Beta-delayed neutron studies of the fission fragments

Robert Grzywacz, University of Tennessee and Oak Ridge National Laboratory

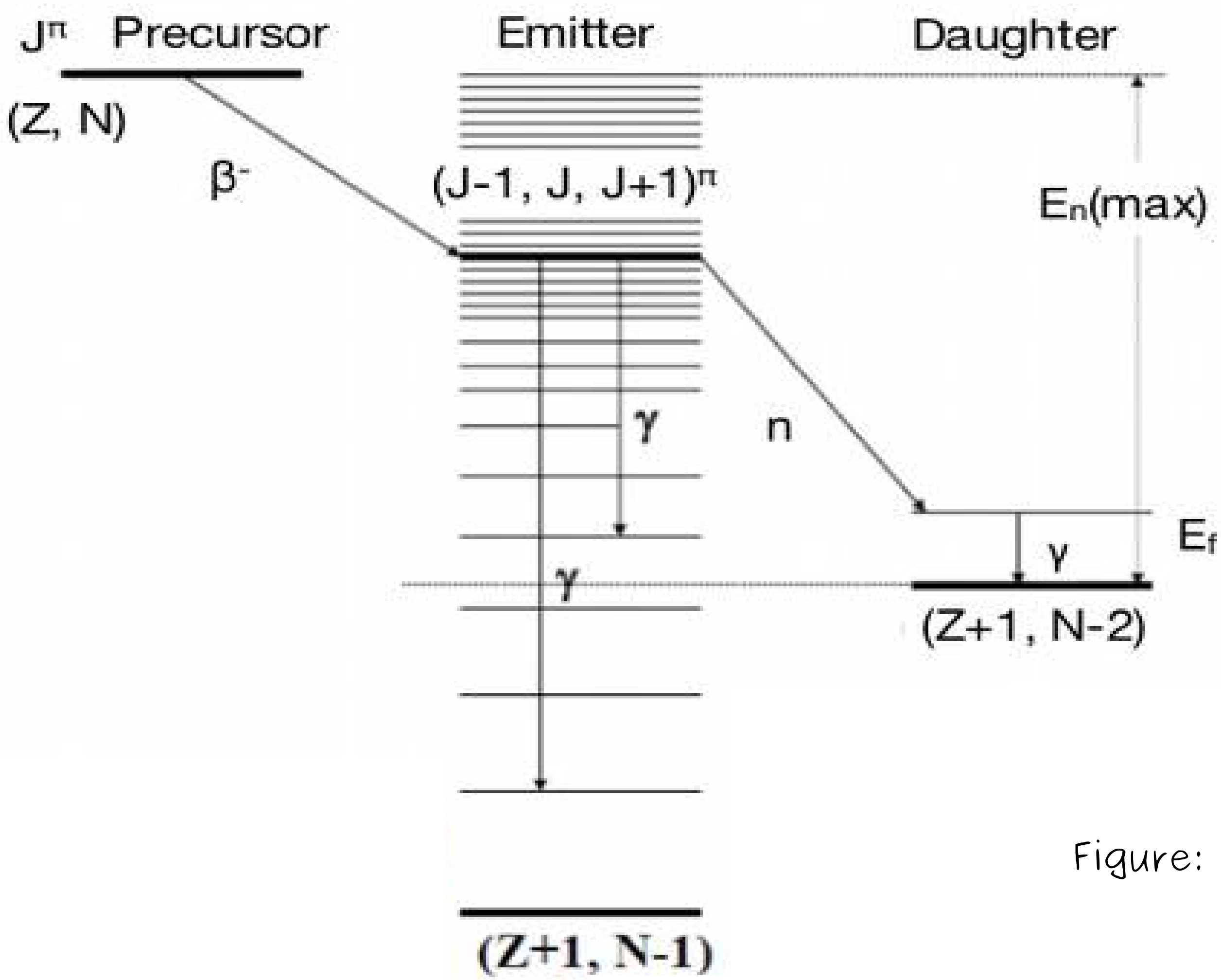
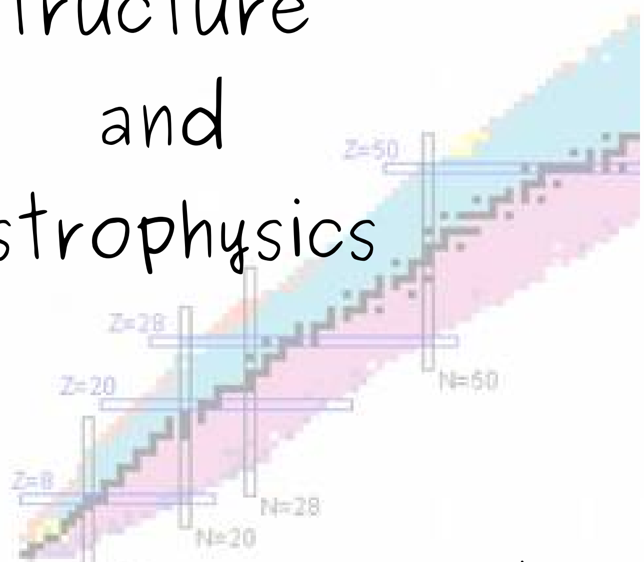


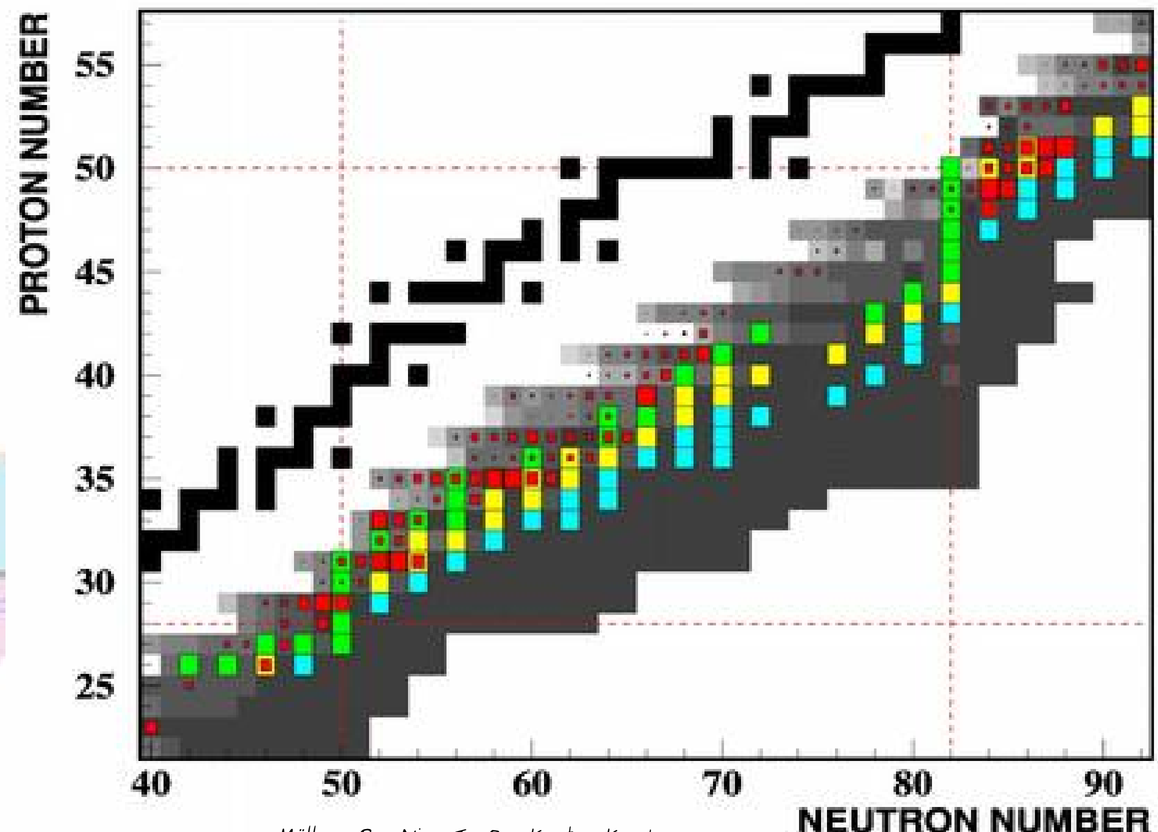
Figure: T. Kawano

βn-emission from exotic heavy nuclei
The uncharted territory

Most of the neutron rich isotopes
and all r-process nuclei
are bn-emitters

structure
and
astrophysics





Möller, P.; Nix, J. R.; Kratz, K.-L.
Atomic Data and Nuclear Data Tables, Vol. 66, p.131 (1997)

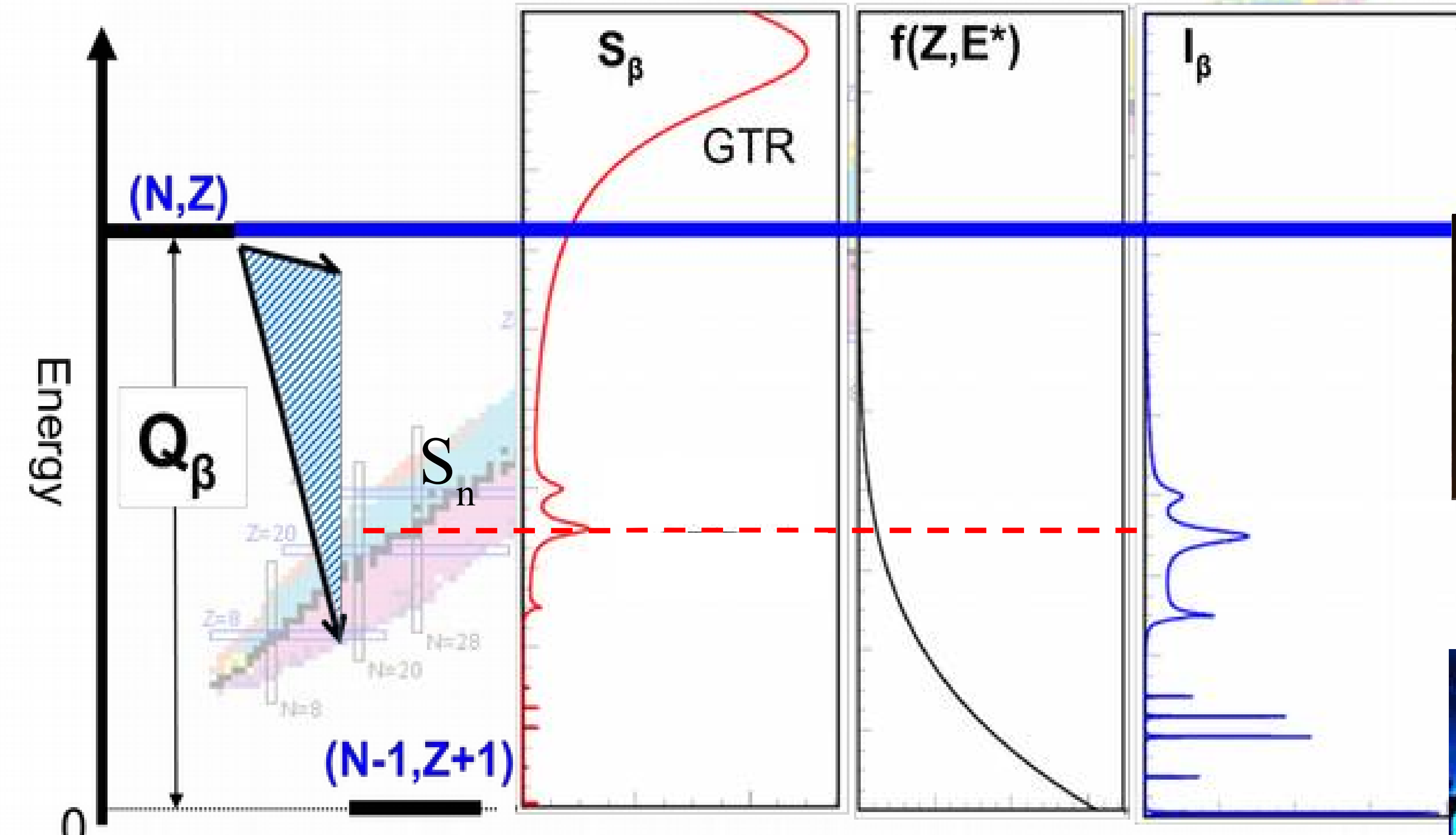
Pn exp (NNDC)

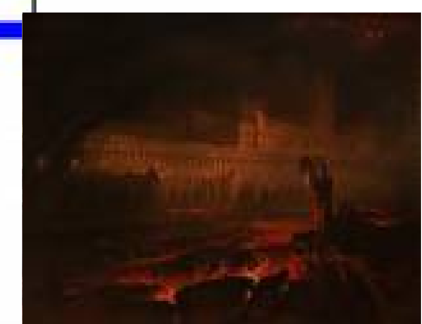
Heavy βn-emitters are poorly studied due to limited accessibility, difficulty in detection of neutrons and complexity of data interpretation. New facilities and new capabilities.

Decay strength distribution lifetimes and branching ratios

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

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





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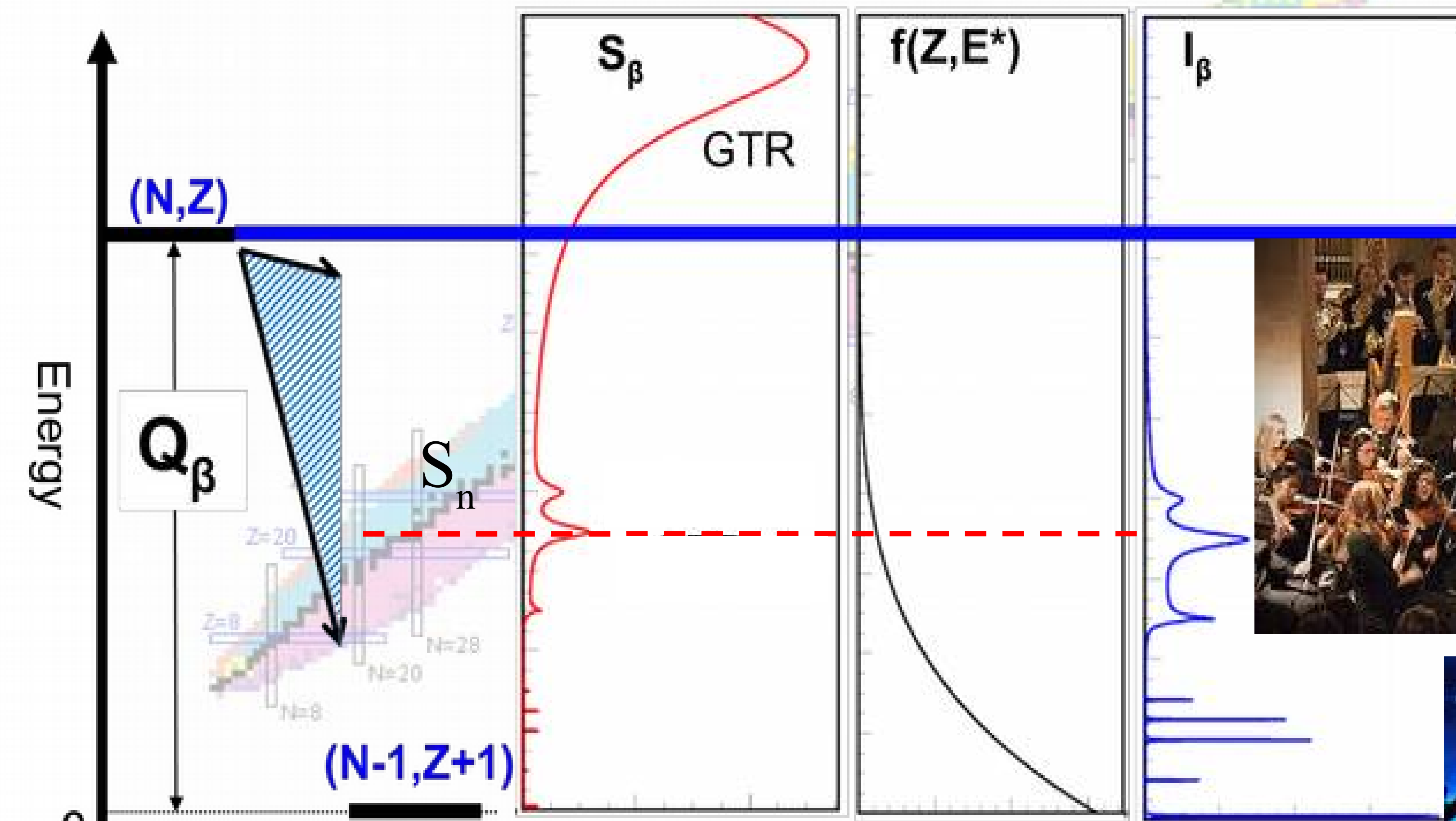

