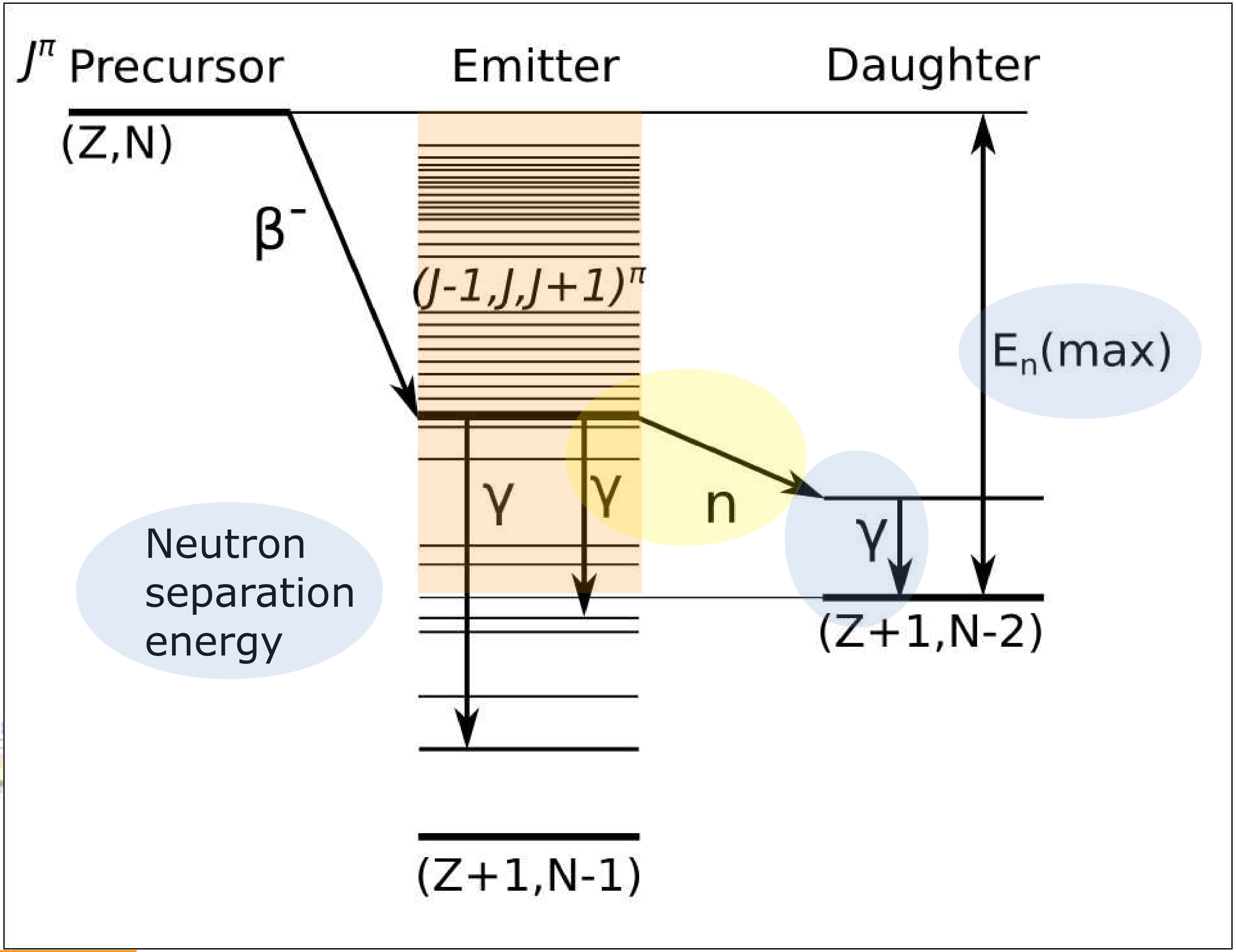
GT selectivity in decays of $^{135,136}Sb$ shell-model predictions





Beta-delayed neutron emission

Shell-structure dominates the first stage



What is the mechanism of the neutron emission: “direct” or via “compound nucleus” ?

Neutrons - no Coulomb barrier !

Direct - fast emission (broad), sensitive to nuclear structure. conserved energy and angular momentum.

Compound - slow emission (narrow), non-sensitive to nuclear structure, conserved energy and angular momentum.

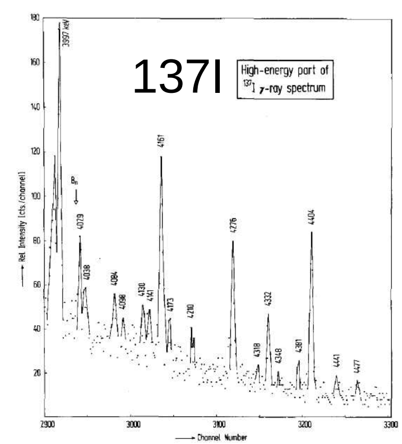
“Bohr hypothesis: The properties of the C. N. do not depend upon the detailed way of formation.”

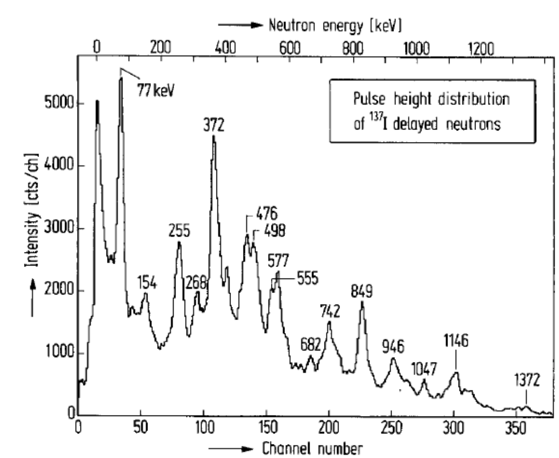
“Obviously”

(Complex) heavy neutron-rich nuclei: compound nucleus.

BUT WHY?

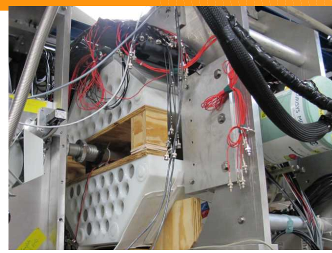
T. Kawano, P. Talou, I. Stetcu, and M. B. Chadwick, Nuclear Physics A 913, 51 (2013).





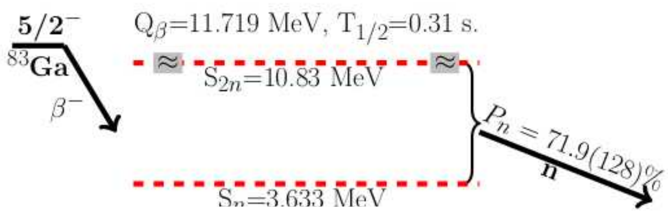
Decay of ^{83}Ga to (N=50) ^{82}Ge

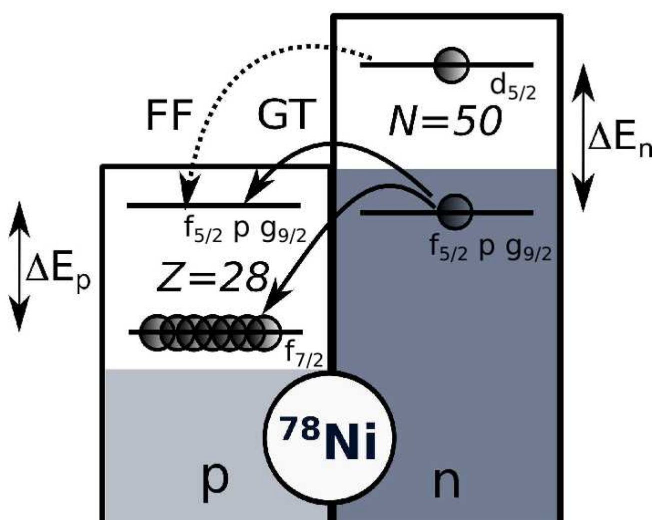
3Hen Detector

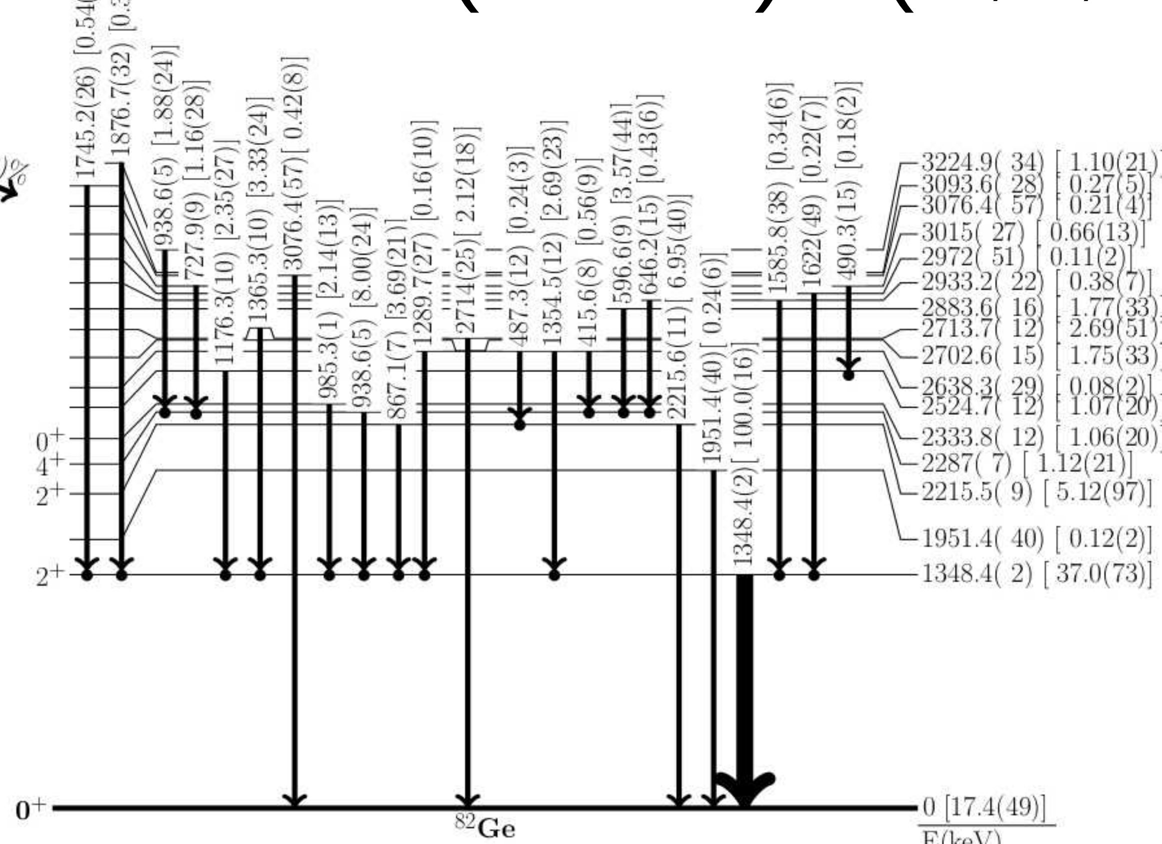


J. Winger et al. Phys. Rev. C 81, 044303 (2010)
M. AlShudifat in preparation

^{83}Ga → ^{83}Ge → ^{82}Ge
N=52 N=51 N=50
Z=31 Z=32 Z=32
5/2- → (3/2-,5/2-,7/2-) → (0+,2+,3+)