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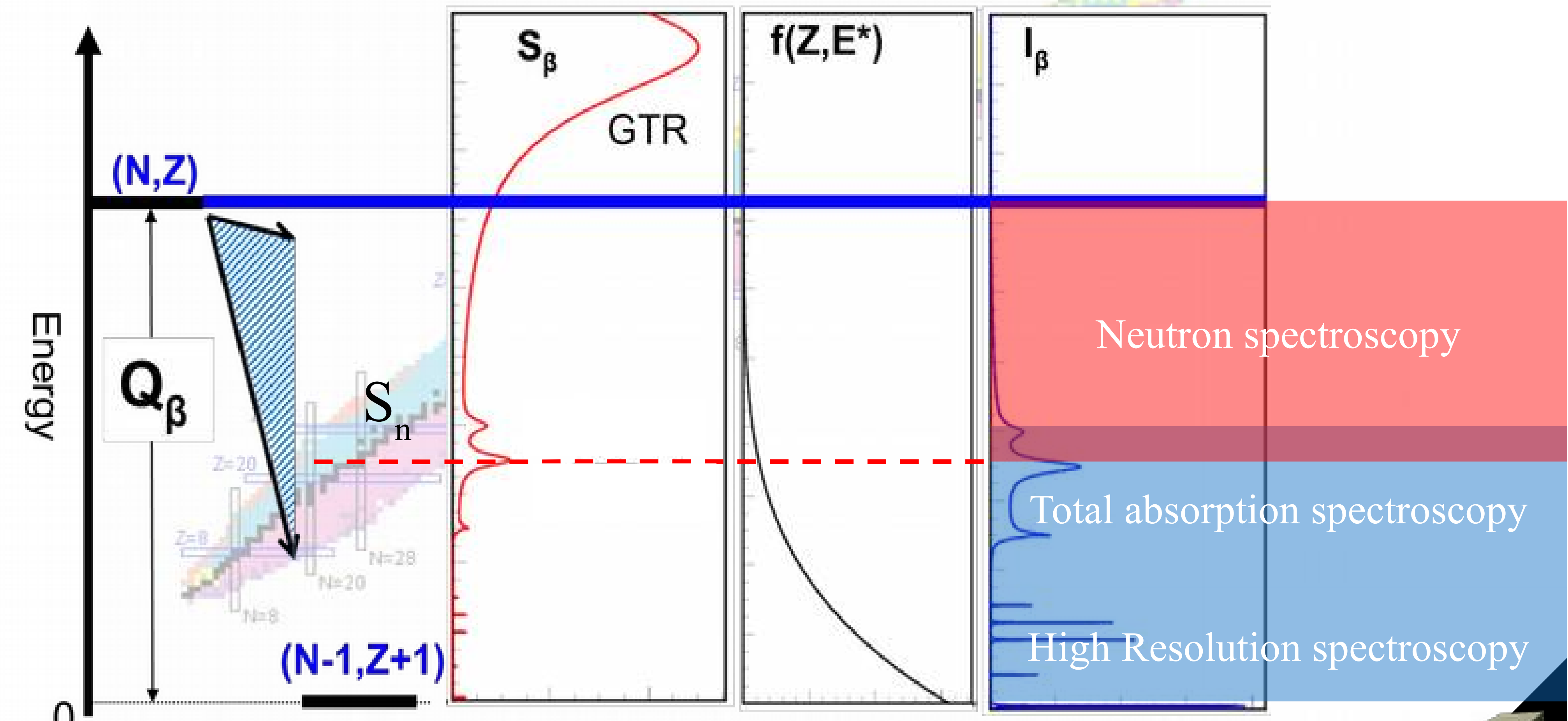
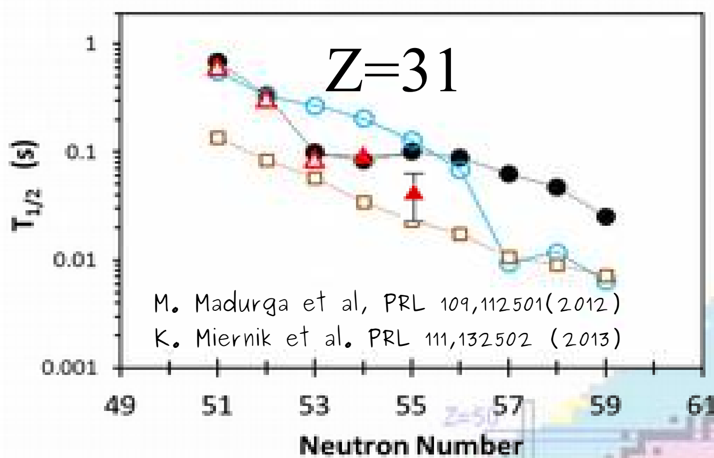


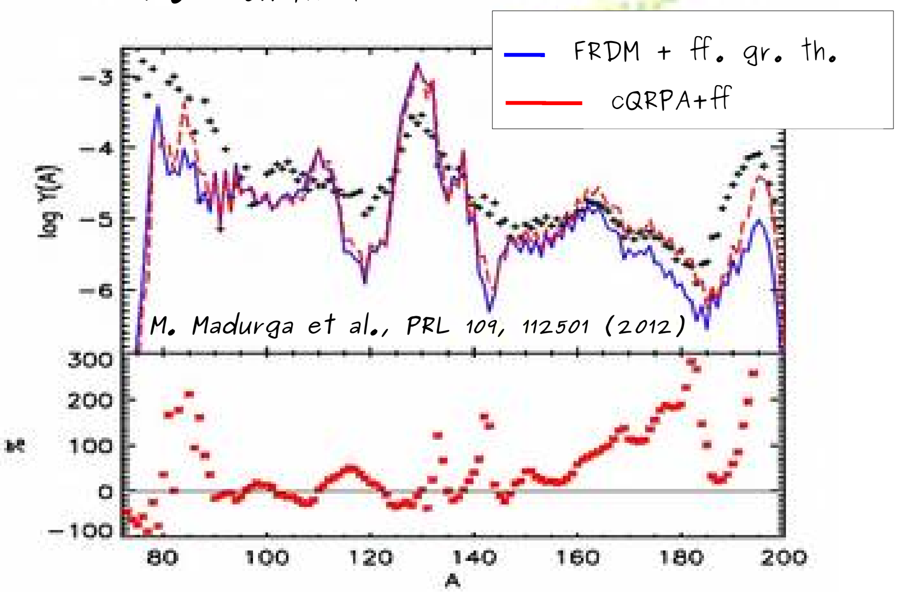
Lifetime and β-delayed neutron emission sensitivities for a (cold) r-process

cold r-process: equilibrium between (n,γ) and β decay

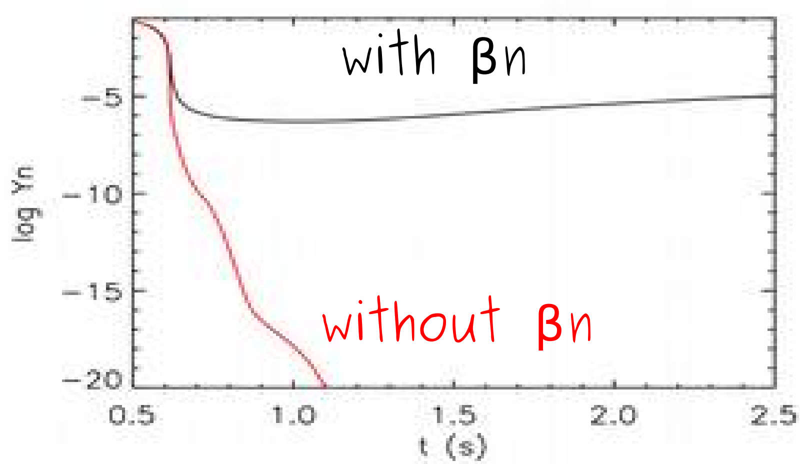
Lifetime sensitivity

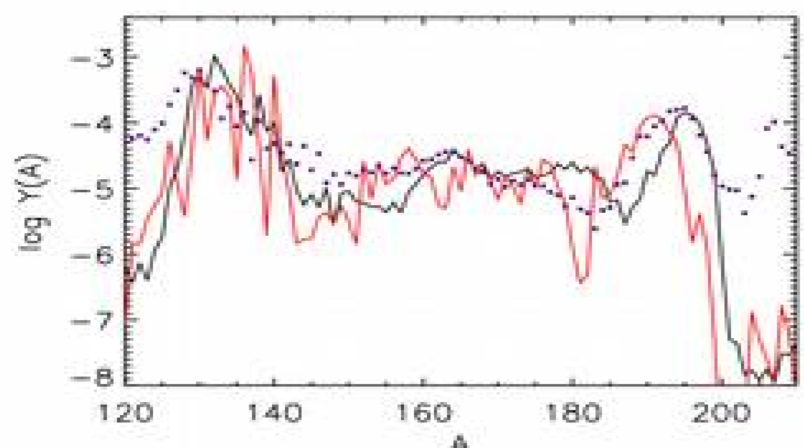


R. Surman



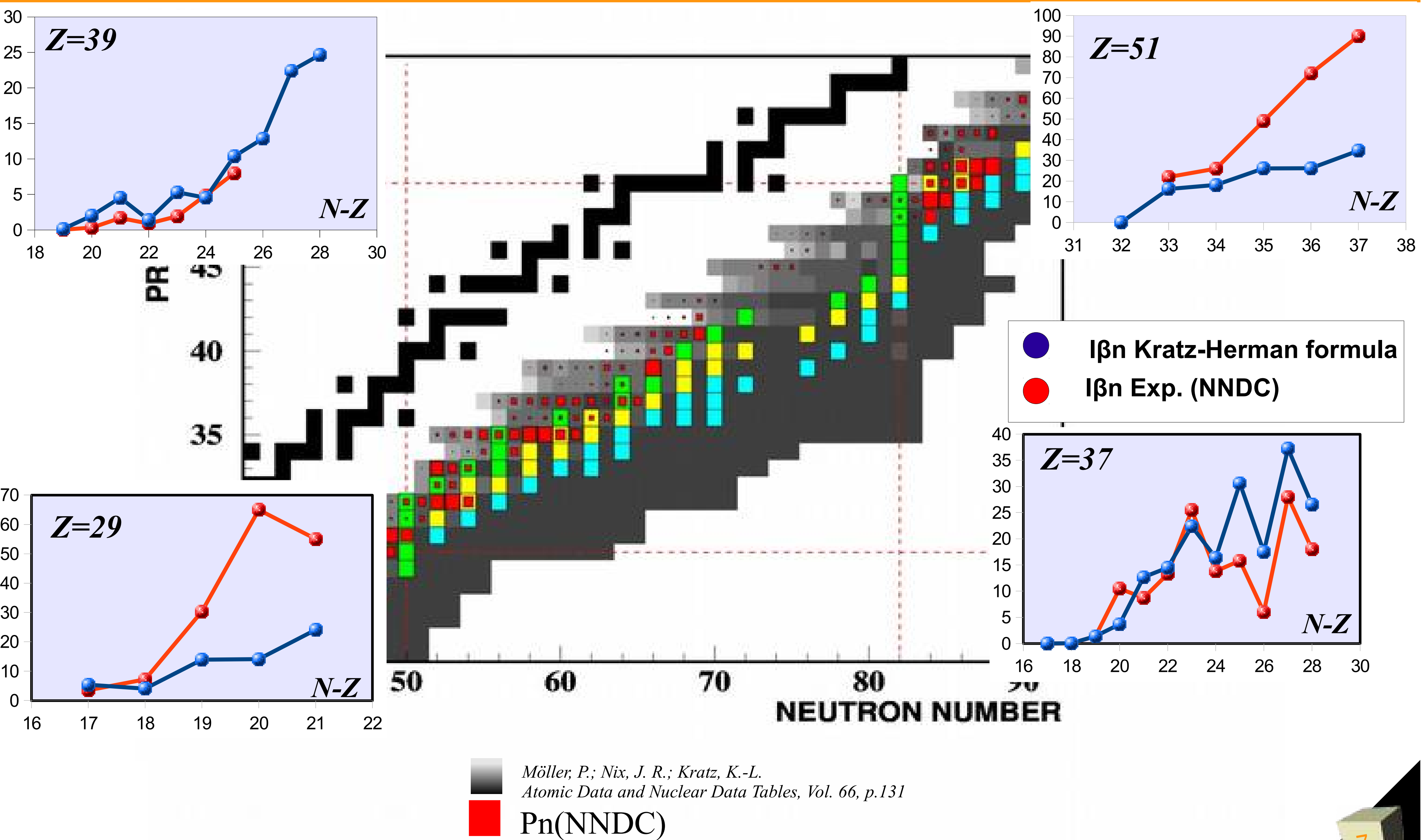
Neutron branching ratio sensitivity



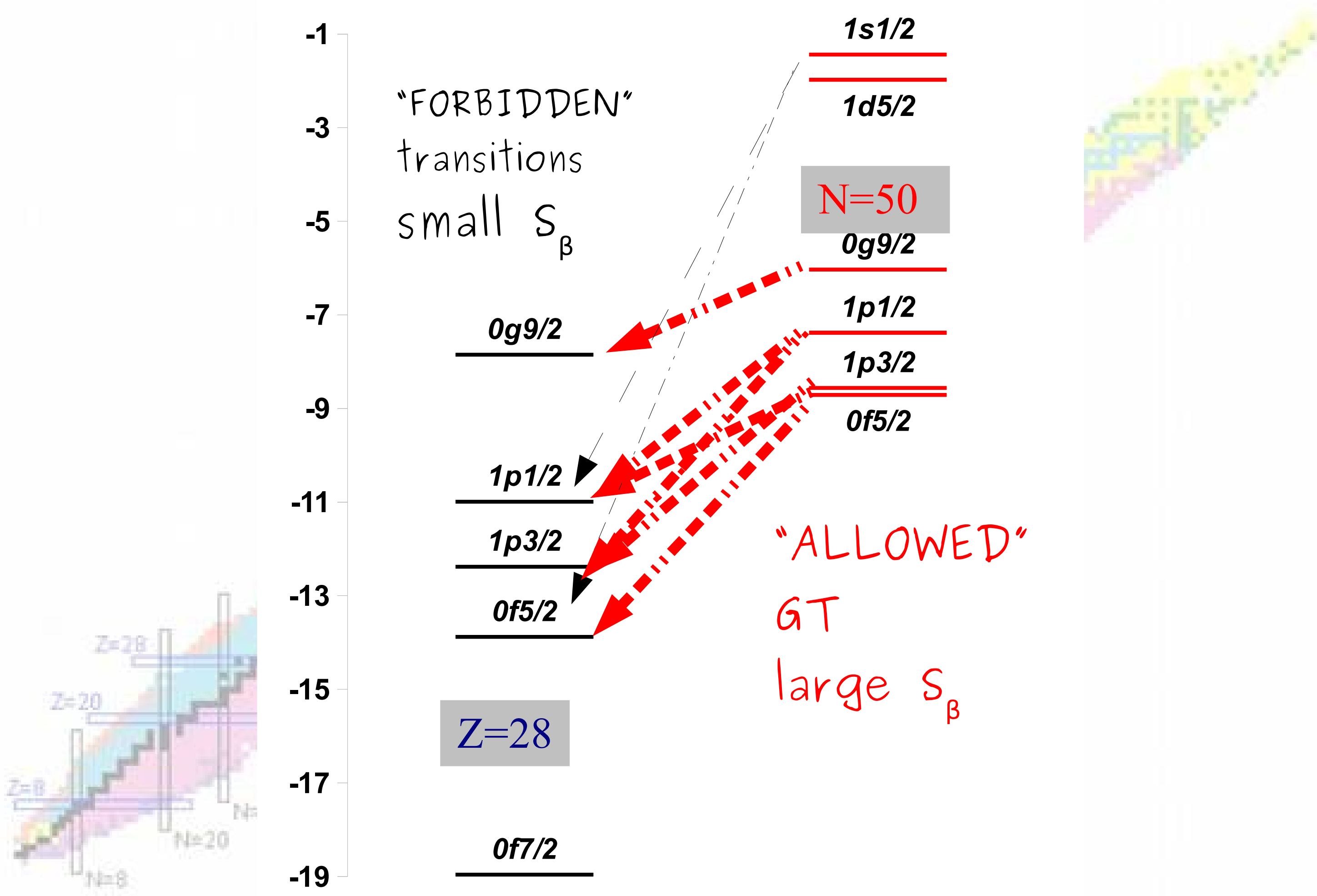


R. Surman et al., arXiv:1309.0059 [nucl-th](2013)

Neutron branching ratios from global formulas
Kratz - Herrmann formula ("average nucleus")



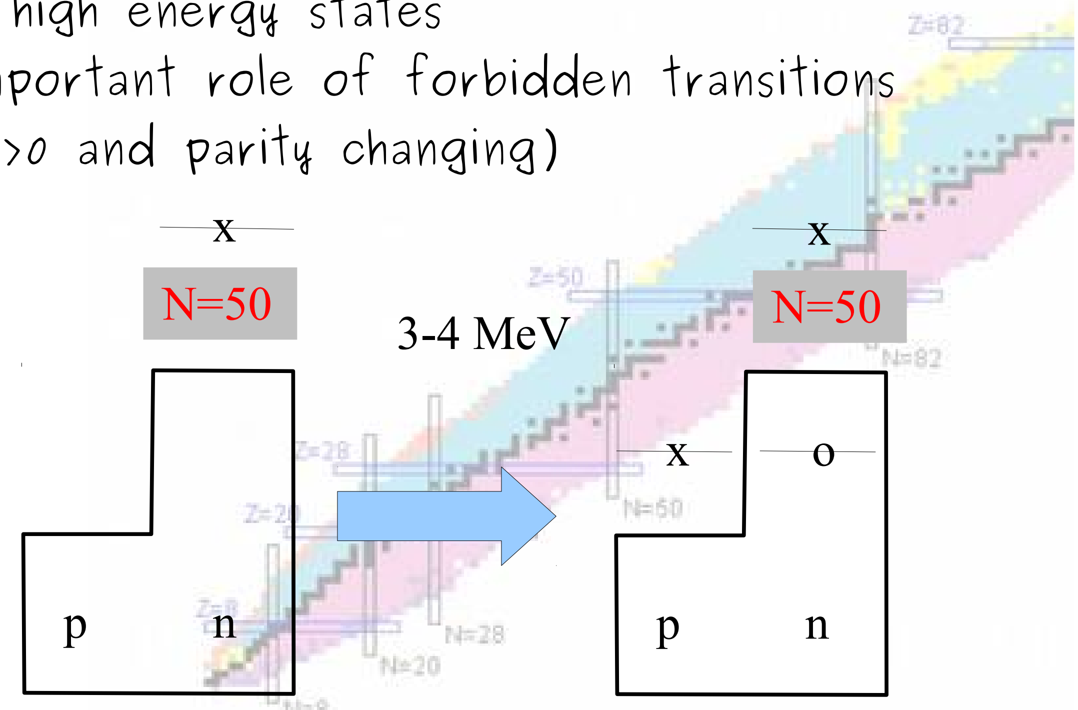
Single particle model of decays near ^{78}Ni

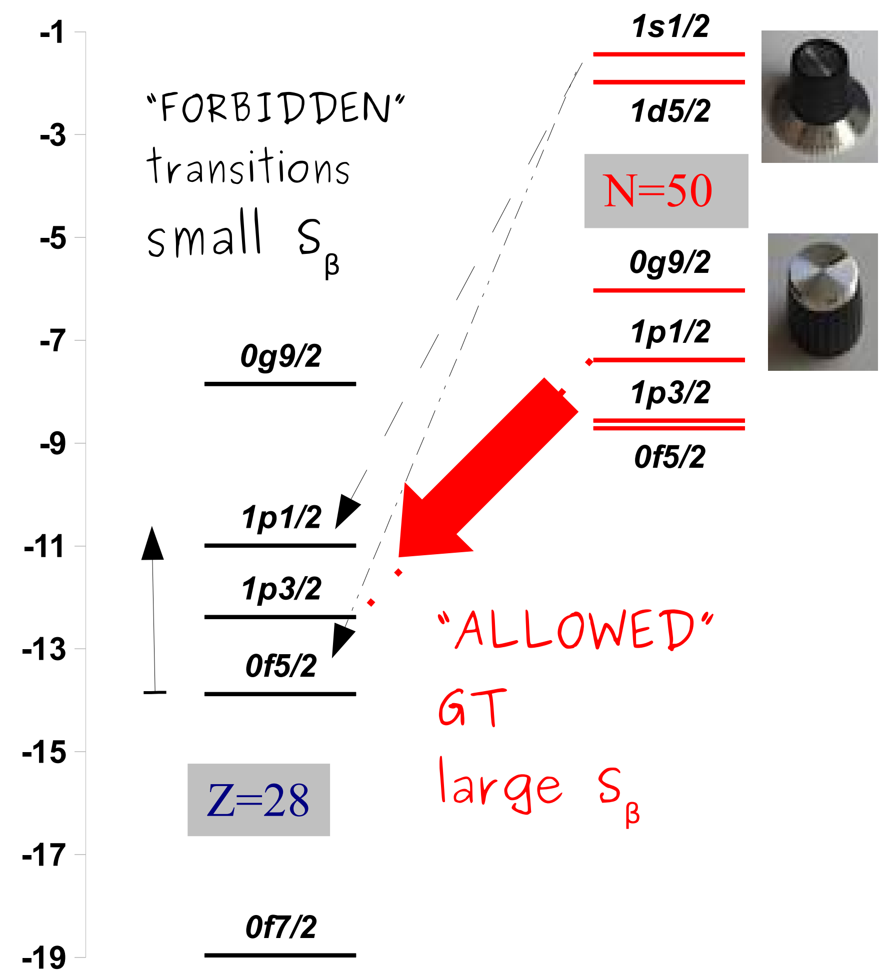


Single particle model of decays near ^{78}Ni for N>50

Single particle description:

- "Valence" nucleons cannot decay via allowed Gamow–Teller transitions between spin orbit partners
- Particle–hole excitations lead to population of high energy states
- Important role of forbidden transitions ($\Delta l > 0$ and parity changing)





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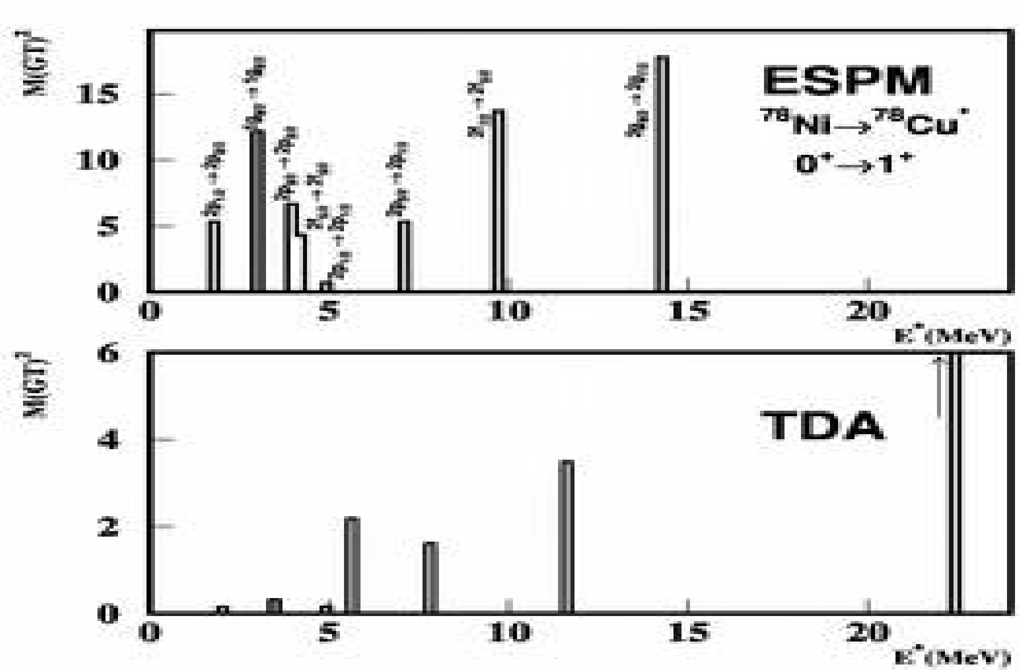
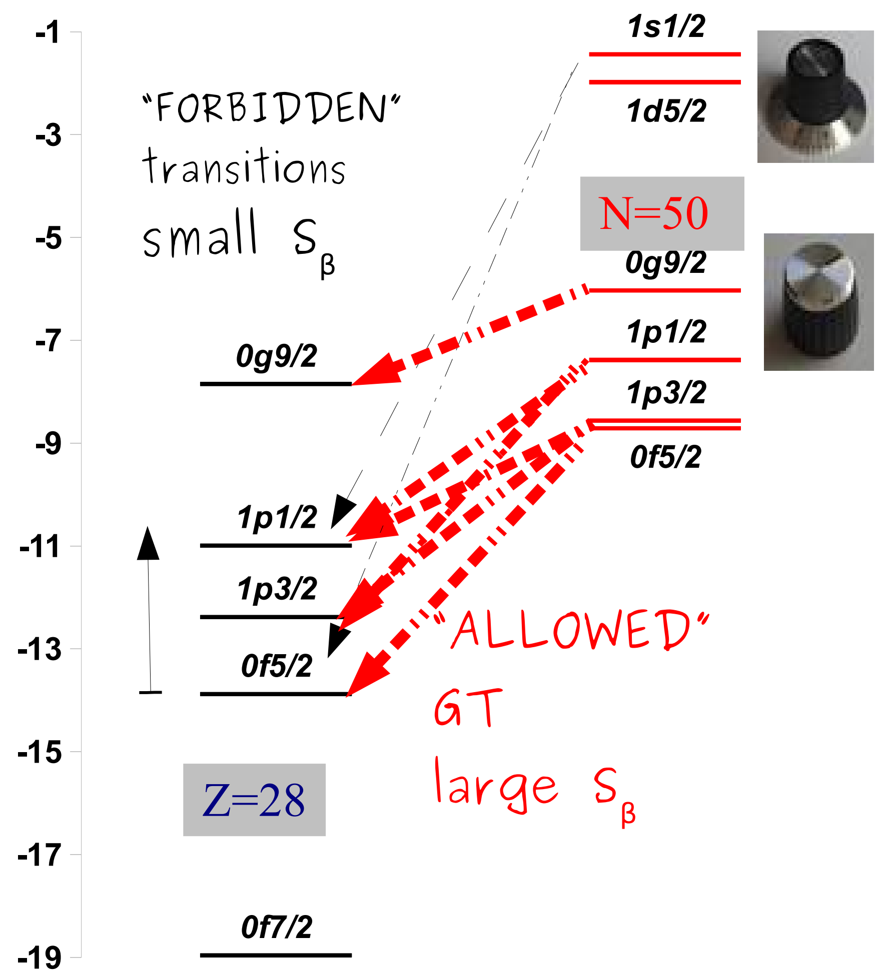


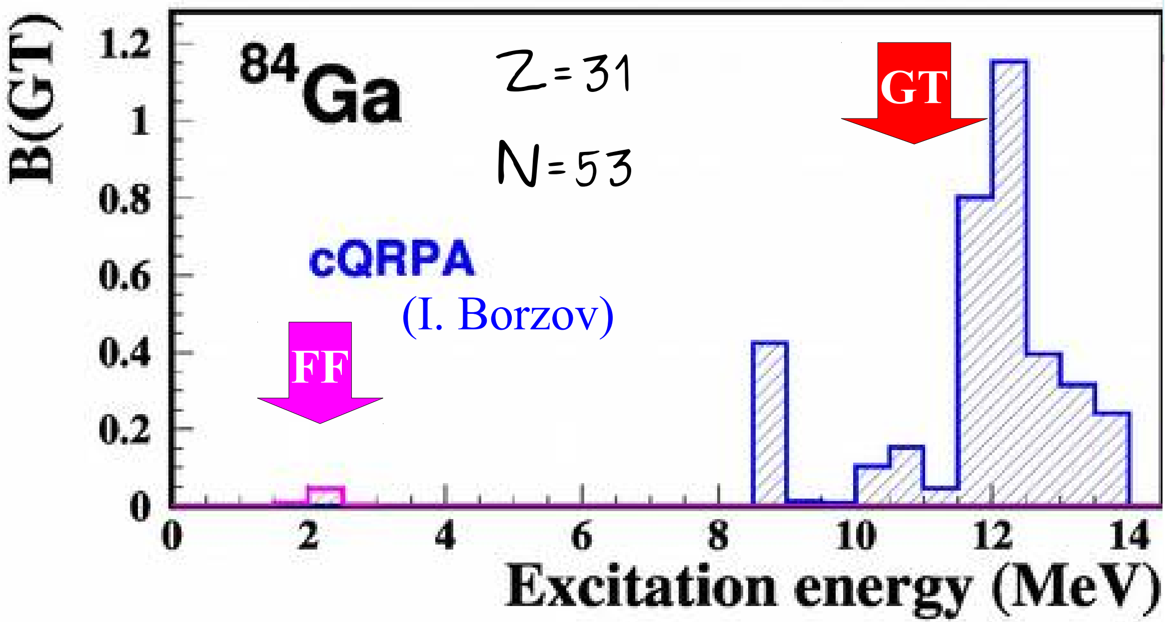


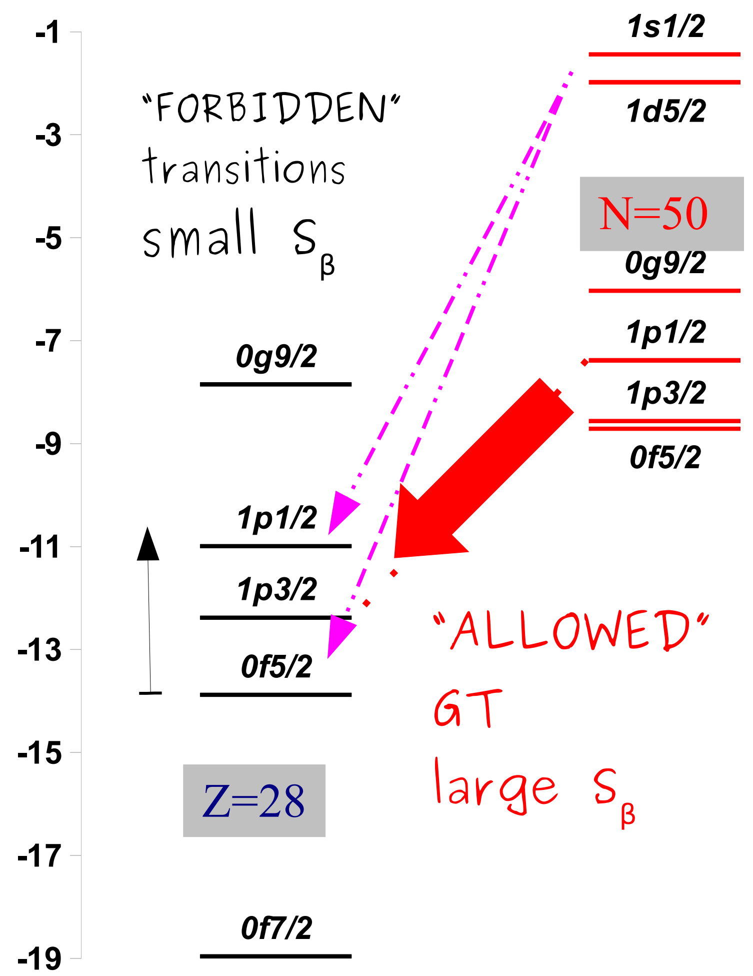
$$B_{GT} = |M_{GT}|^2 = N_\nu \cdot \left(1 - \frac{N_\pi}{2j_f+1}\right) \cdot |M^0_{GT}|^2$$

Beta decay of neutron rich nuclei beyond N=50

Single particle description:

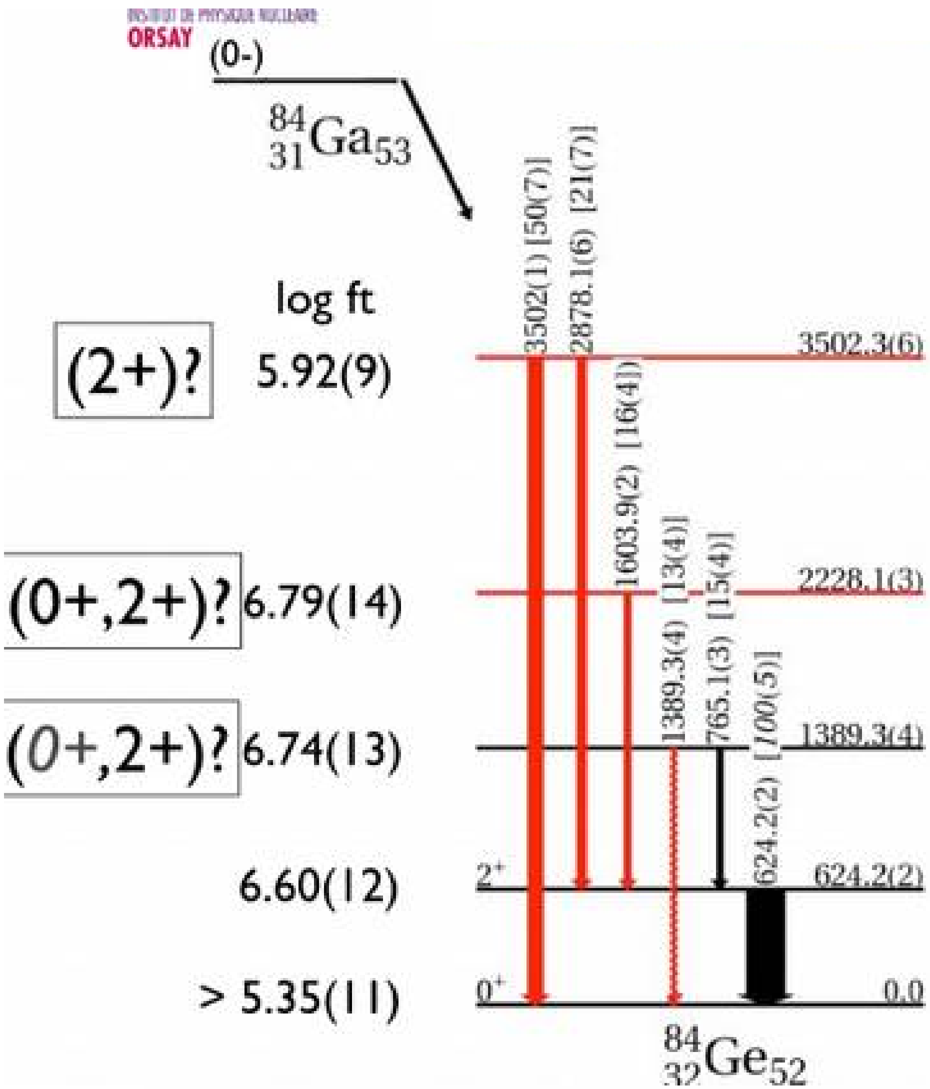
- "Valence" nucleons cannot decay via allowed Gamow–Teller transitions between spin orbit partners
- Particle–hole excitations lead to population of high energy states