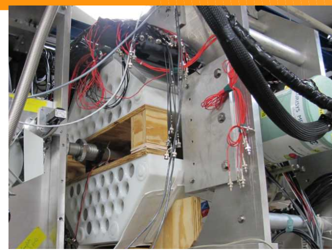






Decay of ^{83}Ga to (N=50) ^{82}Ge

^{3}Hen Detector



J. Winger et al. Phys. Rev. C 81, 044303 (2010)
M. AlShudifat in preparation

^{83}Ga → ^{83}Ge → ^{82}Ge
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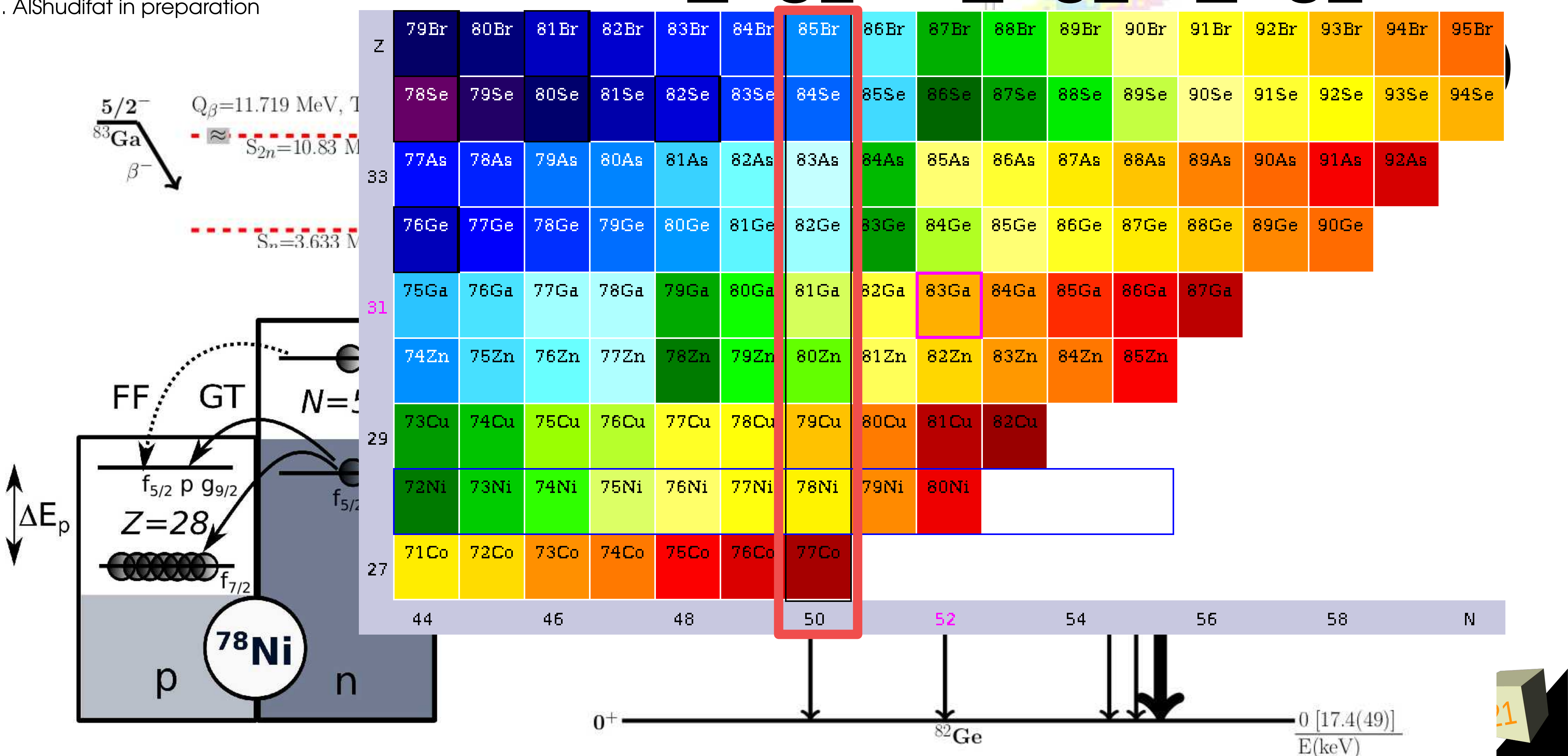
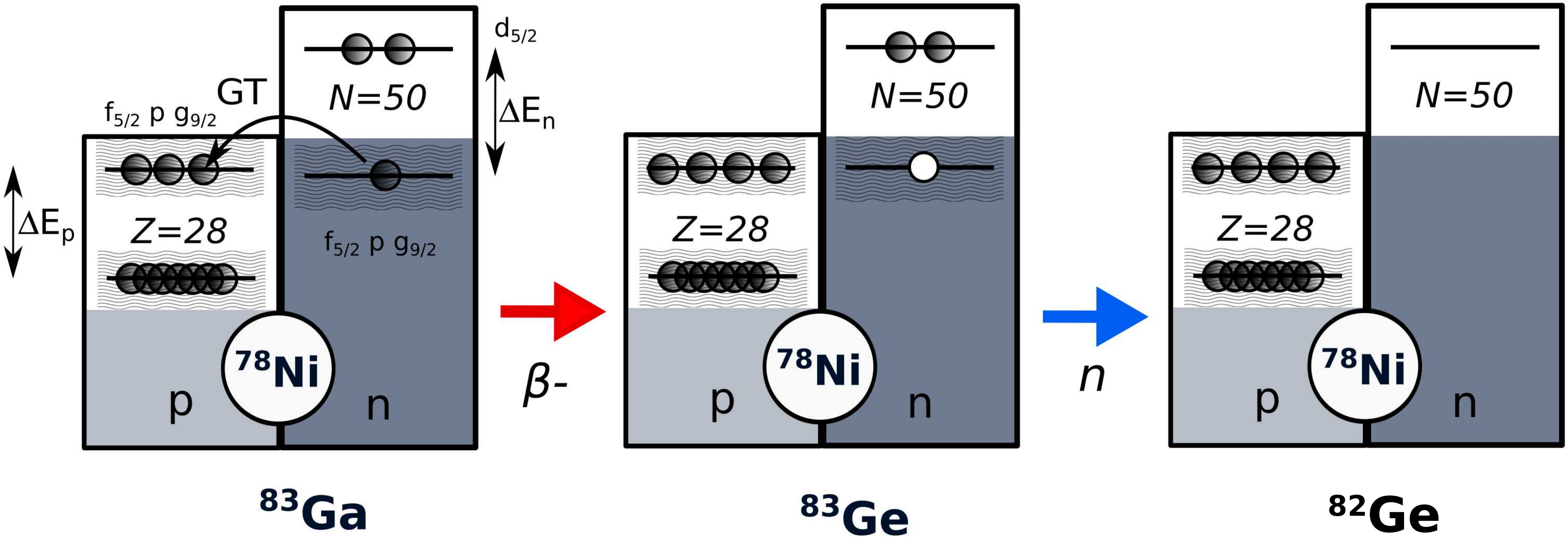


Decay of ^{83}Ga to (N=50) ^{82}Ge

Beta decay

Neutron emission



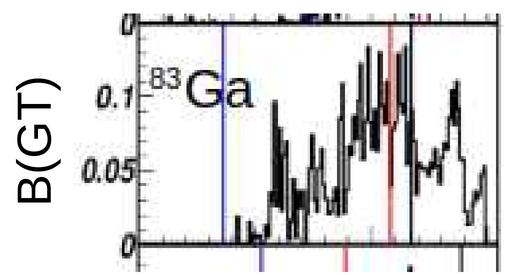
NO spectroscopic overlapp between ^{83}Ge* and ^{82}Ge

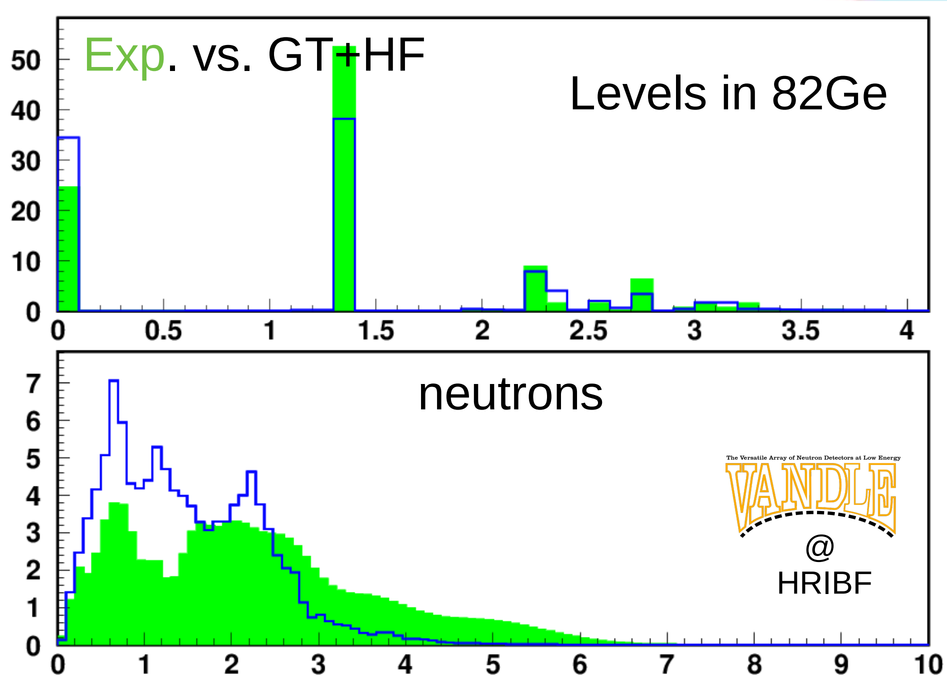
Statistical model and decay of ^{83}Ga to (N=50) ^{82}Ge

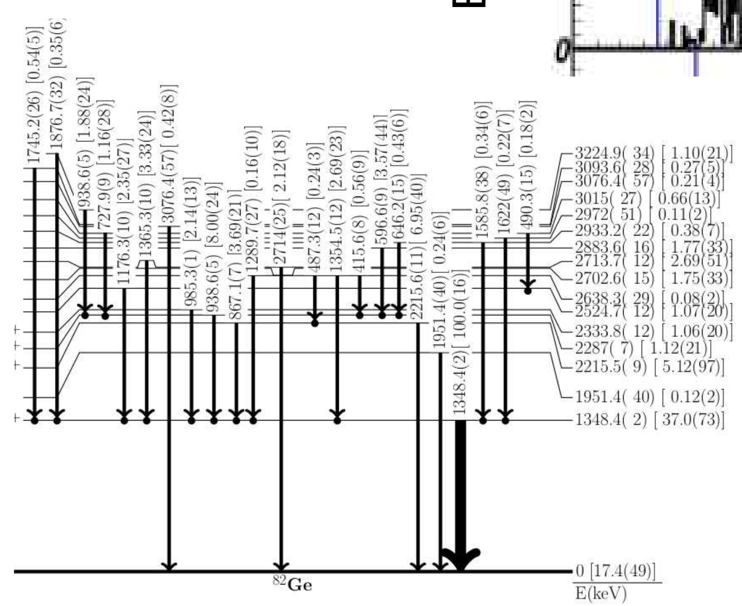
BGT from shell model.
Hauser-Feshbach statistical emission code for neutrons and gammas.

Calculations use Kawano HF model (coh code) and shell-model B(GT) (nushell).

Population of states in ^{82}Ge is NOT sensitive to SM structure of ^{83}Ge GT states.
Nueutron emission proceeds through components of the wave functions, which are not captured by the shell model.