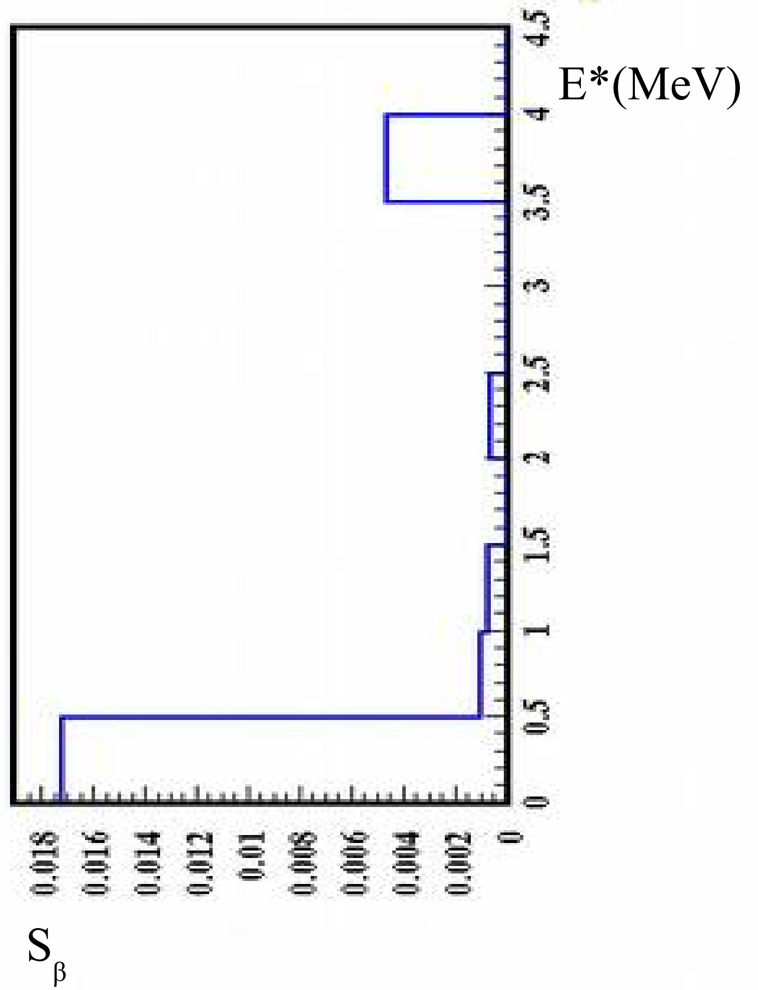


Forbidden and allowed transitions separated in energy scales (and decay modes).

Forbidden decay of 84Ga



(K. Kolos et al. Phys. Rev. C)



VANDLE – neutron time of flight and γ-ray detector

The Versatile Array of Neutron Detectors at Low Energy

Funding: Center of Excellence for Radioactive Ion Beam Studies for Stewardship Science – DOE NNSA

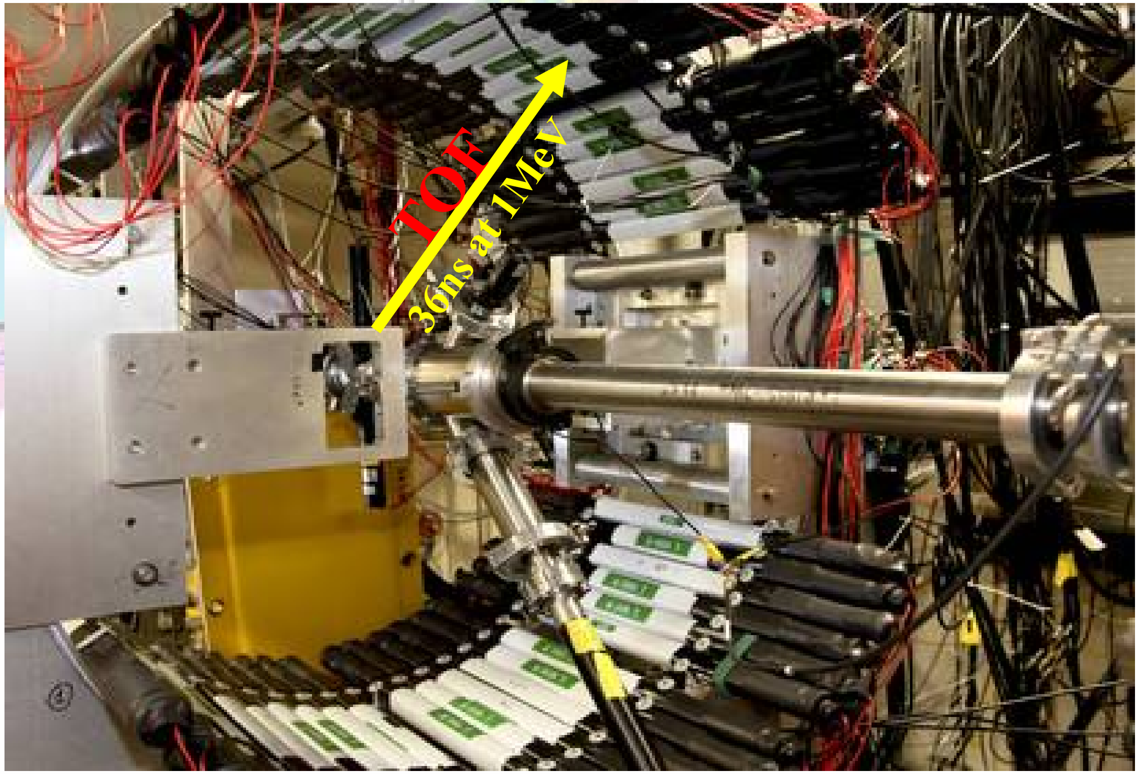
Design goal:
Maximize the detection efficiency in the broad energy range (100 keV – 6 MeV)
Measure neutrons and gammas .

First implementation at HRIBF experiment:

- 48 bars 3x3 x 60 cm^3
- Ω = 10% (23%) of 4π
- 3% (6%) total efficiency @ 1MeV
- 50 cm TOF radius
- 40–60% efficiency beta "START" detector

Gamma rays:

- 2 clovers, 3% efficient @ 1MeV



Fully digital system (250 MSPS):

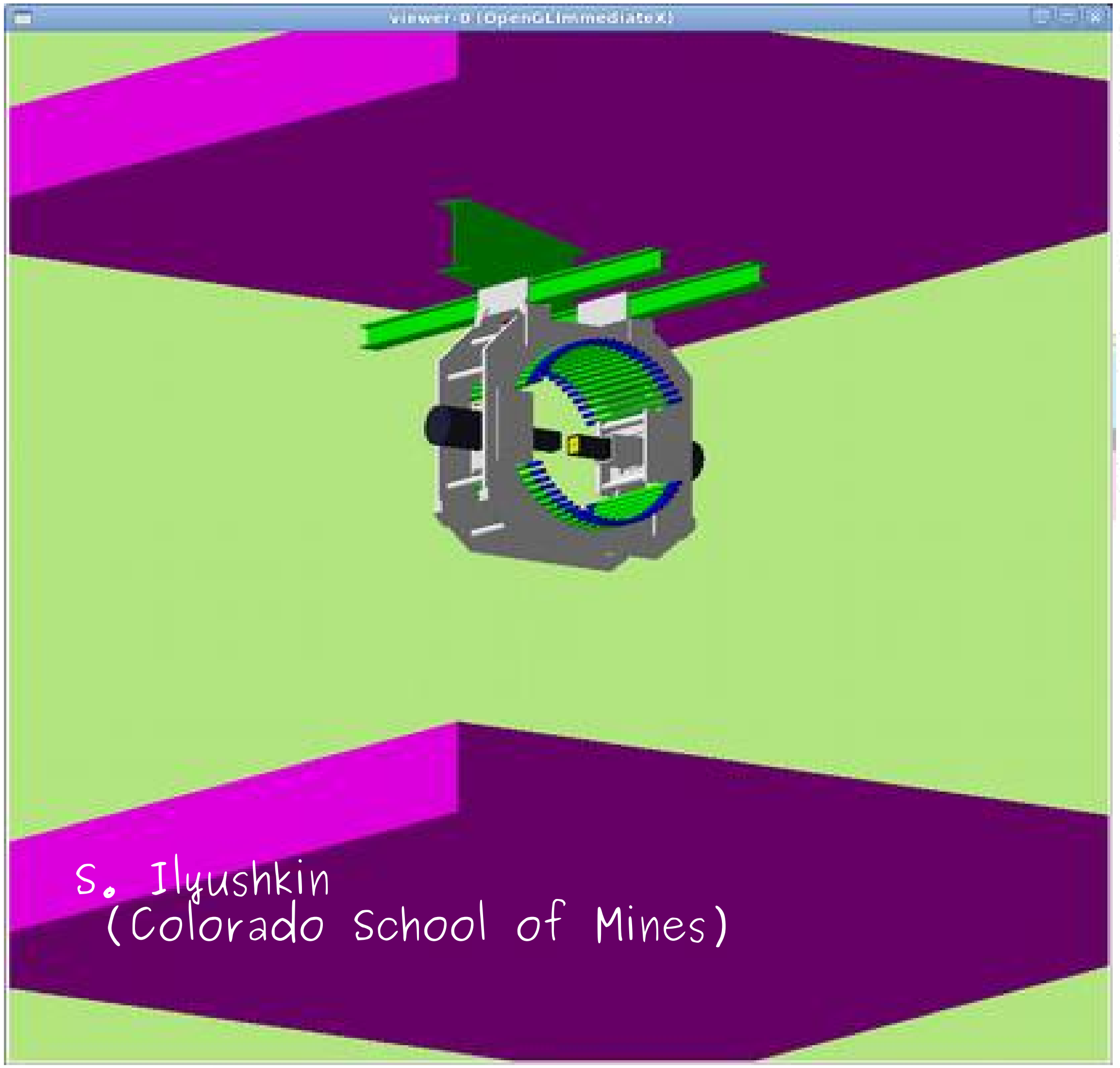
Sub–nanonsecond timing with 4ns digitization period

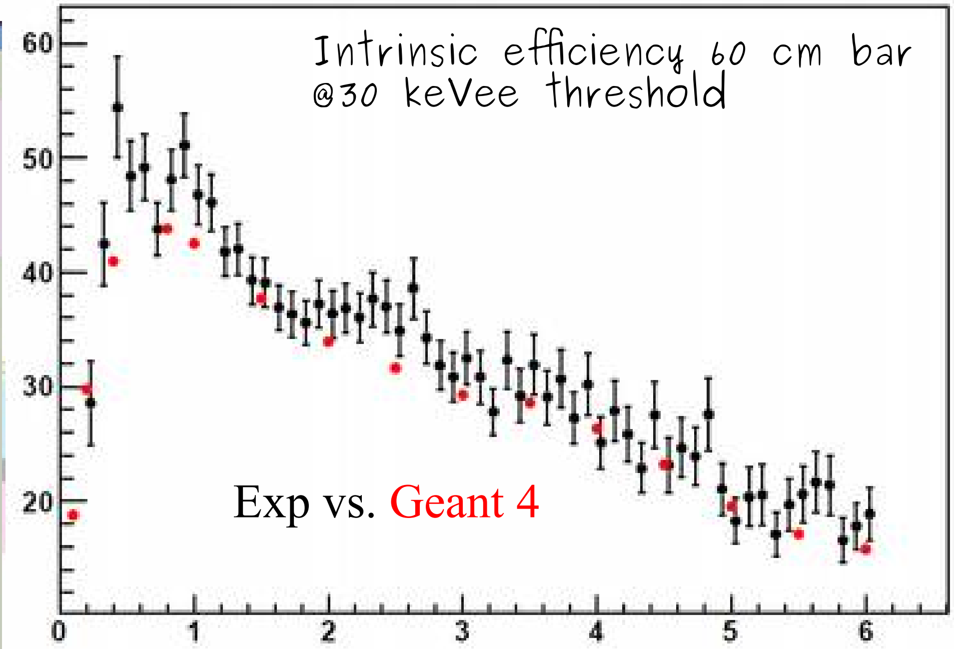
Low neutron detection threshold

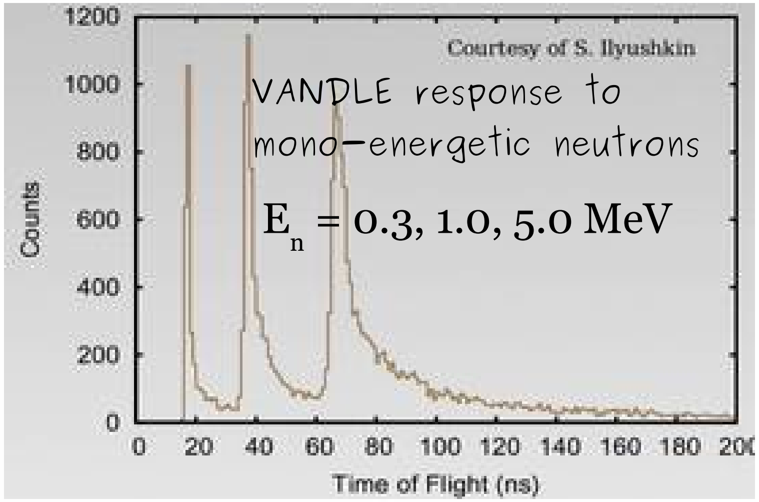
Portability and flexibility

S. Paulauskas et al. NIM A737,22(2014)

GEANT 4 model of VANDLE







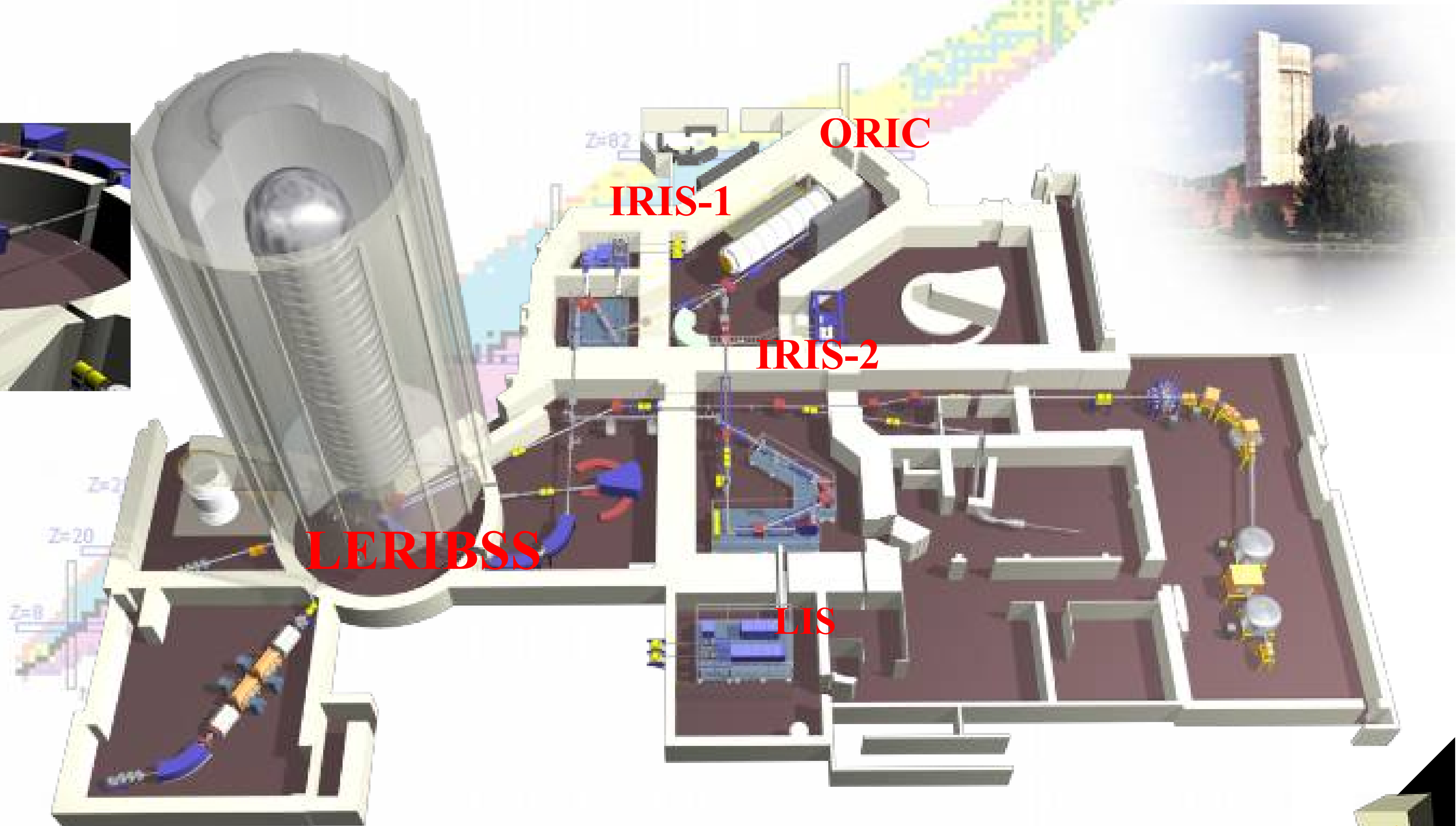
Holifield Radioactive Ion Beam Facility

Low-energy Radioactive Ion Beam Spectroscopy Station (LeRIBSS)

Intense beam (~10 μA) of (50MeV) protons on UCx targets

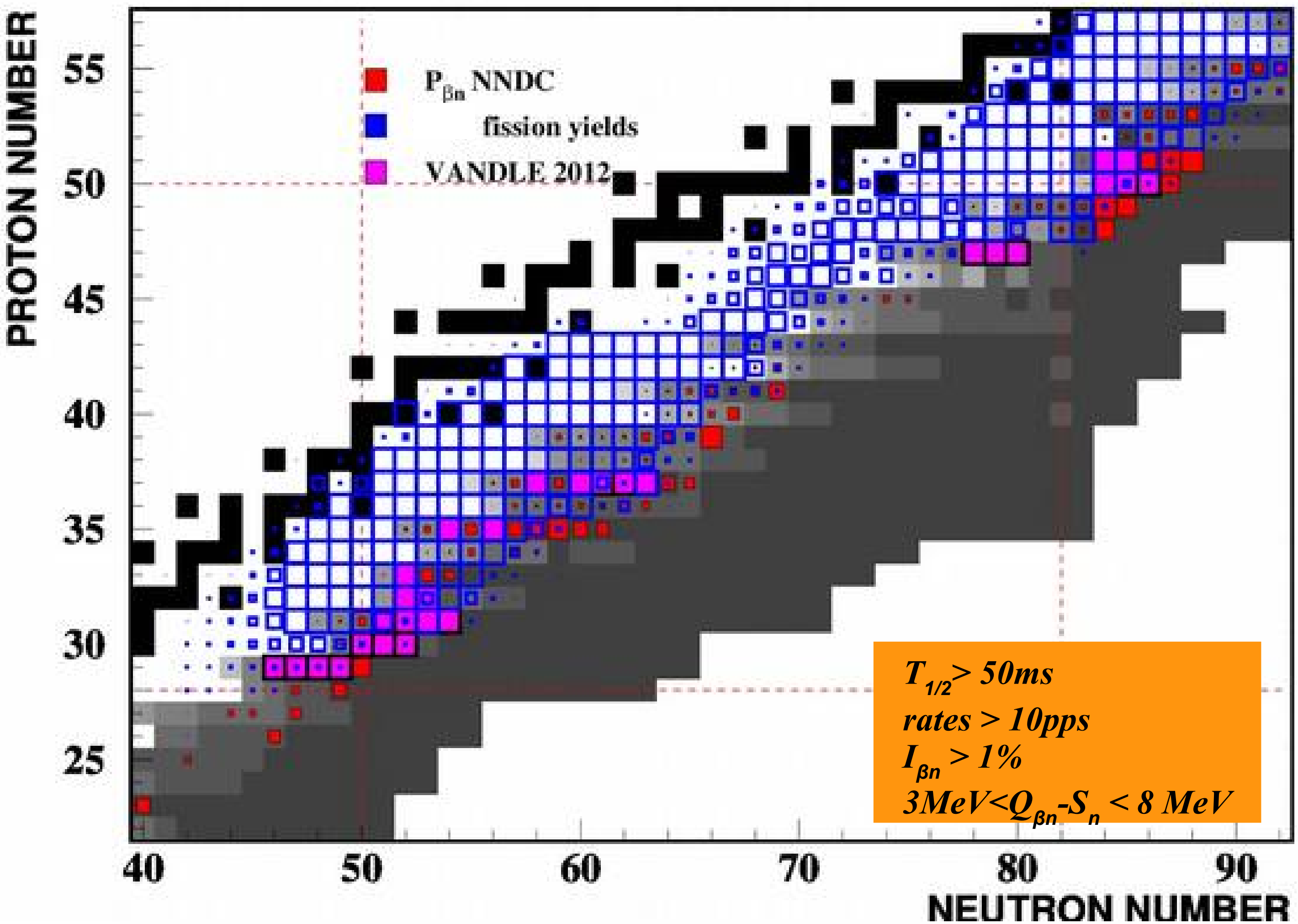
Isobar separation essential for success of the experiments !

IRIS-1/IRIS-2 platforms, negative and positive ions.



Beta-delayed neutron emitters near r-process path studied at HRIBF/LeRIBSS in February 2012

VANDLE commissioning experiment
Selection of isotopes with large $Q_\beta - S_n$ and $I_{\beta n}$
29 cases measured, focus on new data

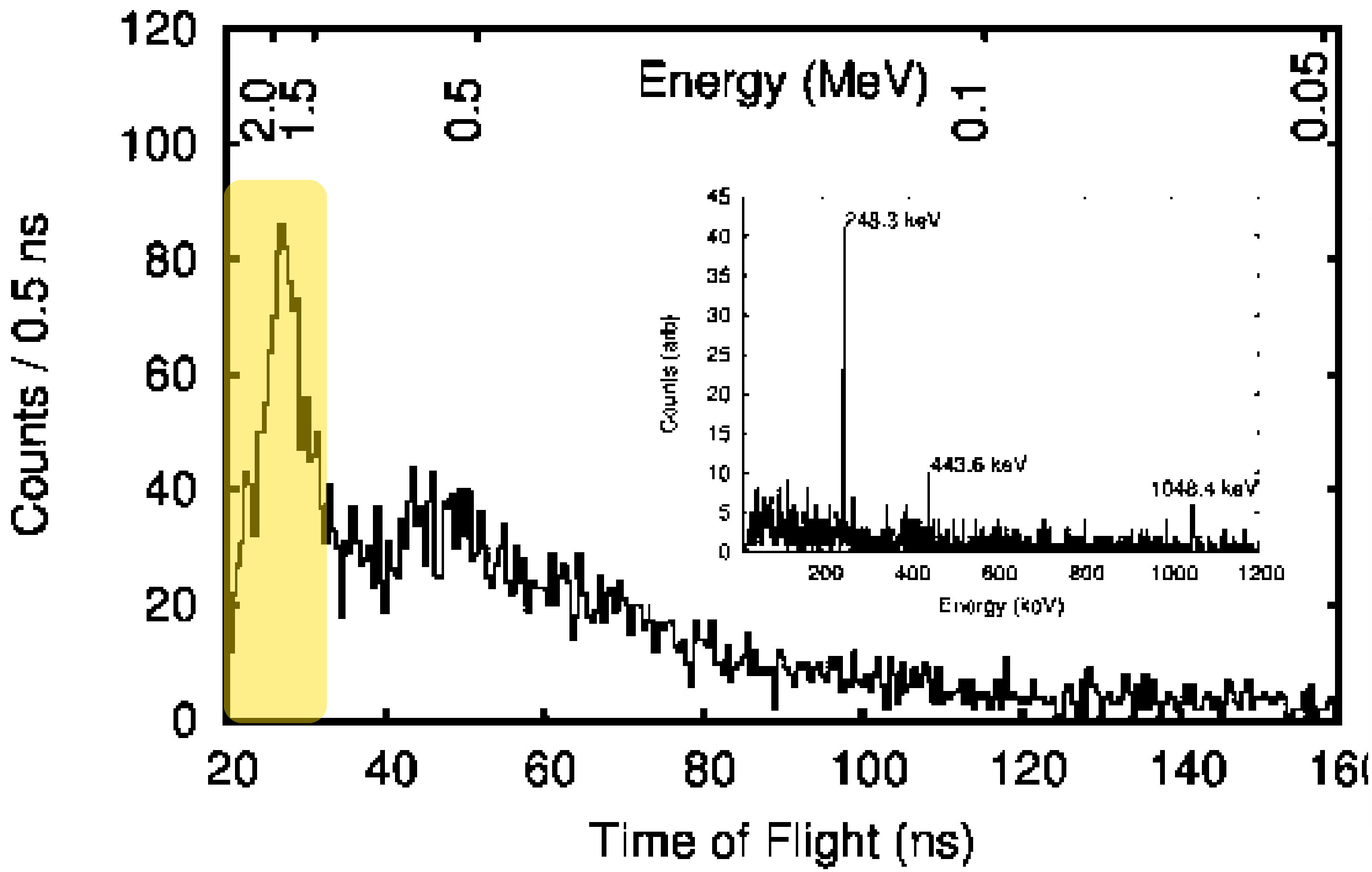


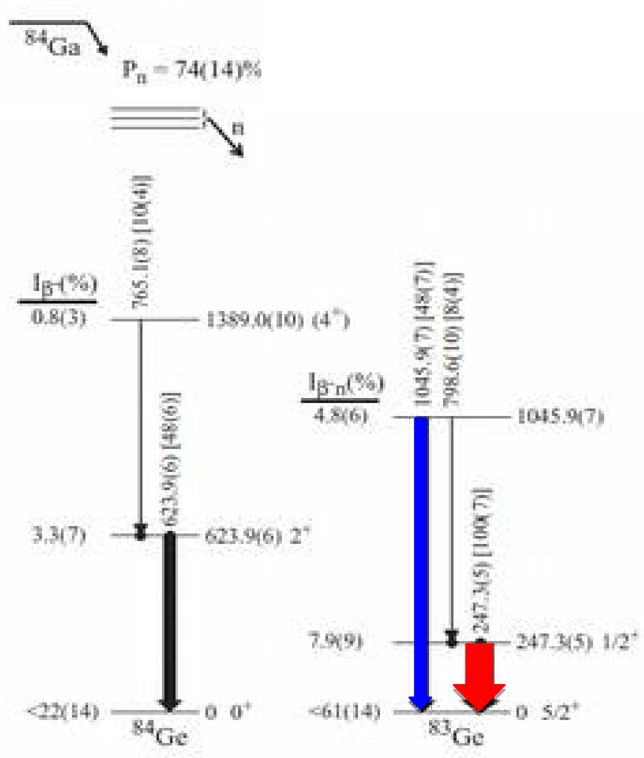
M. Madurga, W. Peters
S. Paulauskas …

and VANDLE

"Resonant" decay of ^{84}Ga (~30 h measurement)

- Q_β = 13.69 $T_{1/2}$=85(10) ms
- $Q_\beta - S_n$ = 8.5 MeV, Pn = 74(14)%





Spectrum deconvolution – from TOF to decay strength

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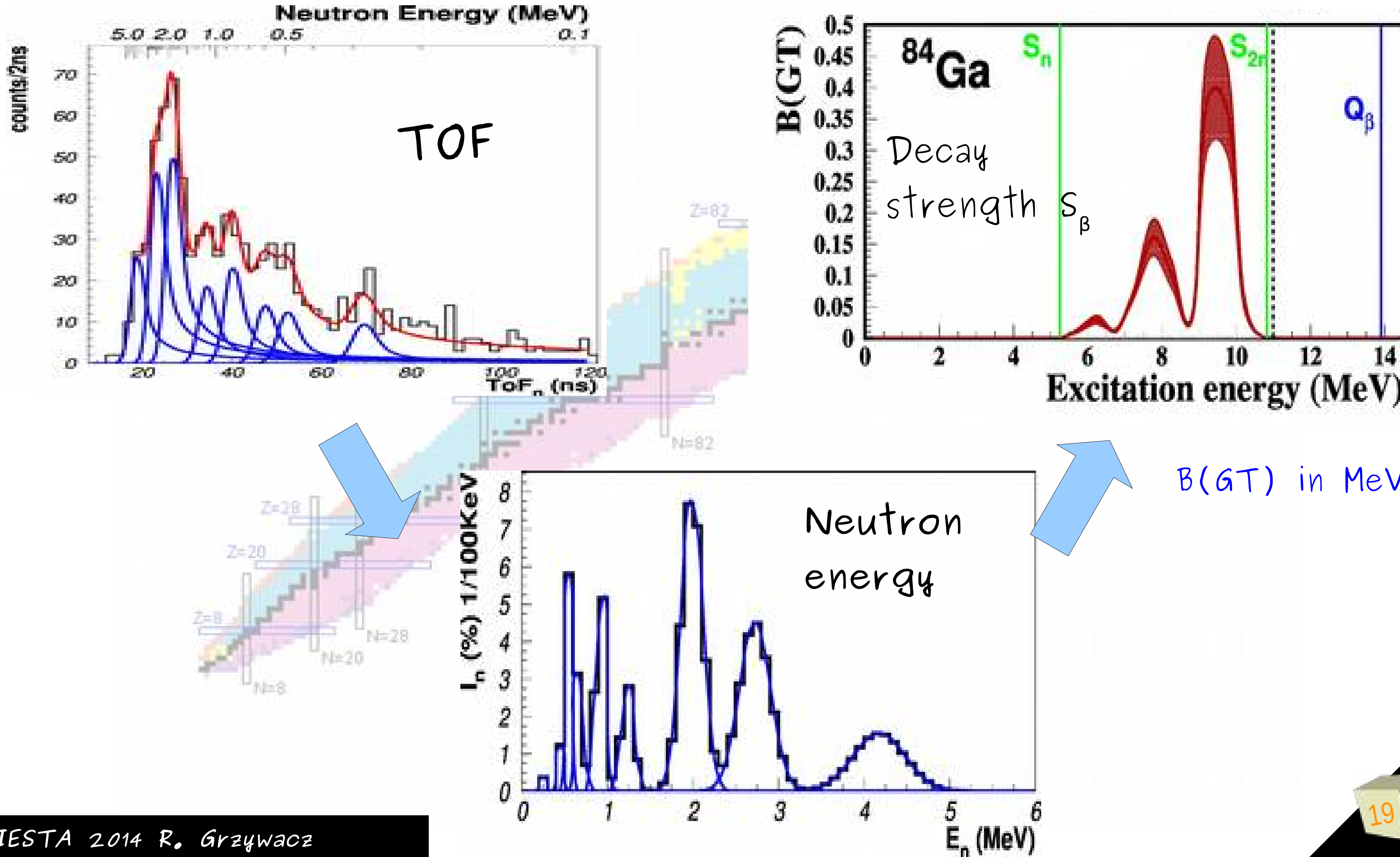
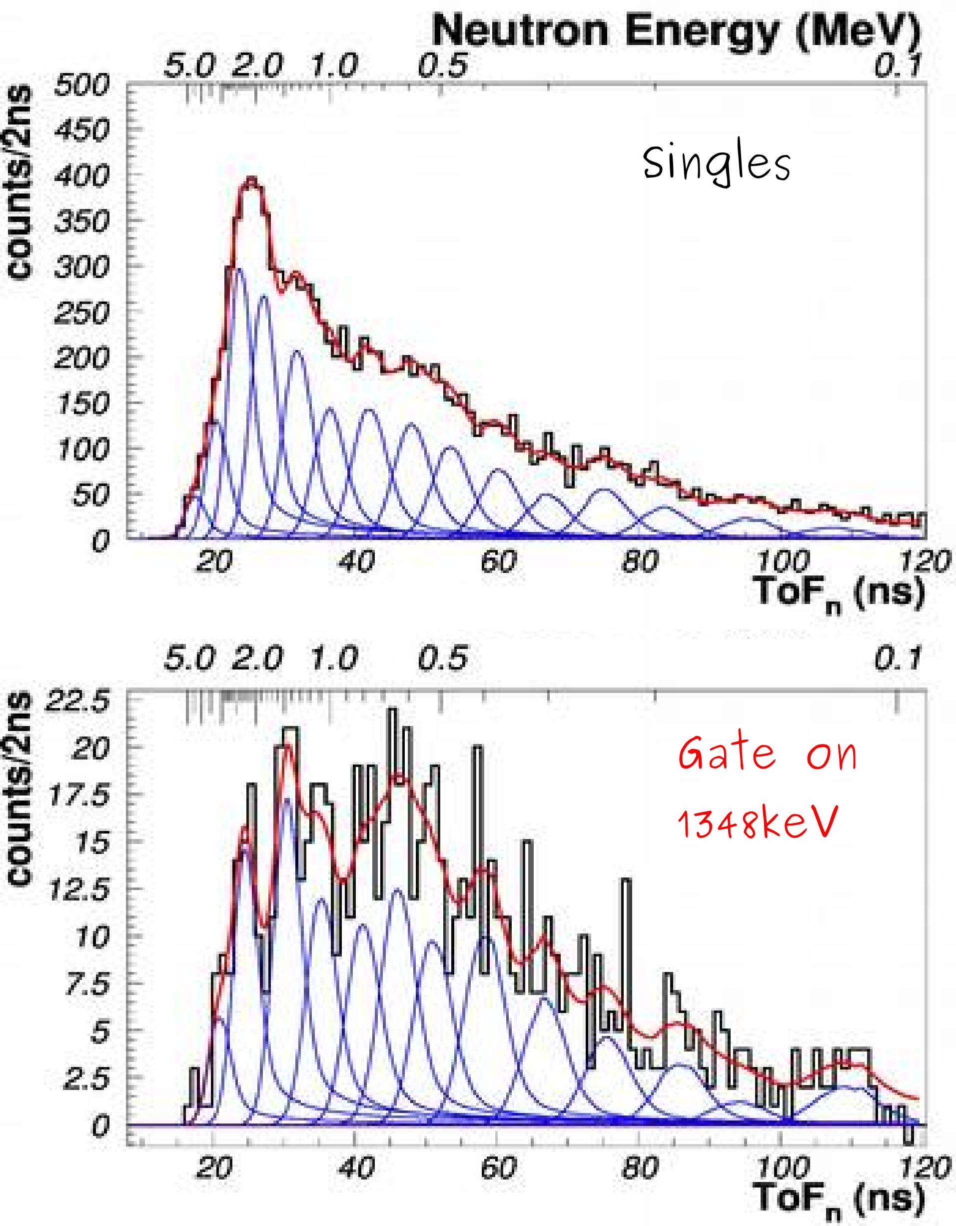
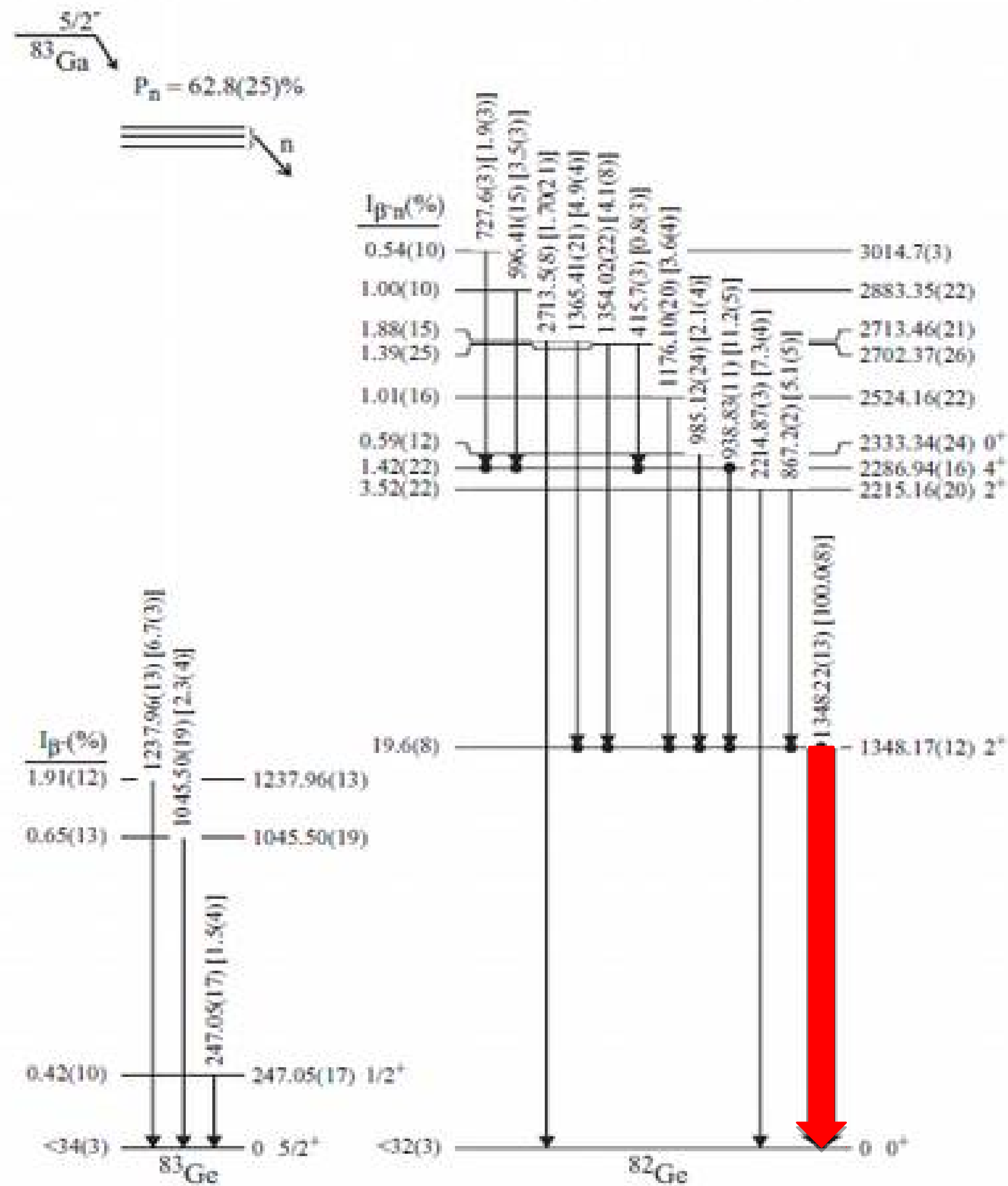