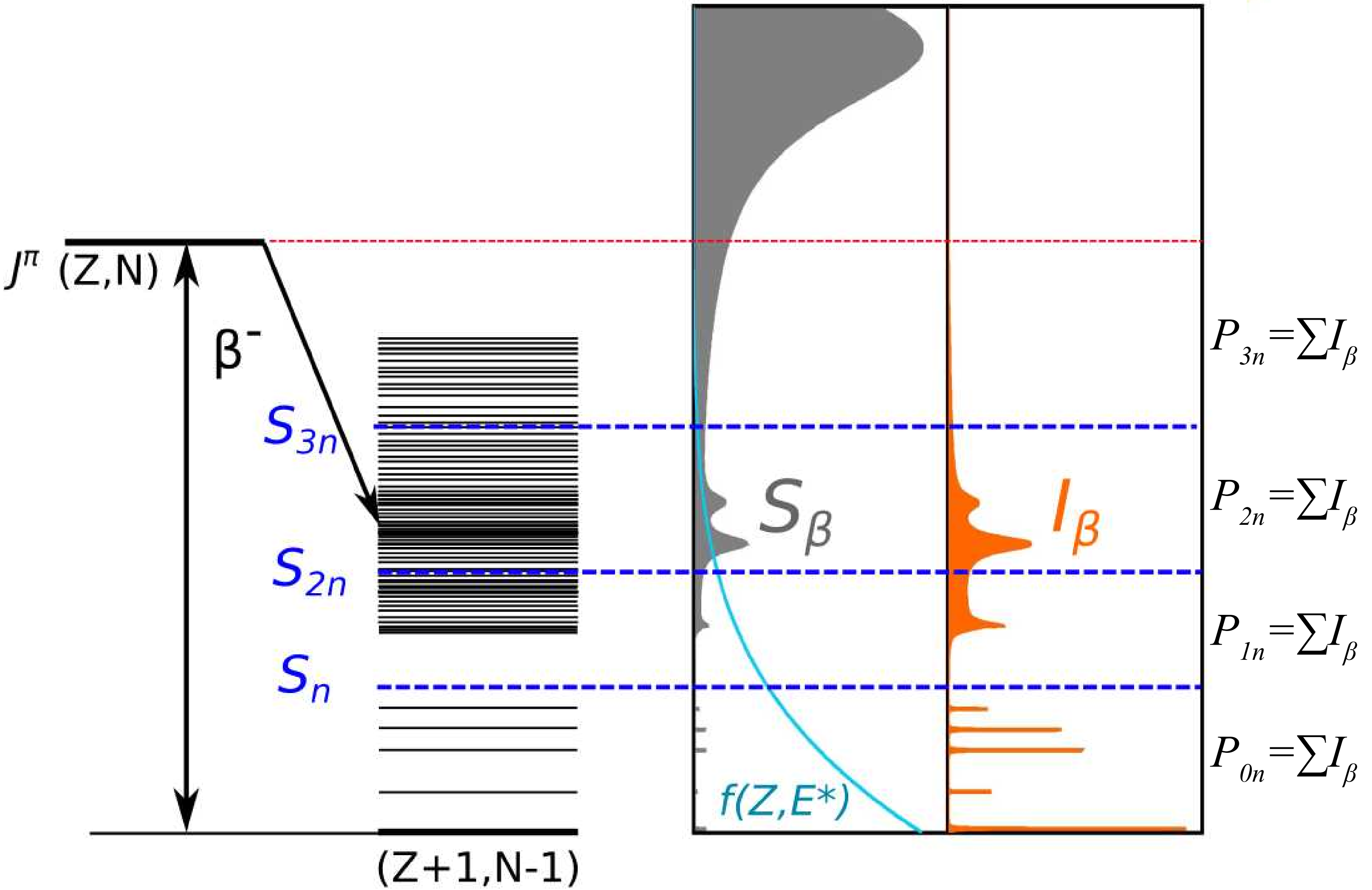




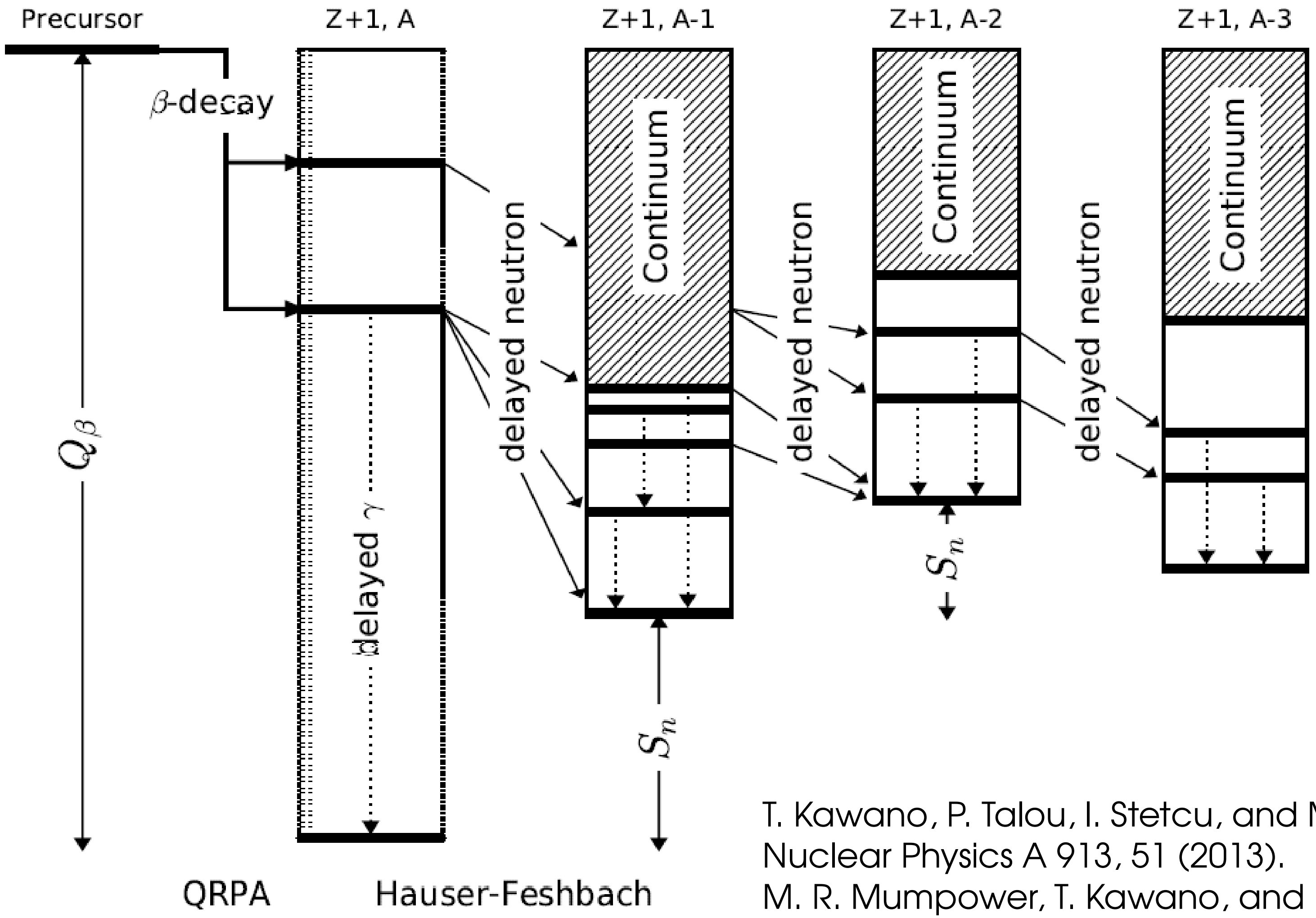


Beta delayed multi-neutron emitters – "cut off" model

P_{xn} proportional to the integrated β-feeding in the respective energy window ??

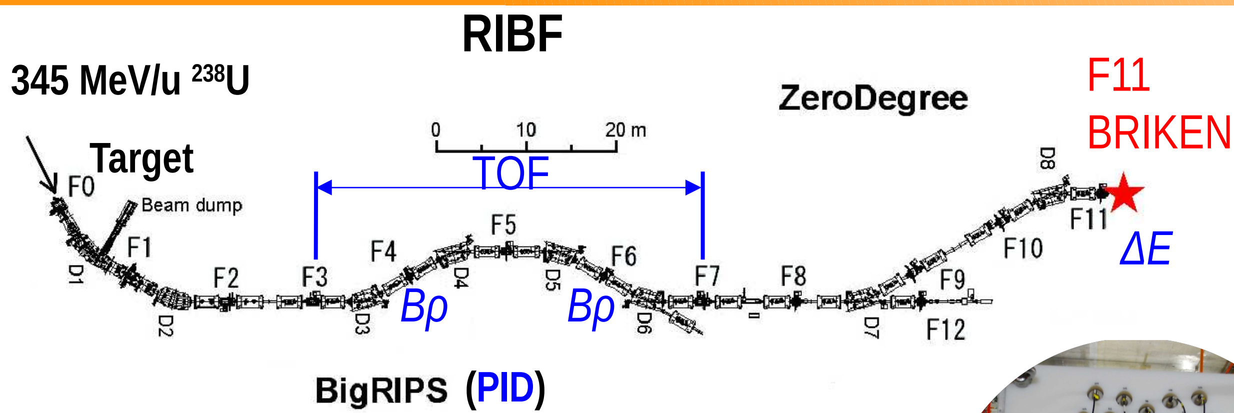


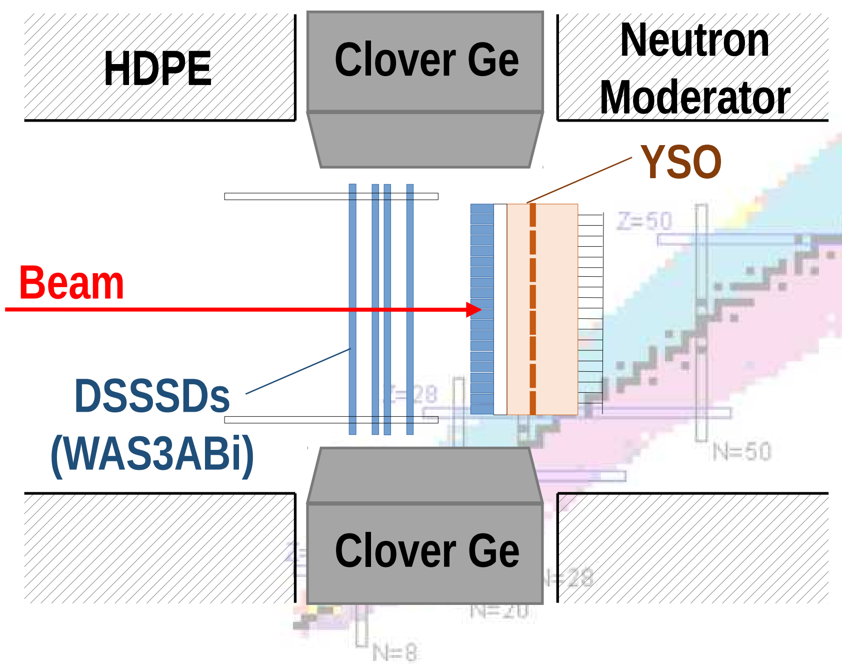
Beta-delayed neutrons and Hauser-Feshbach model

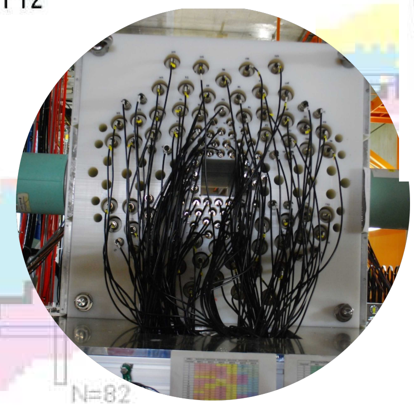


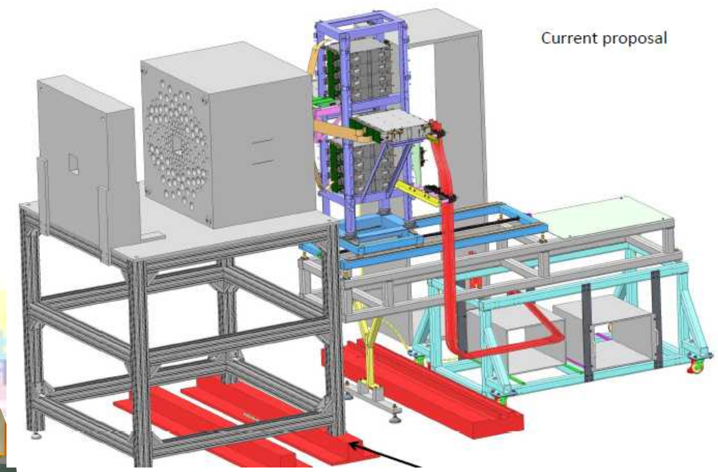
T. Kawano, P. Talou, I. Stetcu, and M. B. Chadwick, Nuclear Physics A 913, 51 (2013).
M. R. Mumpower, T. Kawano, and P. Möller, Physical Review C 94, 064317 (2016).

BRIKEN - neutron counter for P_{xn} measurements (2017 experiment)







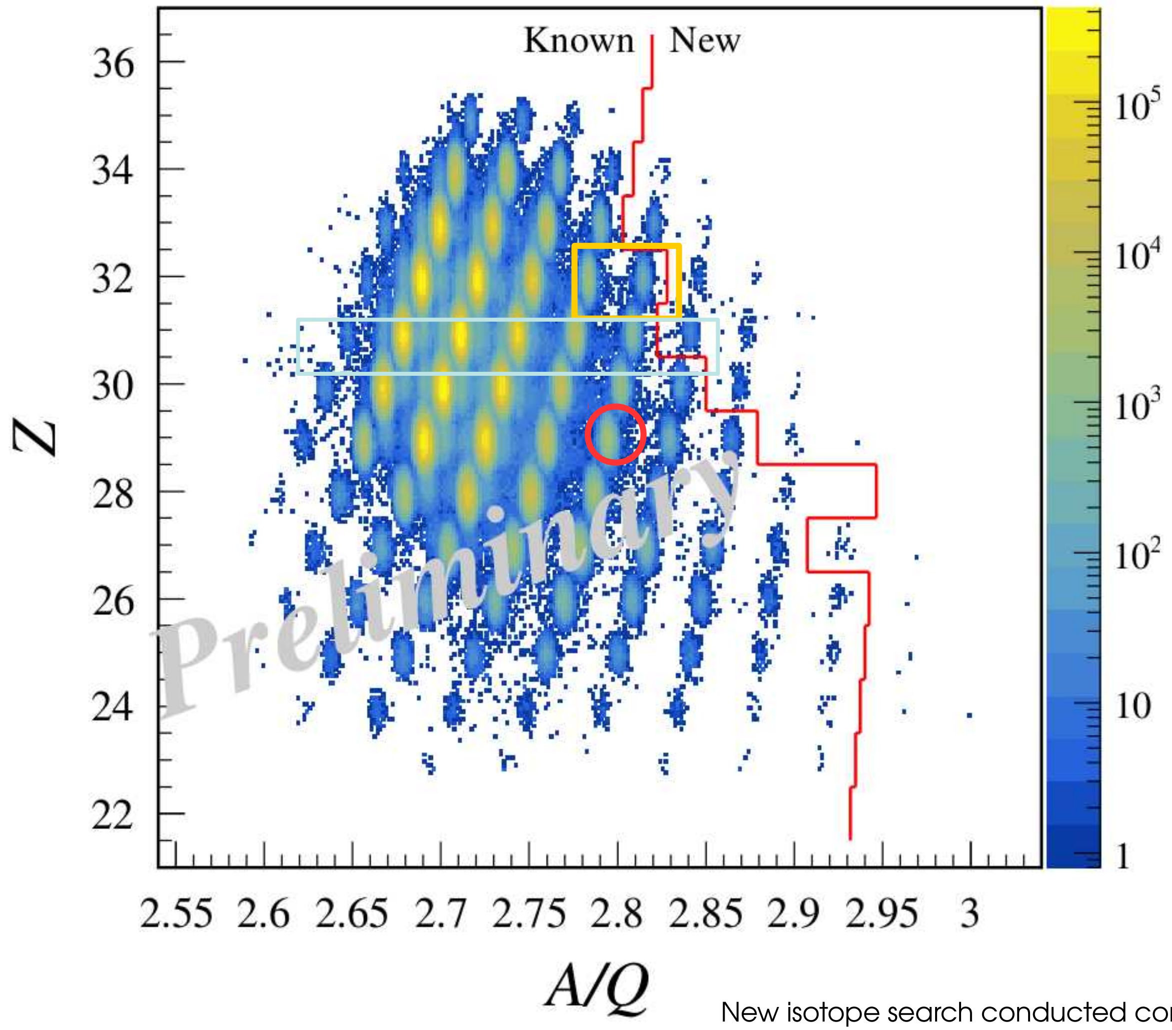


BRIKEN exp. in Oct./Nov. 2017 at RIBF

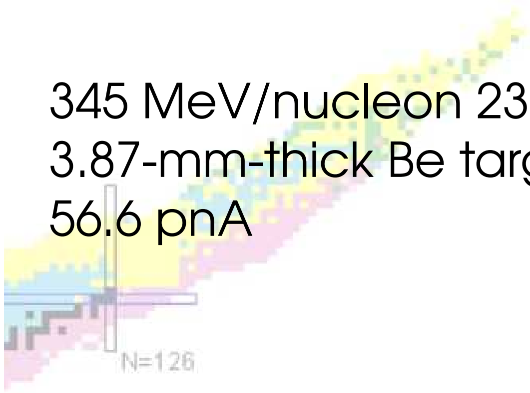
- In-flight fission of 345 MeV/u ^{238}U
- Region around and beyond 78Ni
- 140 ^3He counters for Pn measurement
- Two ORNL clover detectors
- Shared implantation between DSSSDs and YSO

A. Tarifeño-Saldivia, et al., J. of Instrum. 12, P04006 (2017)

Isotope reach for the BRIKEN experiment

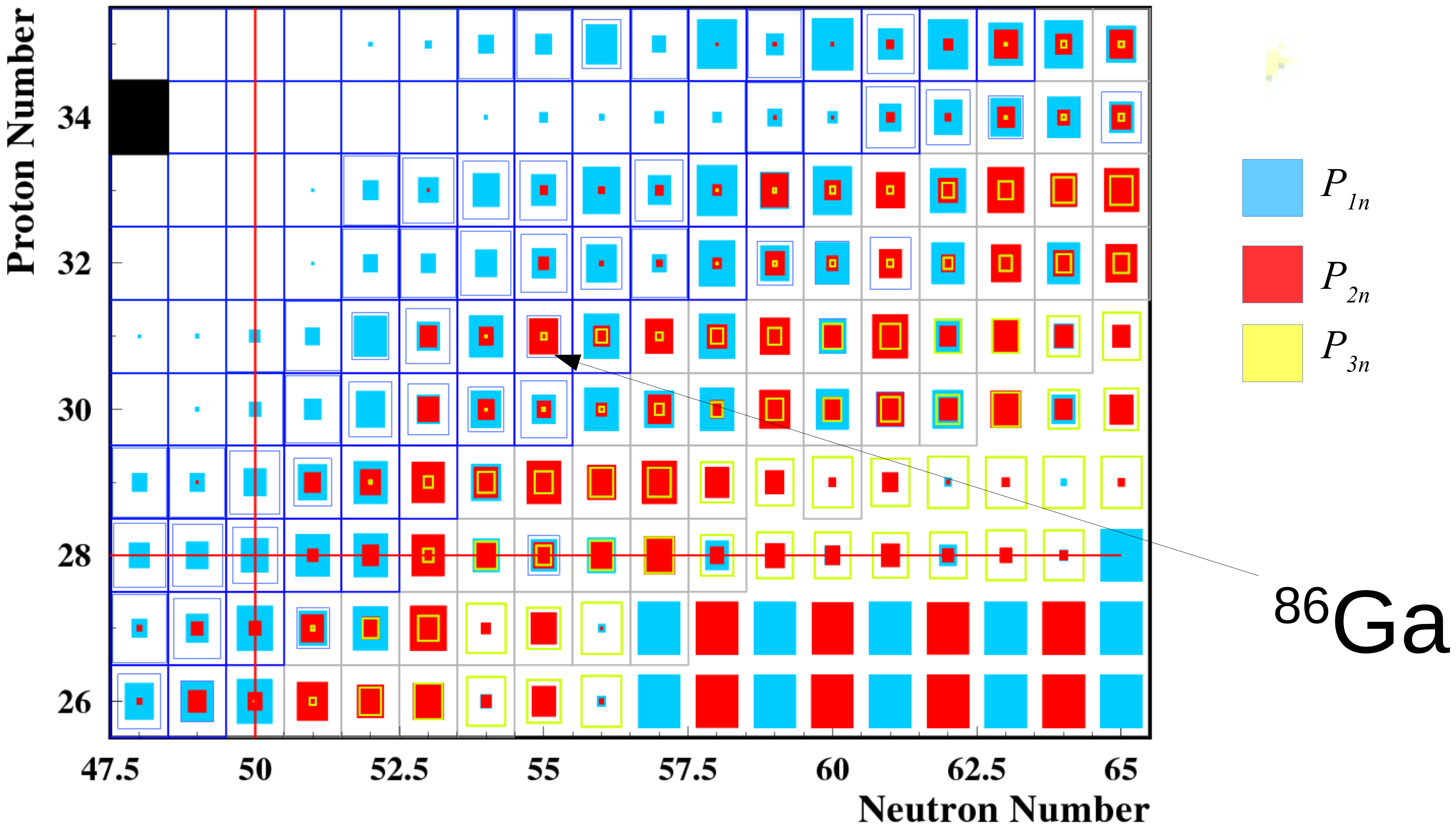


345 MeV/nucleon 238U beam
3.87-mm-thick Be target.
56.6 pnA



New isotope search conducted concurrently with BRIKEN campaign
Y. Shimizu, N. Fukuda, K. P. Rykaczewski,R. K. Grzywacz, J. L. Tain, I. Dillmann,
S. Nishimura, H. Takeda, H. Suzuki, D. S. Ahn, N. Inabe, K. Yoshida, H. Ueno, N. T. Brewer,
B. C. Rasco, D. W. Stracener, and J. M. Allmond, for the BRIKEN collaboration
2018 RIKEN Accel. Prog. Rep..