B(GT) in MeV^{-1}

Neutron+gamma coincidences

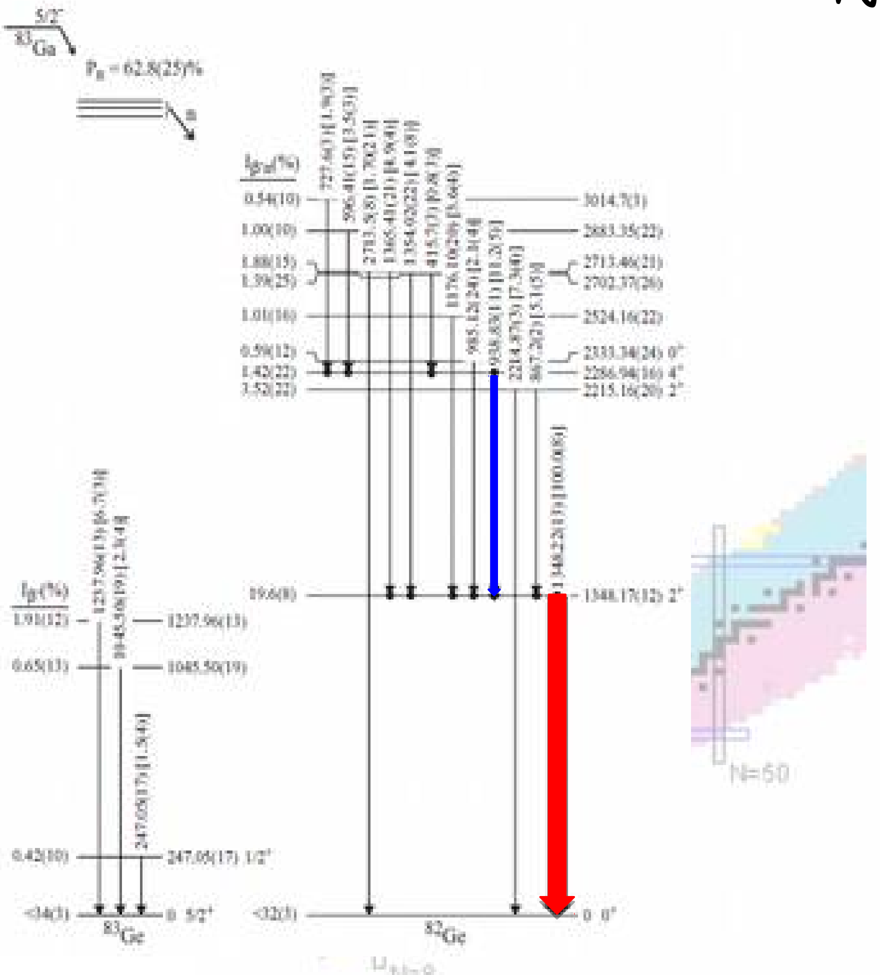


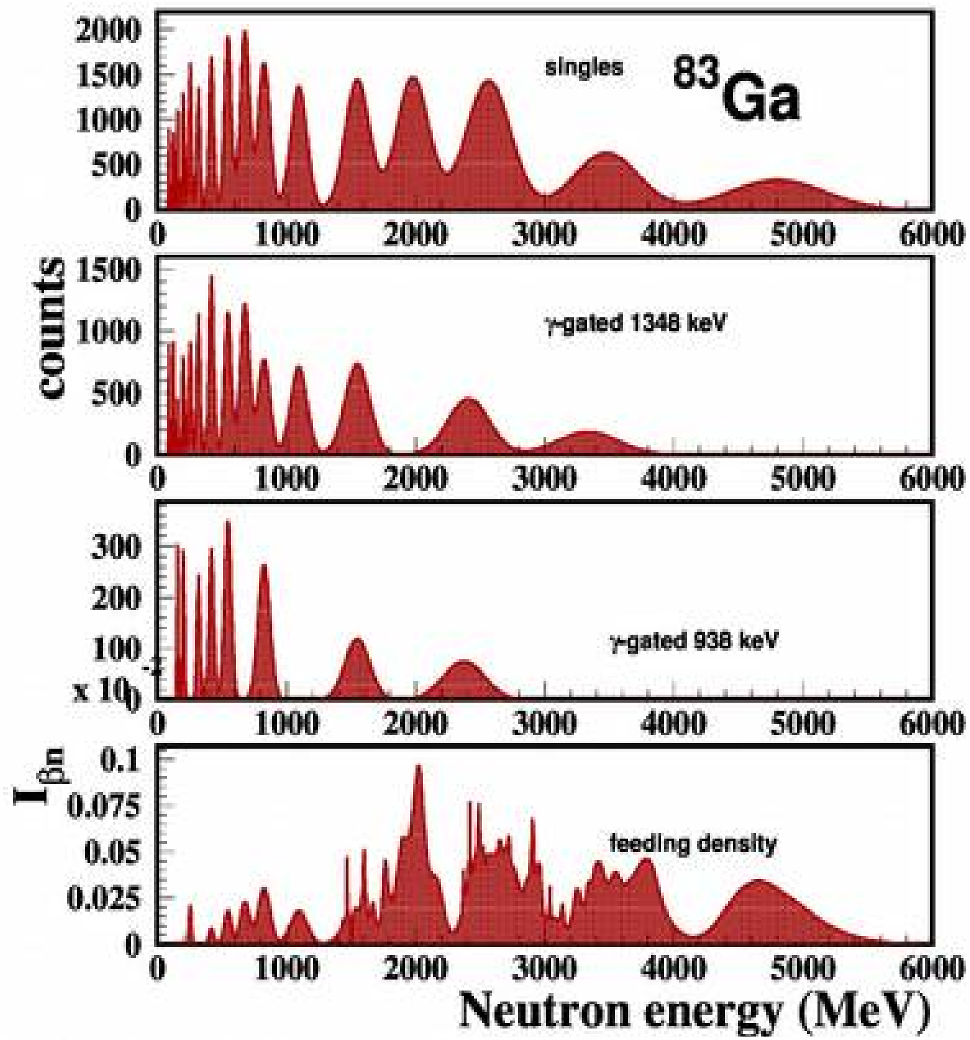


J.A. Winger Phys. Rev. C 81

Neutron+gamma coincidences

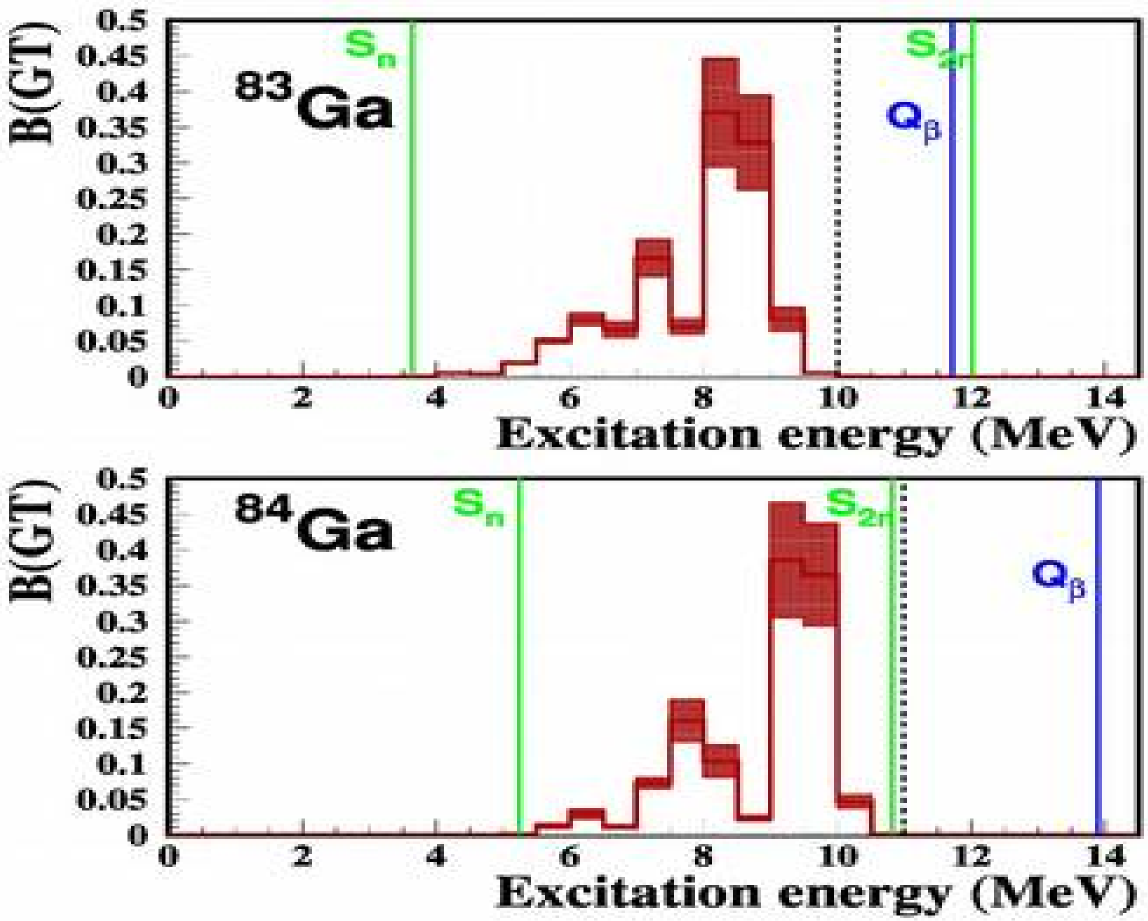
Neutron spectrum deconvolution





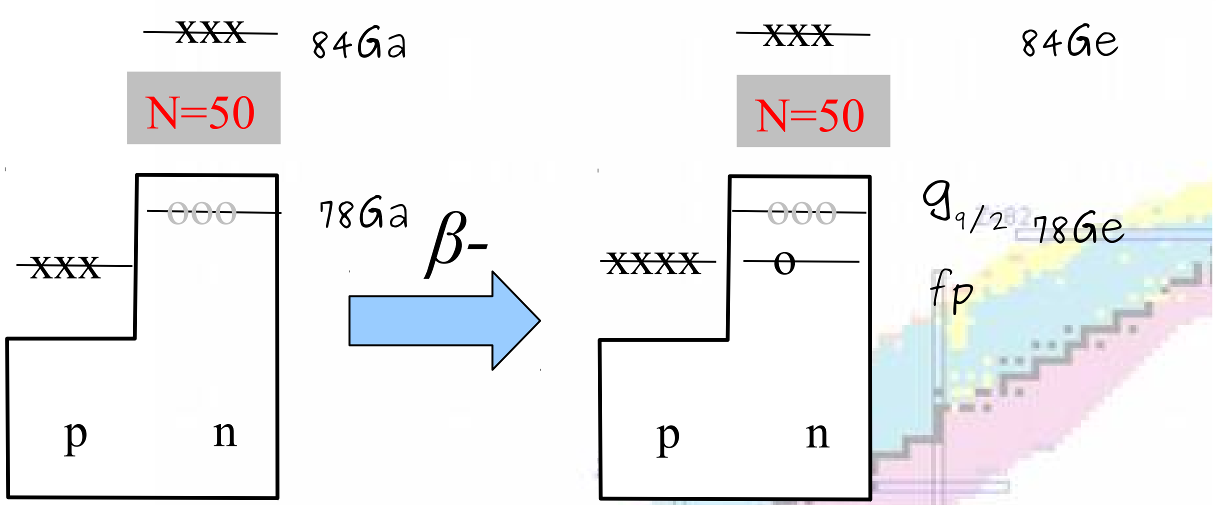
^{84}Ga and ^{83}Ga decay strength from neutrons

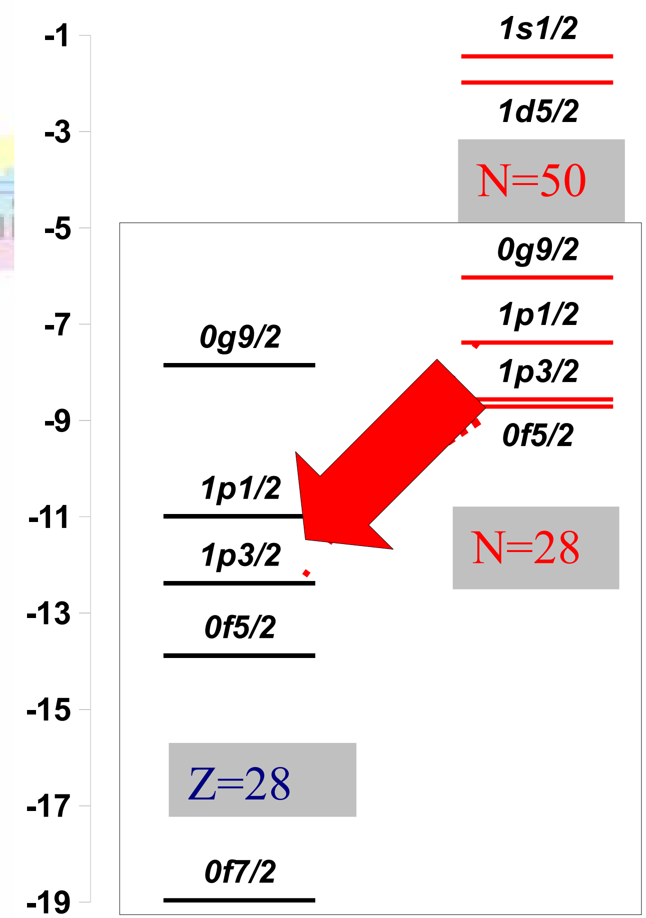
- observed large beta strength at high excitations in the daughter
- structures in the neutron spectrum



Shell-model interpretation
sd-neutrons as spectators

Beta decay of N<50 nuclei (shell model)
(Nushell with ^{56}Ni core and jj44bpn interactions).