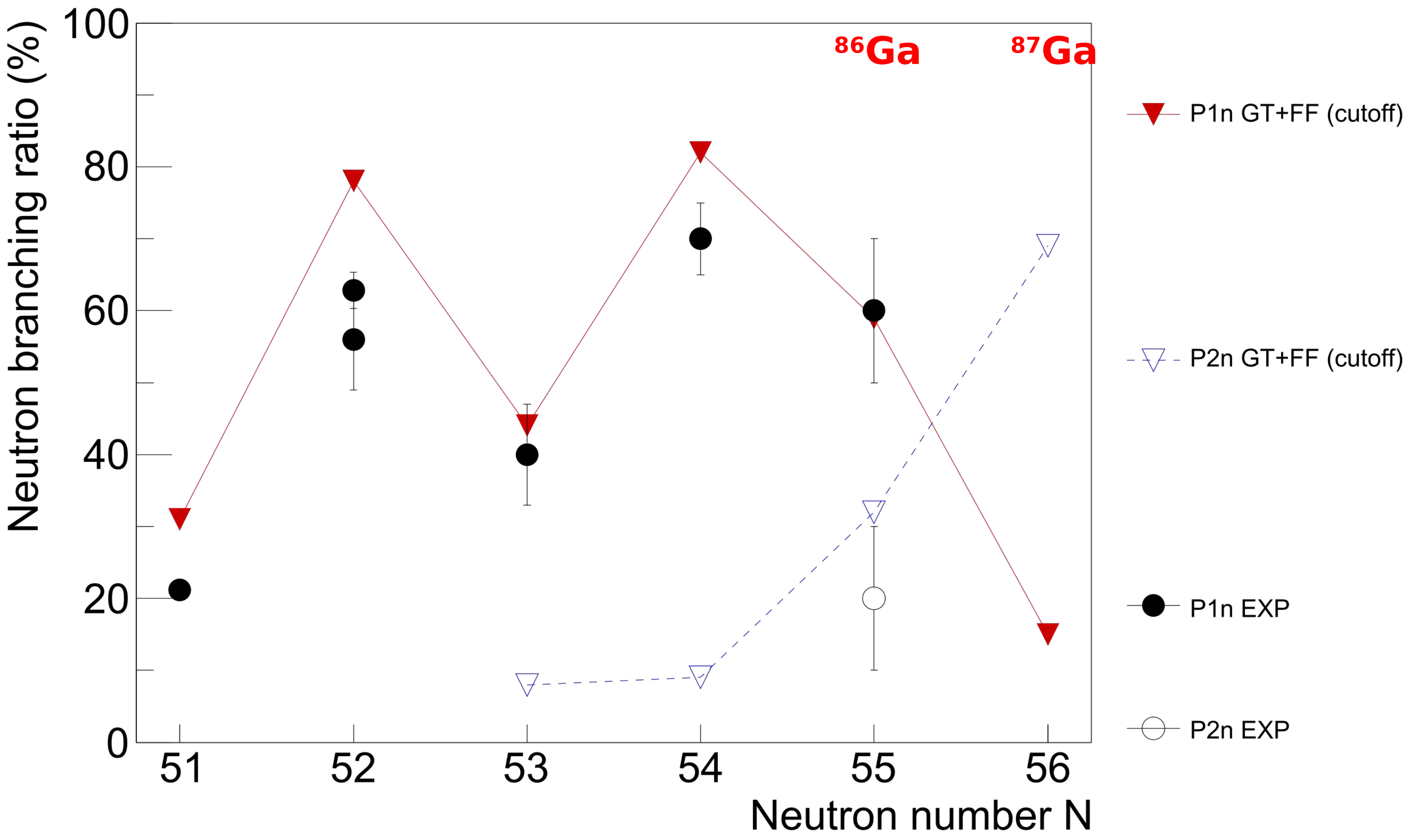
P_{xn} near ^{78}Ni...



P. Moeller, B. Pfeier, and K.-L. Kratz, Physical Review C 67, 055802 (2003).

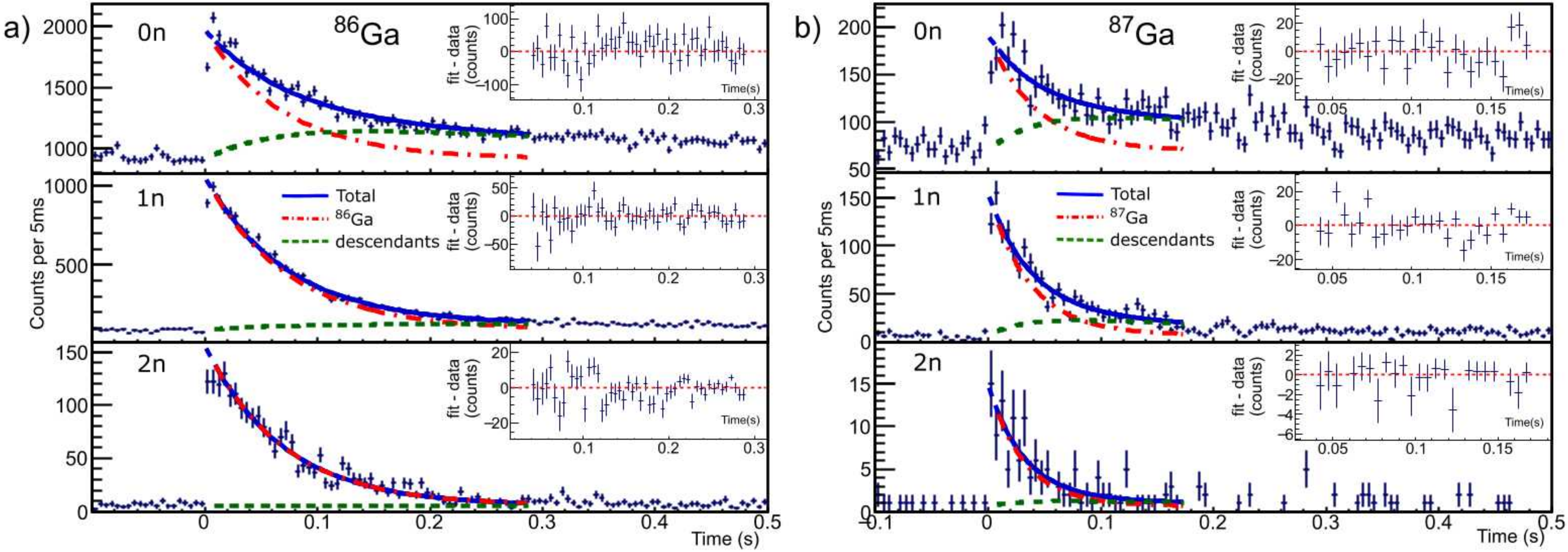
Experiment and shell-model + cut-off
Expected strong β2n emission in ^{87}Ga

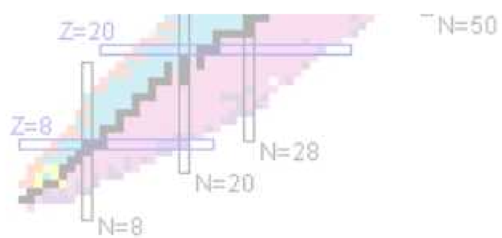
Z=31



M. Madurga et al. PRL 117, 092502 (2016)
K. Miernik et al. PRL 111 (2013) 132502
K. Miernik et al. Phys. Rev. C (2018)

The P_{1n} and P_{2n} extracted from the data

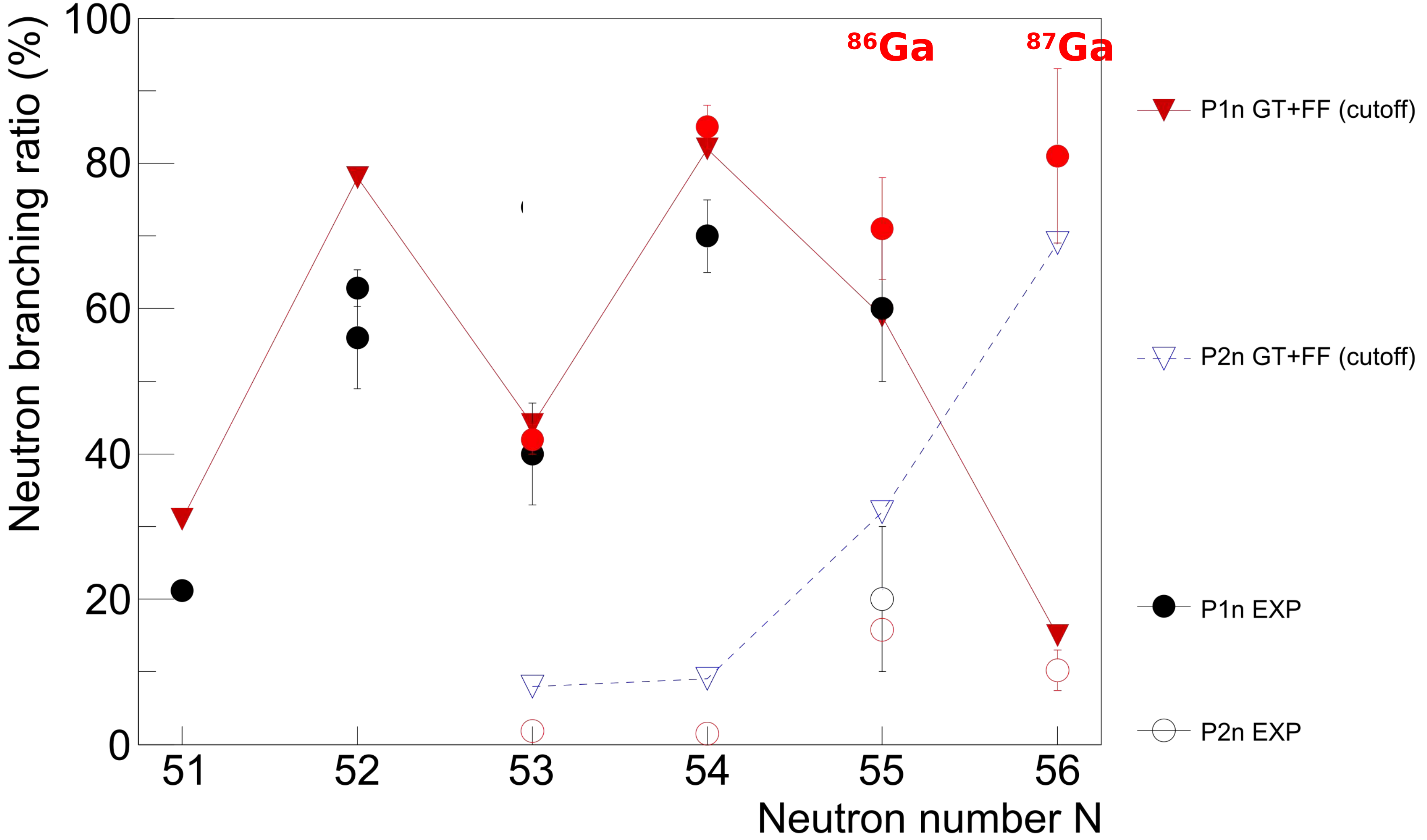




R. Yokoyama et al. Phys. Rev. C 100, (2019) 031302(R)
B. C. Rasco *et al*. NIM A ***911***, 79 (2018)

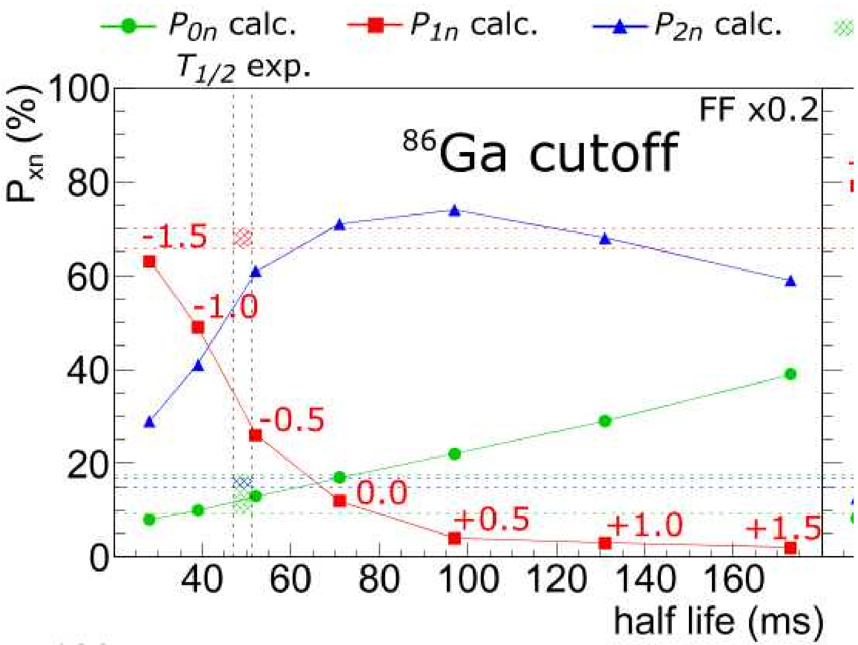
Experiment reveals β1n dominant in the decay of ^{87}Ga