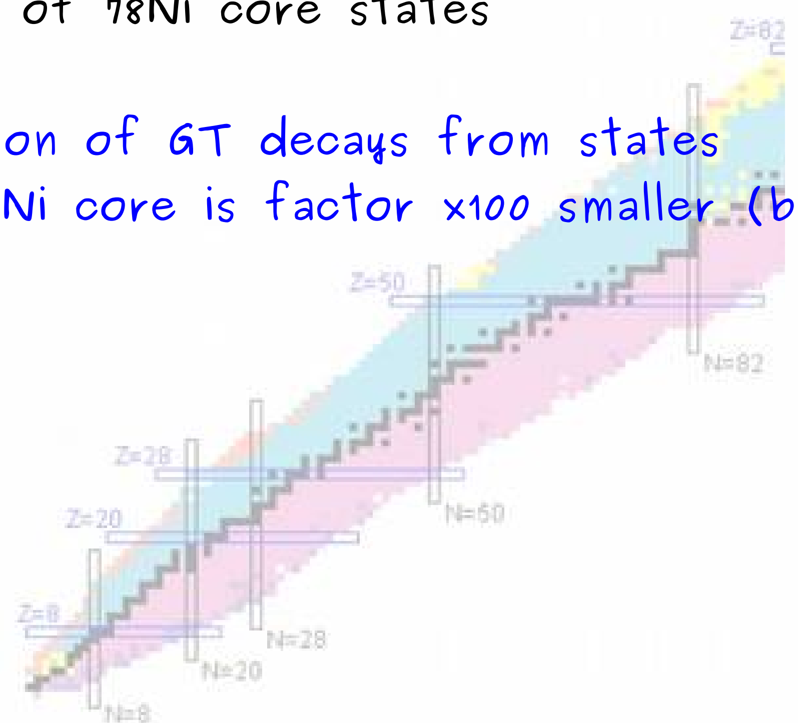


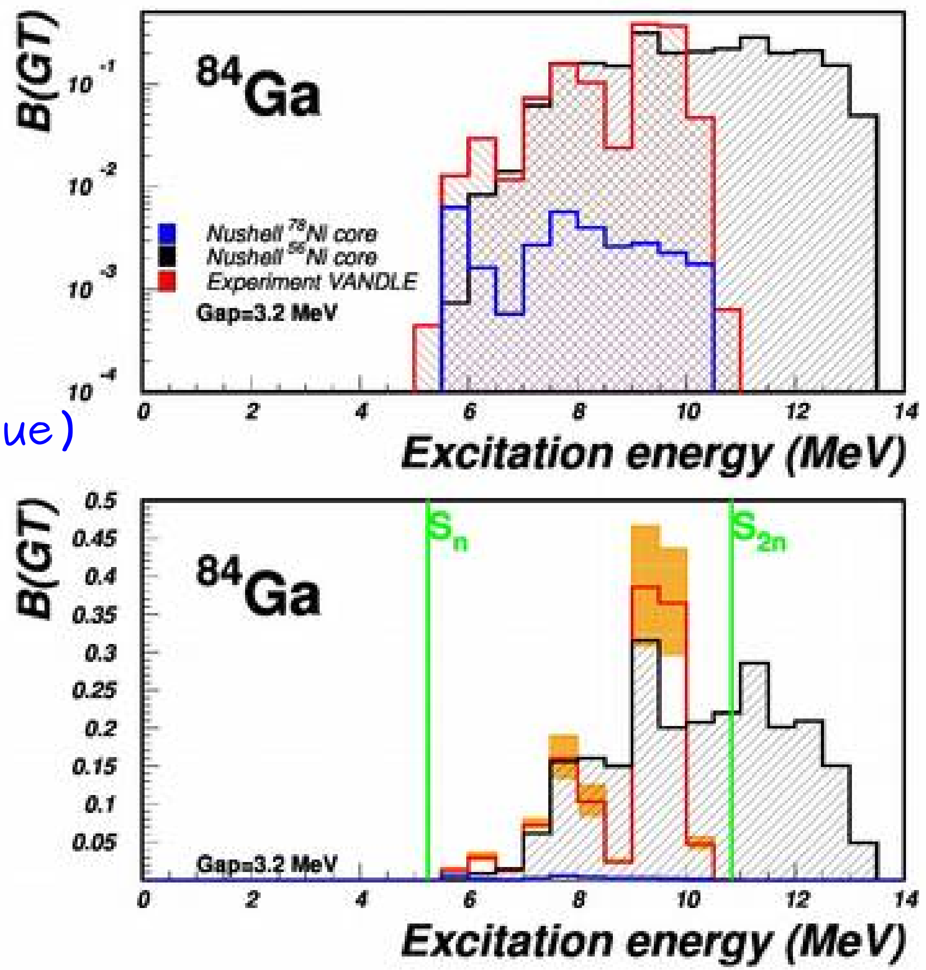
$B(GT)_{EXP}$: 84Ga(N=53,Z=31)
may look like
$B(GT)_{THE}$: 78Ga (N=47,Z=31)
shifted by ~3 MeV
(N=50 shell gap)

BGT for ^{83}Ga and shell model

-observed large beta strength at high excitations compatible with GT-decay of 78Ni core states

-contribution of GT decays from states outside 78Ni core is factor x100 smaller (blue)





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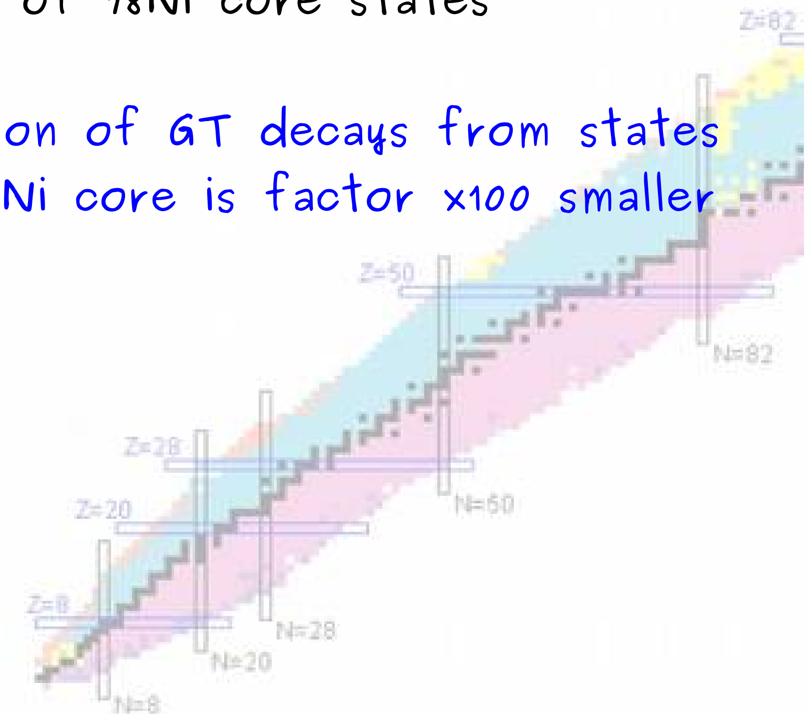
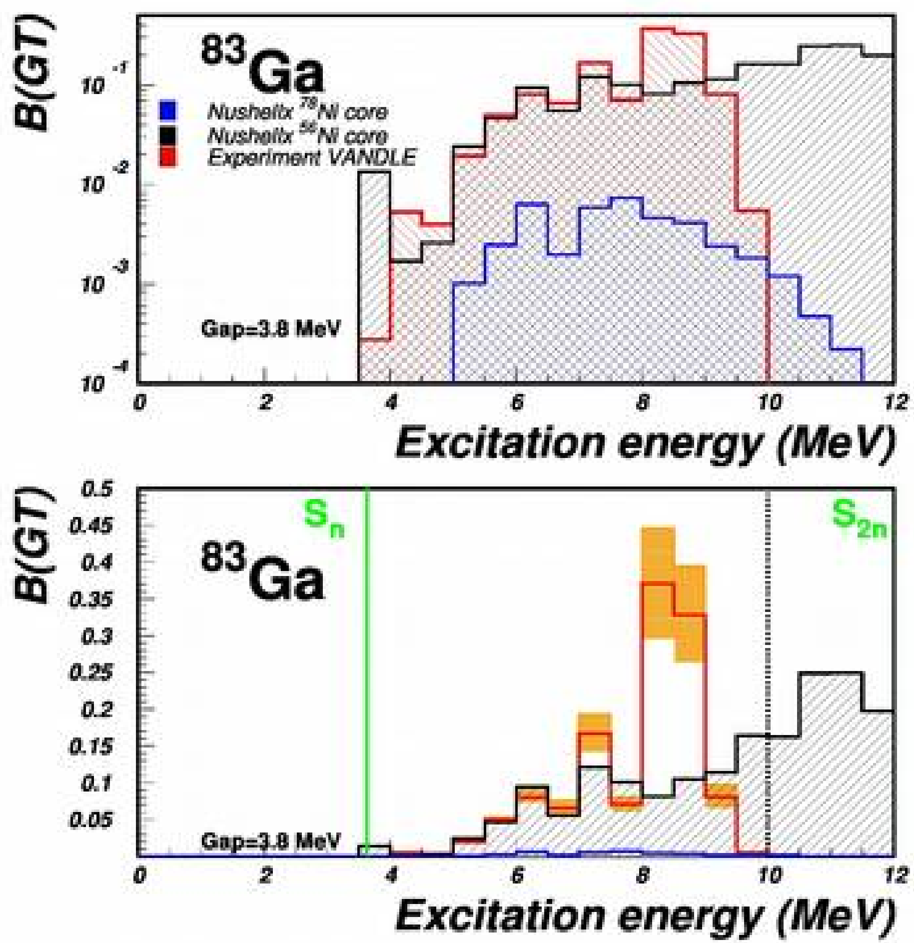
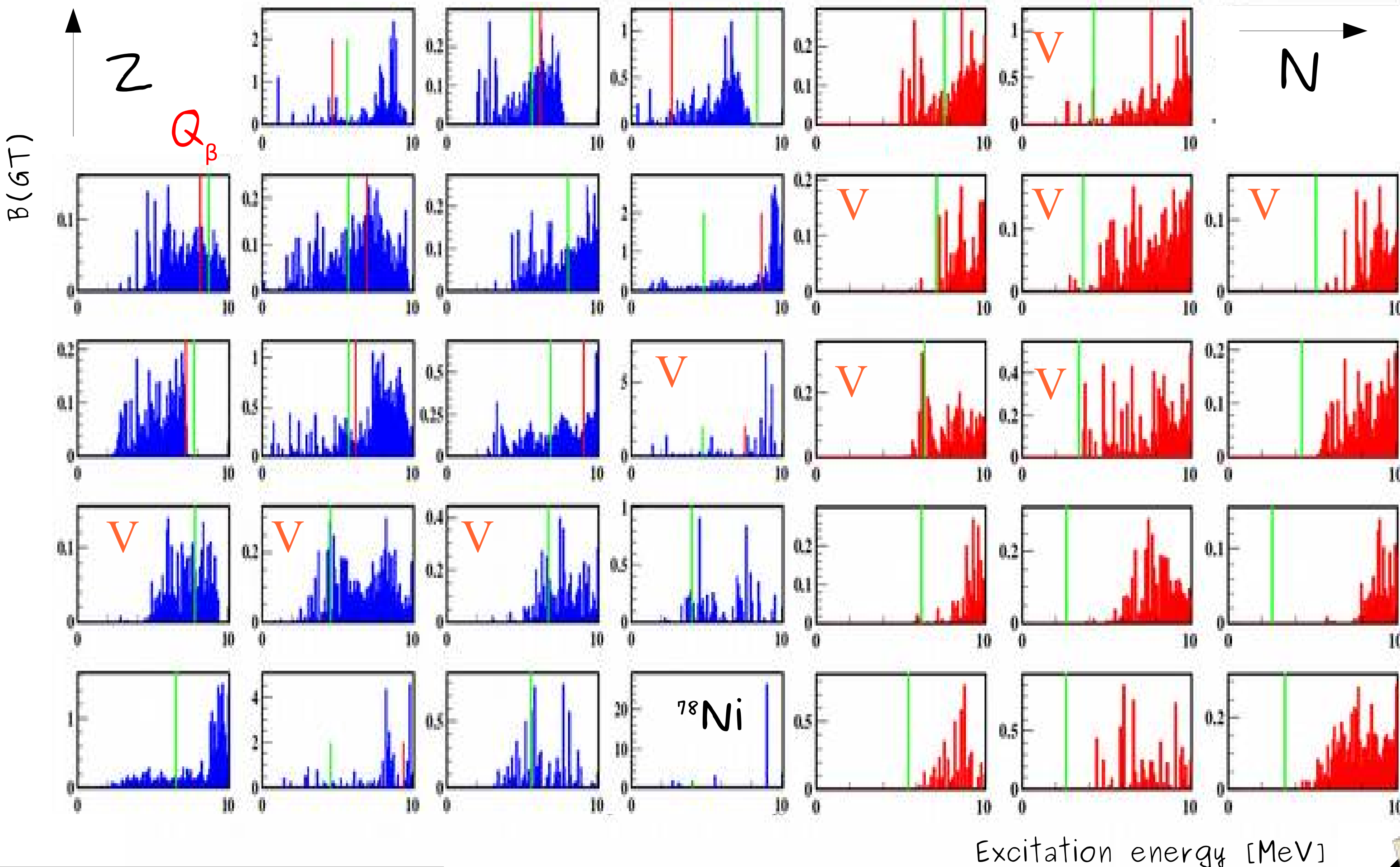
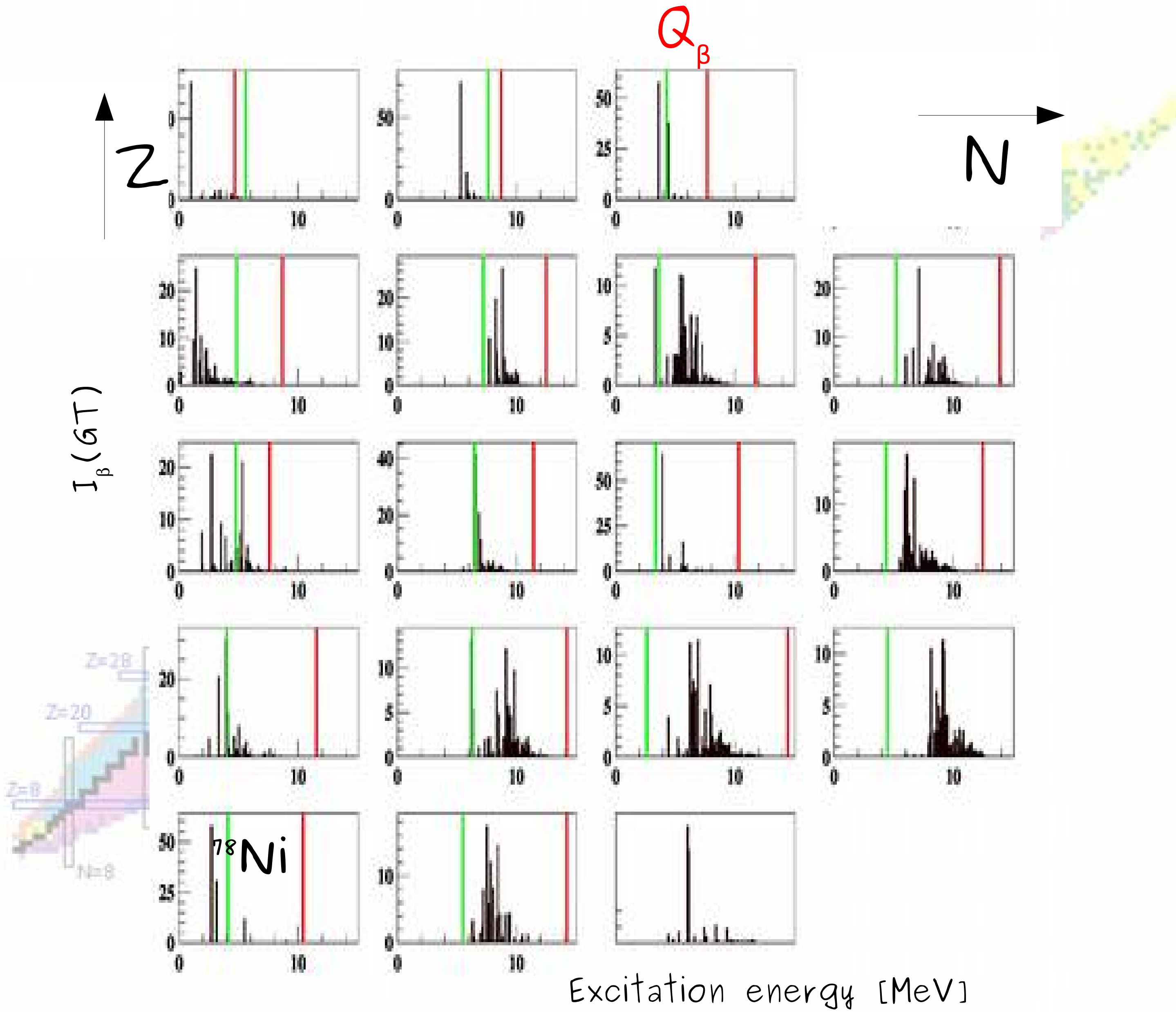