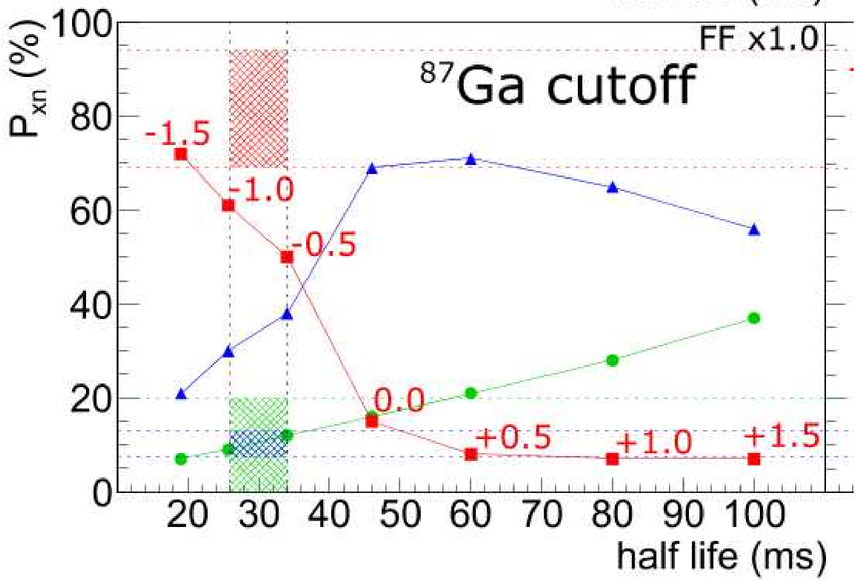
Z=31

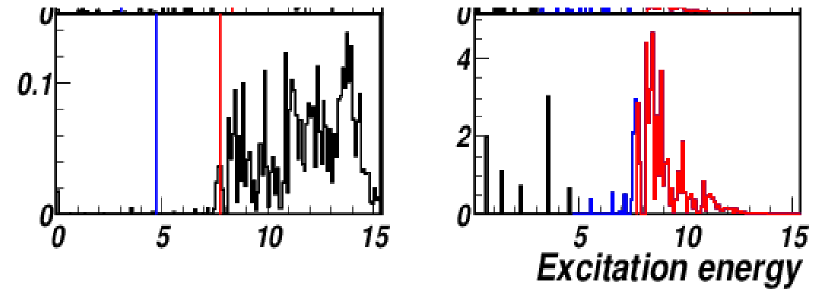


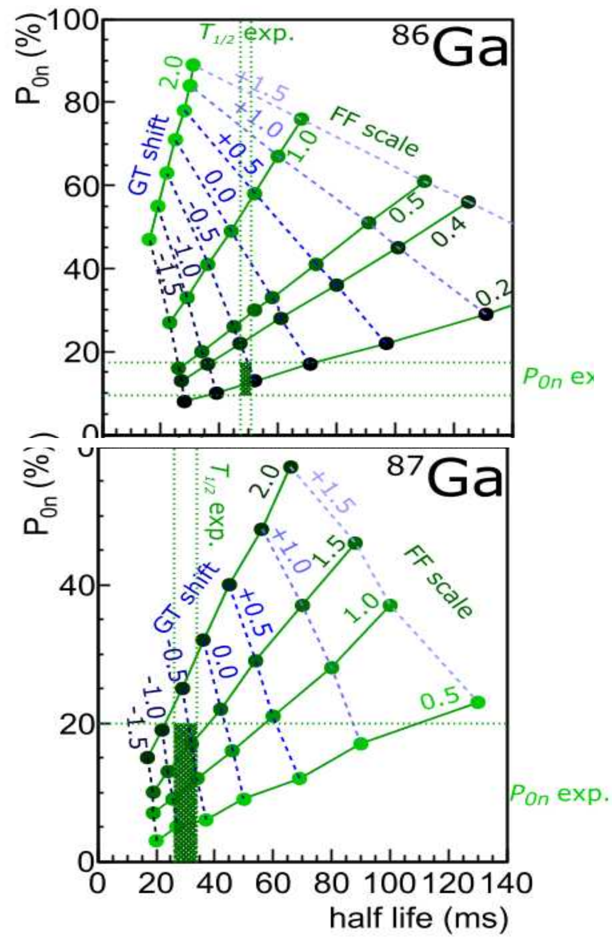
Cut off model cannot reproduce new results.

The P_{0n},P_{1n} and P_{2n} for ^{86,87}Ga cannot be reproduced by the SM (cut off)



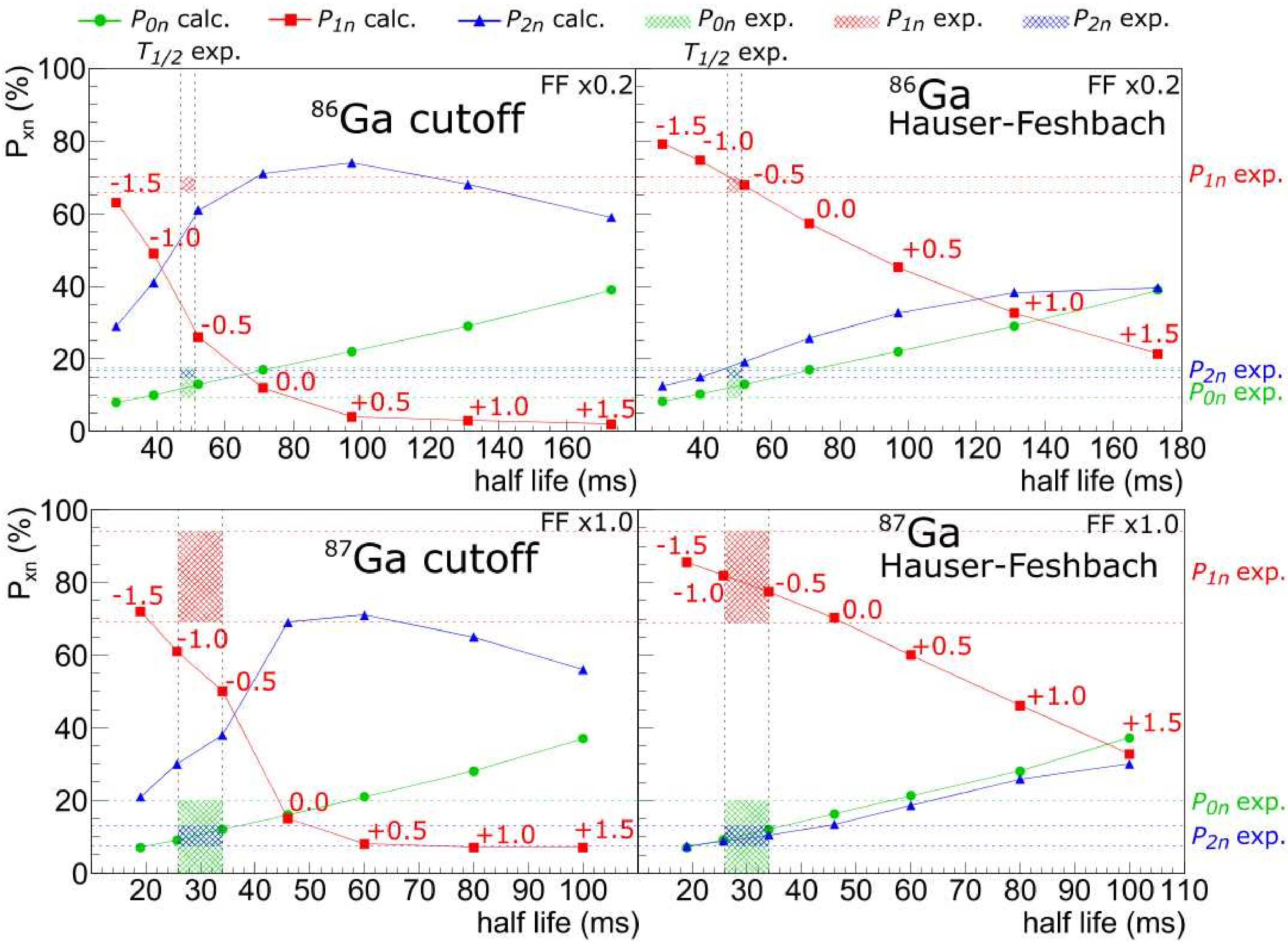






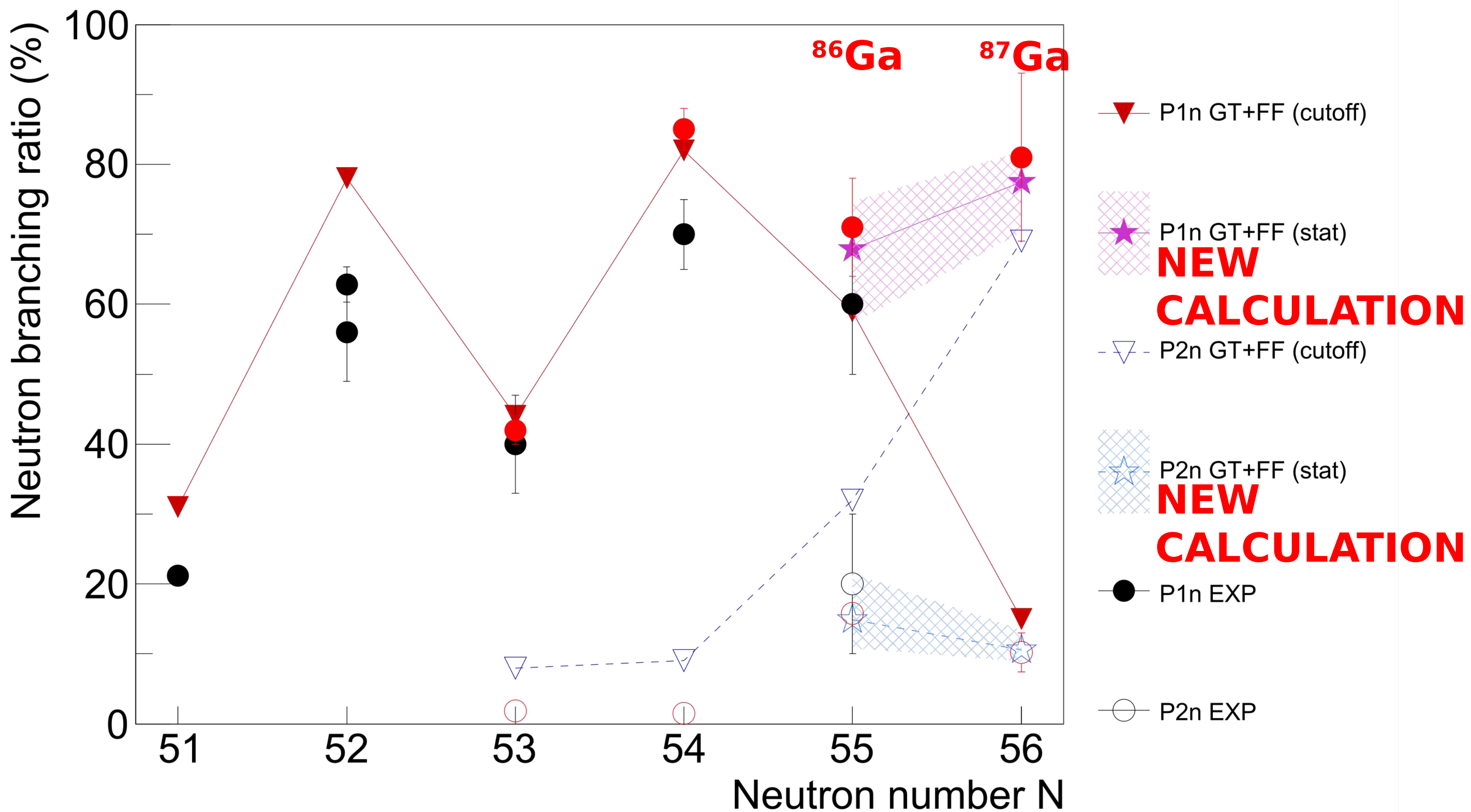
The necessity to use HF

coh/beoh code (Kawano with Koning Delaroche optical model)



Shell-model + statistical model

Z=31

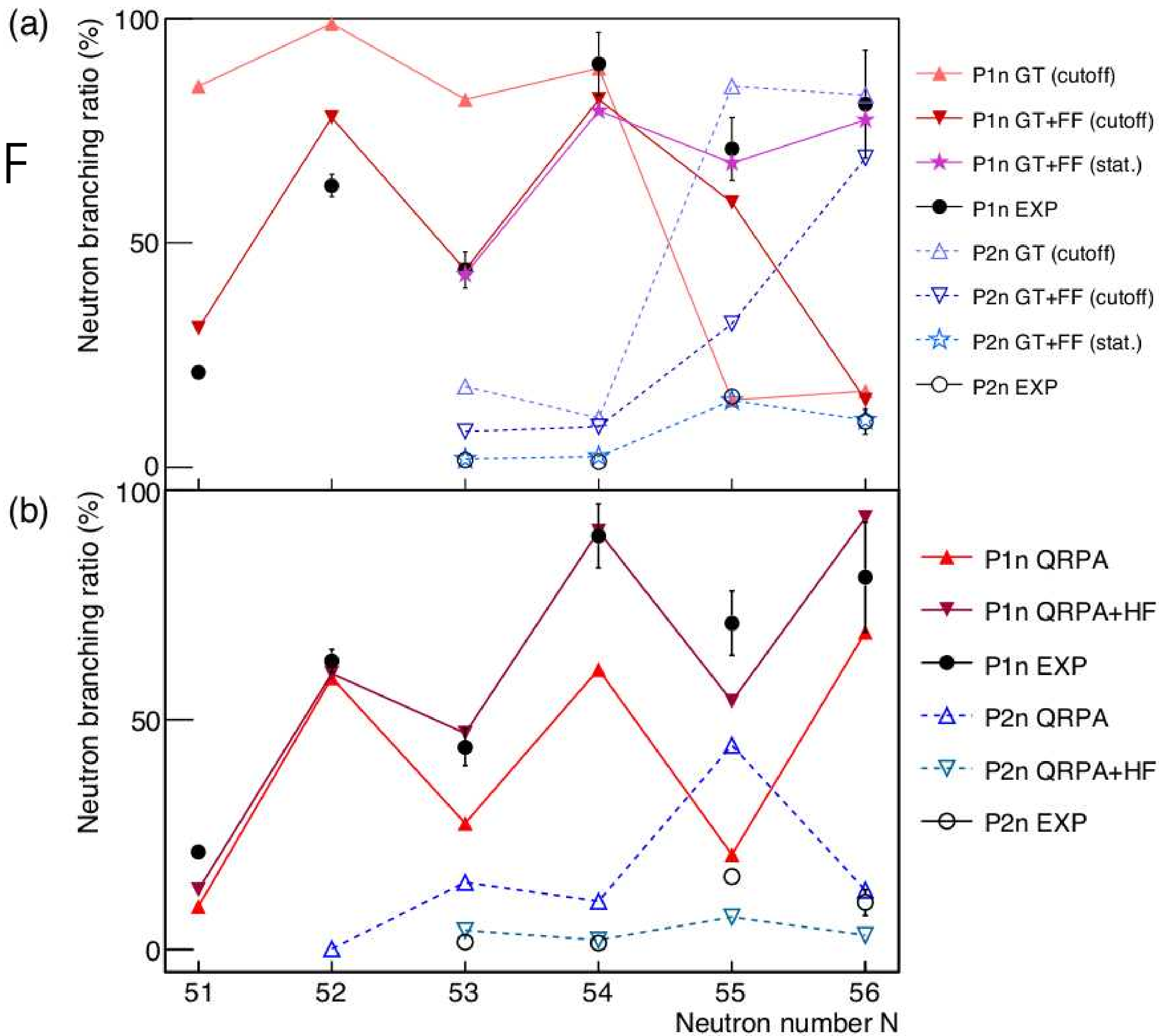


Shell-model/QRPA + statistical model (HF)

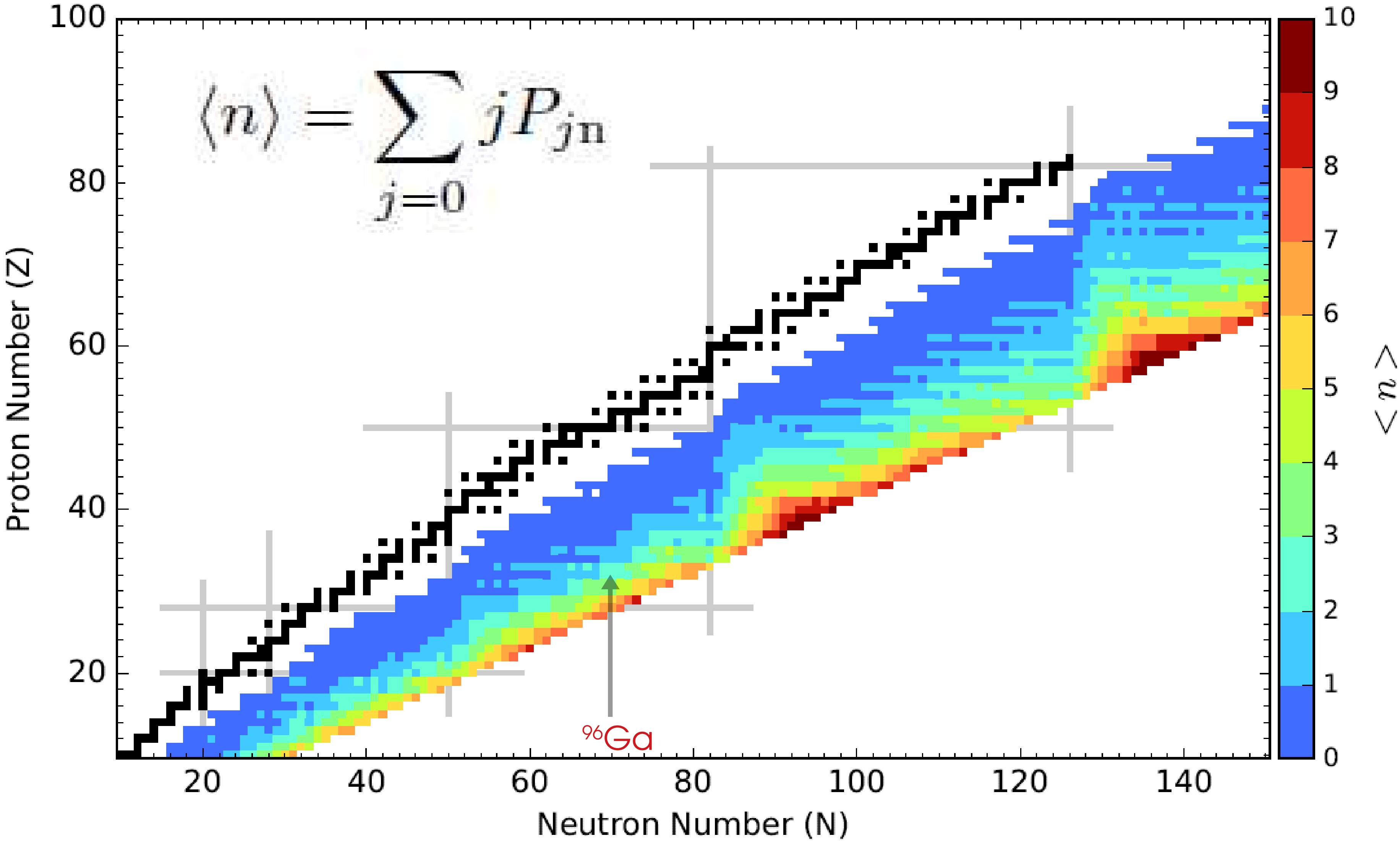
Shell-model B(GT) +HF

QRPA B(GT) +HF

P. Möller, M. R. Mumpower, T. Kawano, and W. D. Myers, Atomic Data and Nuclear Data Tables 125, 1 (2019),

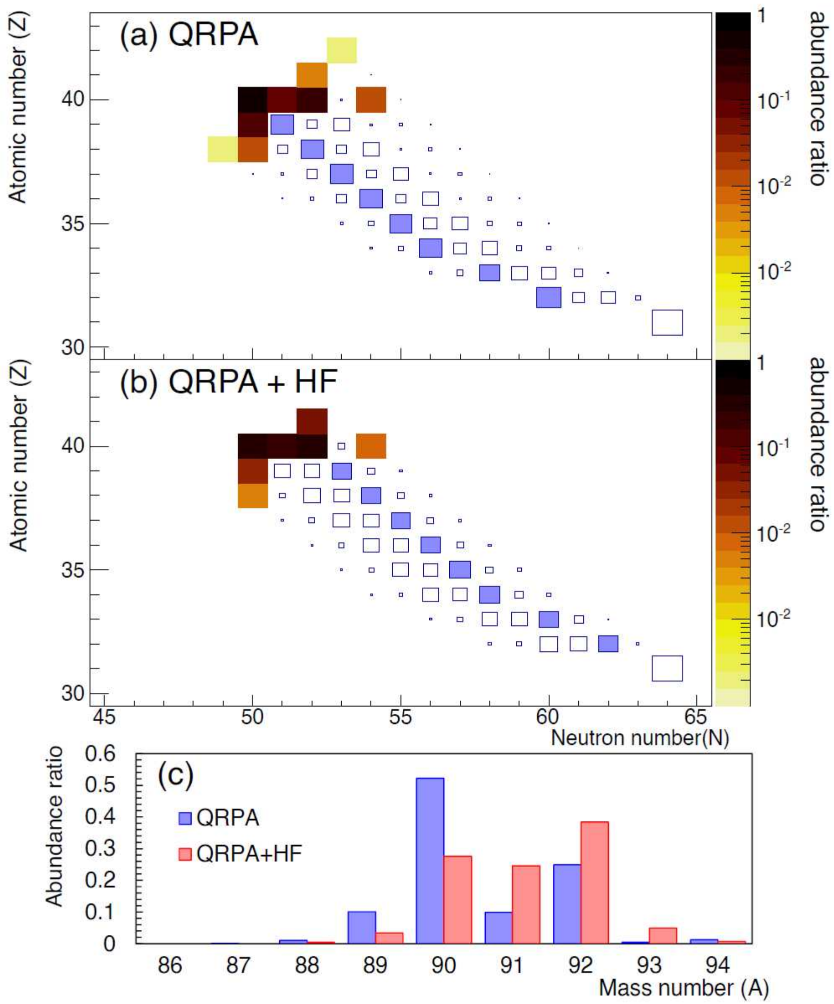


Beta-delayed neutrons and Hauser-Feshbach (QRPA)



M. R. Mumpower, T. Kawano, and P. Möller, Physical Review C 94, 064317 (2016)
P. Möller, M. R. Mumpower, T. Kawano, and W. D. Myers,
Atomic Data and Nuclear Data Tables 125, 1 (2019),

r-process consequences - decay of ^{96}Ga

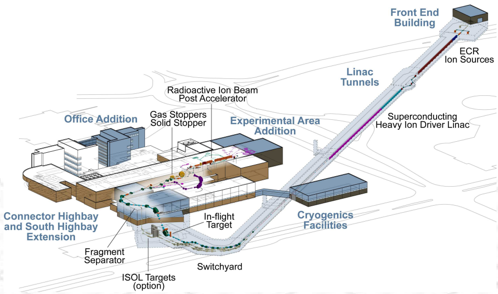


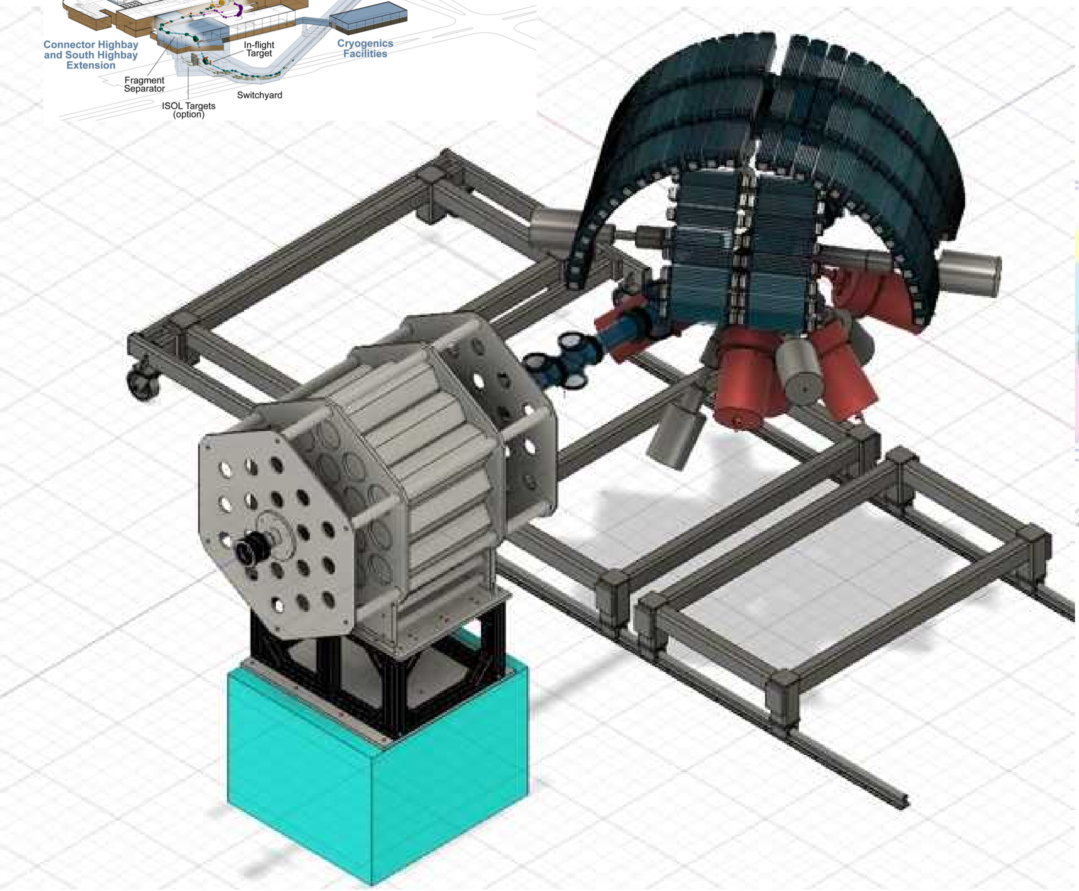
Cut off model

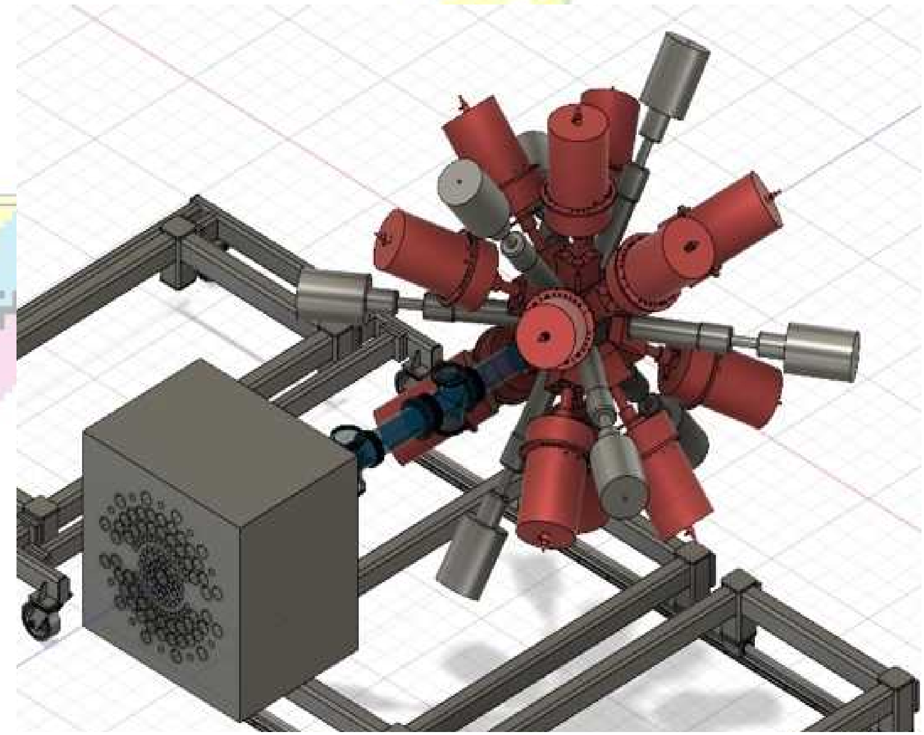
Statistical model

The decay path shifts to higher A

FRIB Decay Station - complete spectroscopy



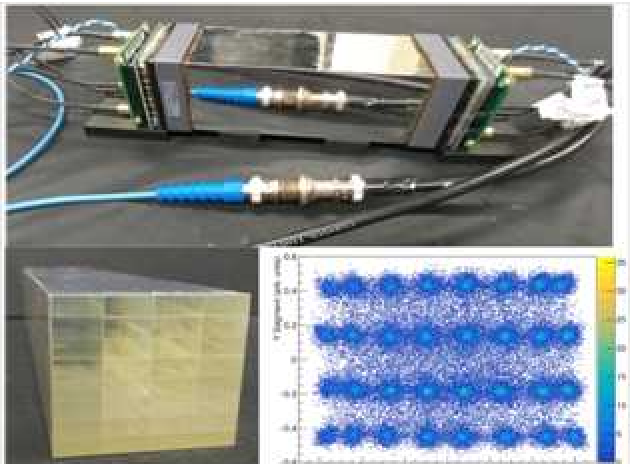


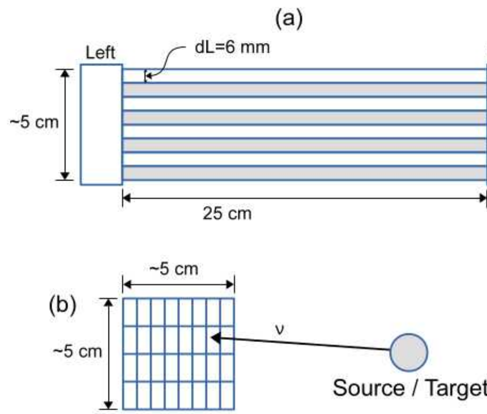


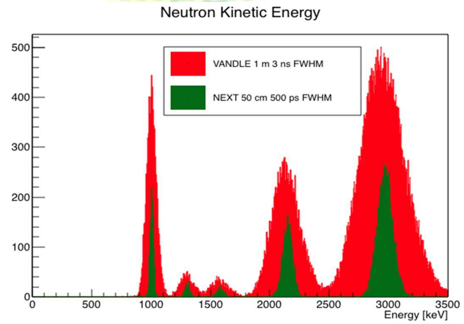
https://fds.phy.ornl.gov/FDS-WP.pdf

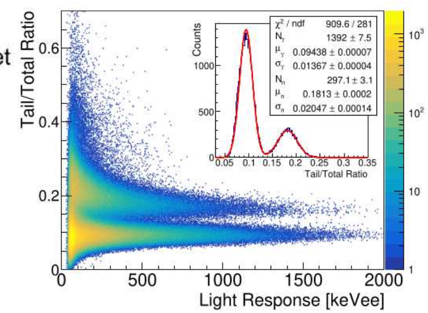
Where are we heading ... next ?

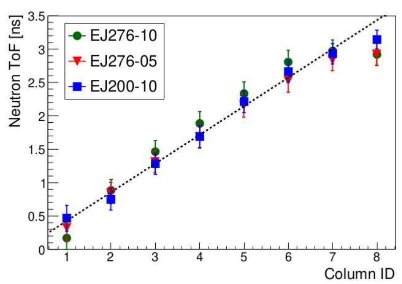
Precision neutron energy measurements with new Neutron dEtector with multi-neutron (Xn) Tracking (NEXT)











Conceptual design and first results for a neutron detector with interaction localization capabilities

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Summary

Neutron energy, P_{xn} and gamma-ray measurements (TAS and discrete) essential to establish true decay patterns and deduce strength distribution needed to constrain nuclear models.

Strong one-neutron emission from two-neutron unbound states in β-decays of r-process nuclei $^{86,87}Ga$.

Multi-neutron emission "pushed" further from stability for heavier nuclei.

The same mechanism (Gamow-Teller transformation) responsible for beta decay also hinders neutron emission:
GT-states in emitter do not overlapp with states in the daughter.

Neutron emission proceeds through "invisible" components of the wavefunctions and can be (functionally) desribed by statistical model (compound nucleus).

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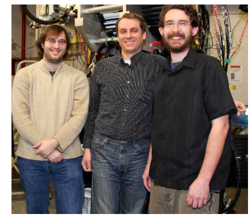

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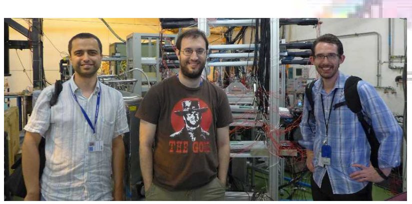

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