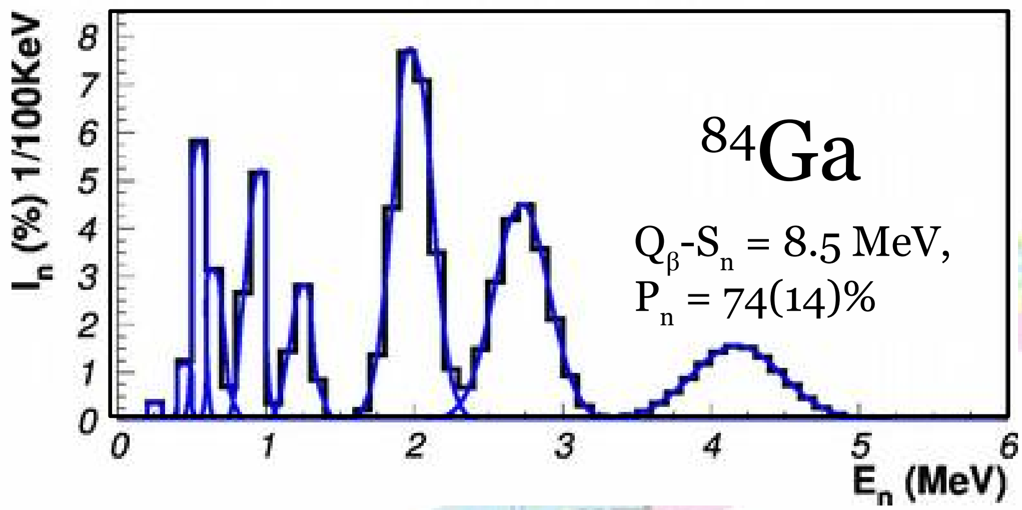
Shell-model B(GT) in ^{78}Ni region



Shell-model predictions of feedings in ^{78}Ni region



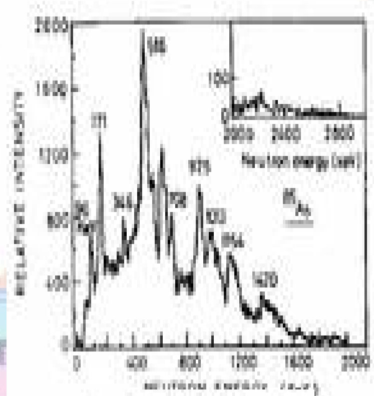
Neutron spectroscopy in very neutron rich heavy nuclei



^{84}Ga

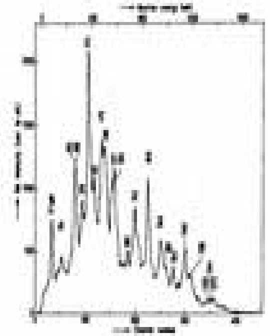
Q_β-S_n = 8.5 MeV,
P_n = 74(14)%

"PANDEMONIUM"
NUCLEI



^{85}As

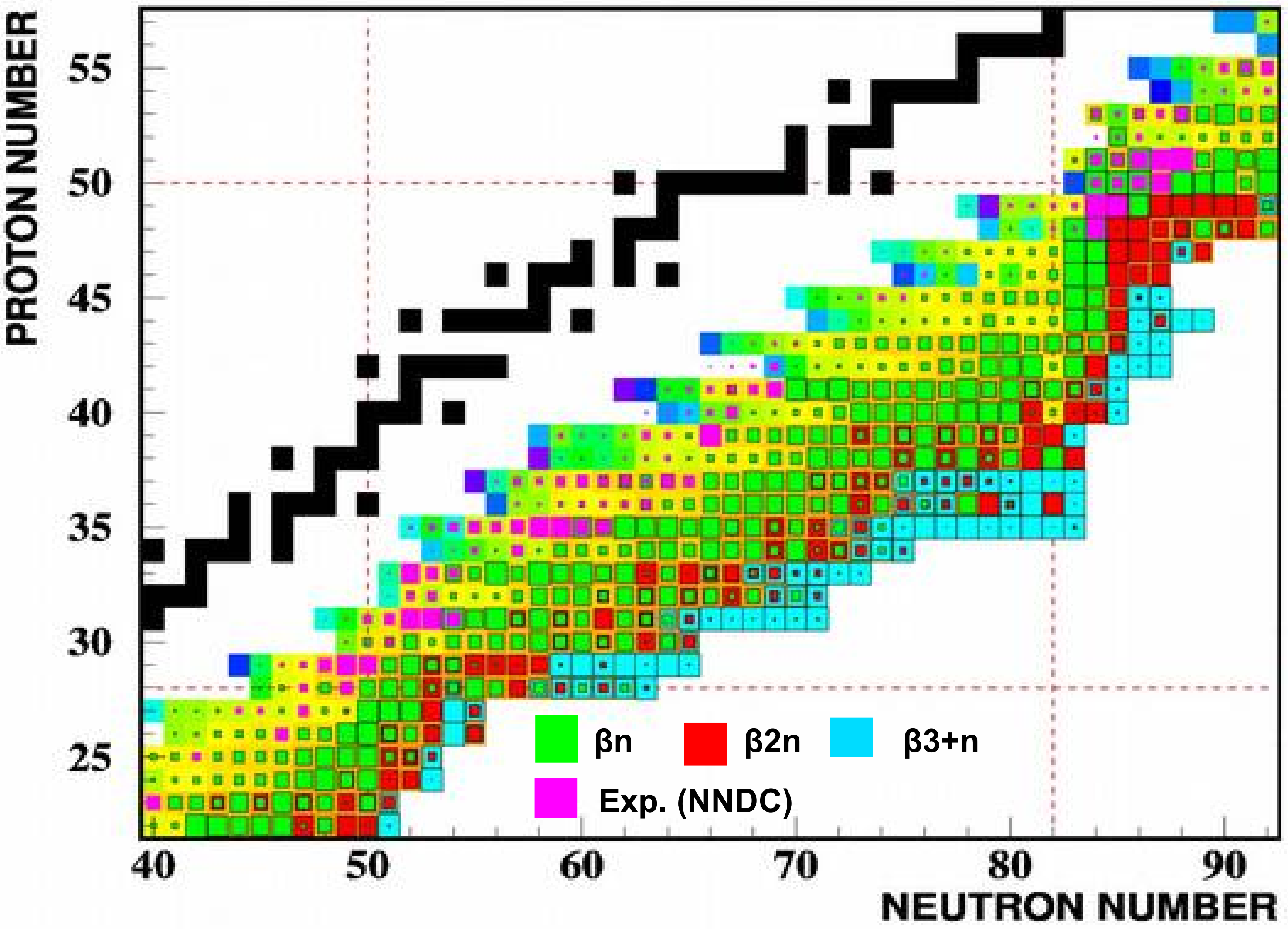
Q_β-S_n = 4.9 MeV, P_n = 60%



^{137}I

Q_β-S_n = 2.0 MeV, P_n = 7%

Beta-xn channels in very n-rich nuclei



Möller, P.; Nix, J. R.; Kratz, K.-L.
Atomic Data and Nuclear Data Tables, Vol. 66,(1997) p.131

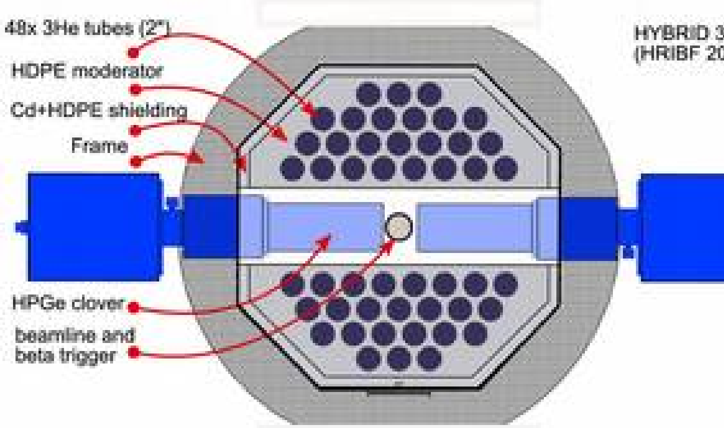
Hybrid-3Hen (HRIBF)

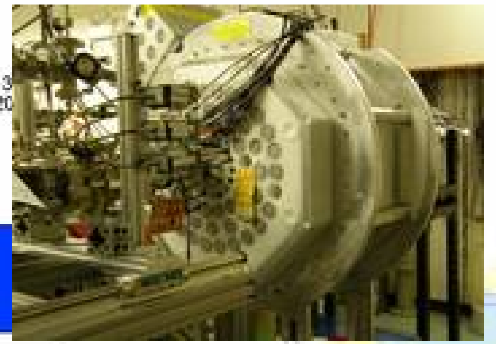
combination of gamma and neutron detection !

$^{3}He + n \rightarrow {}^{3}H + {}^{1}H + 765keV$

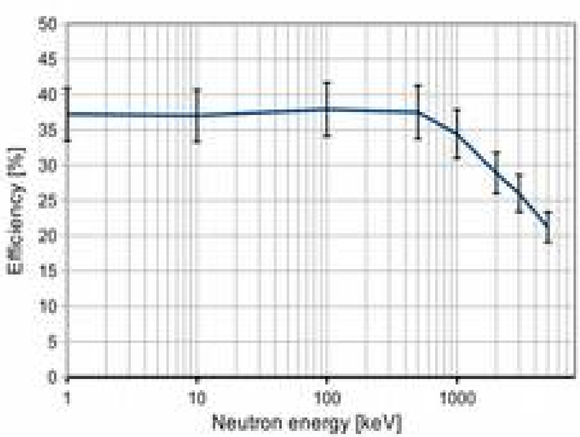
3Hen Detector

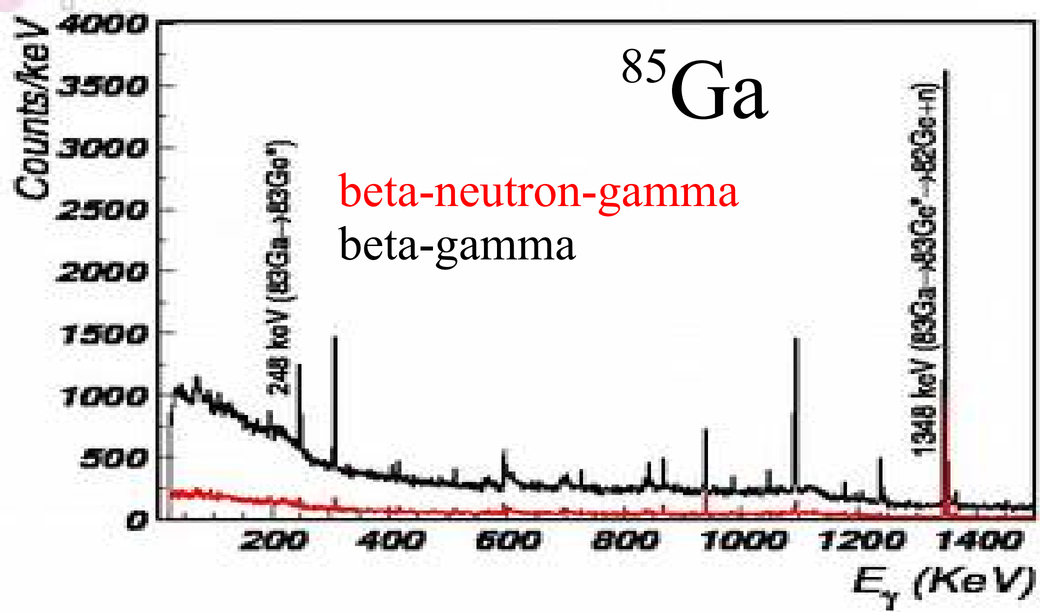
48x ^{3}He tubes + 2 clover detectors





R. Grzywacz et al. Act. Phys. Pol. 45(2014) 217

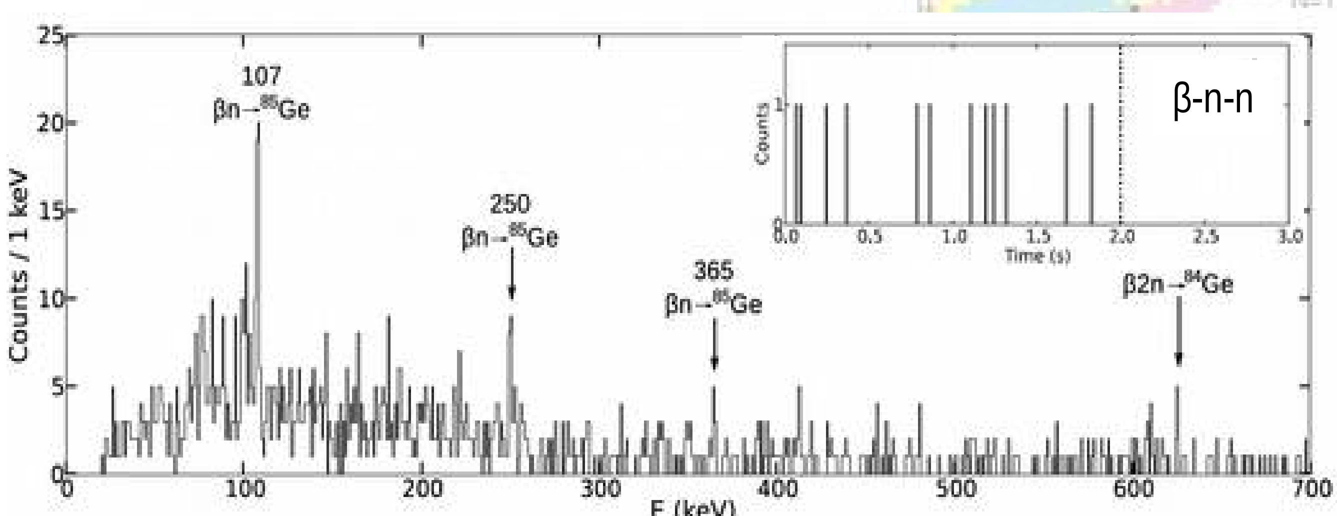


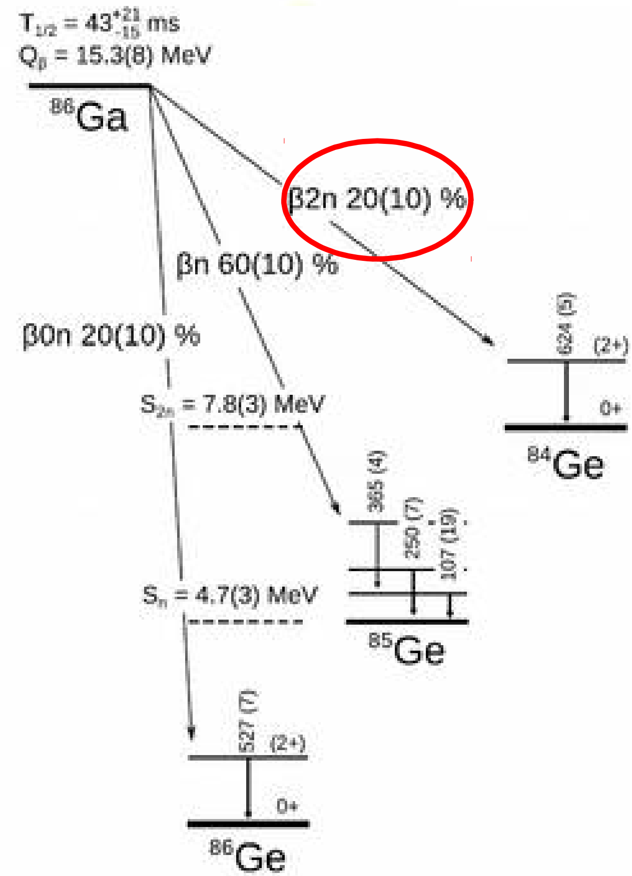


Beta-delayed 2n emission in ^{86}Ga decay
β1n ~ 60 %, β2n ~ 20%

Very powerful combination of RILIS +Isobar separator+3Hen!

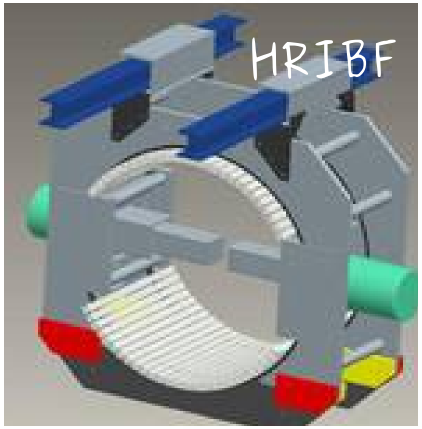
Pure beam (Laser Ion Source)
Production rates comparable or better than at RIKEN
First confirmation of the predicted **large β2n branching ratios**
$I_{\beta 1n}$ / $I_{\beta 2n}$(FRDM–QRPA) 21% /44%,
$I_{\beta 1n}$ / $I_{\beta 2n}$(DF3a+CQRPA) 28% /22%



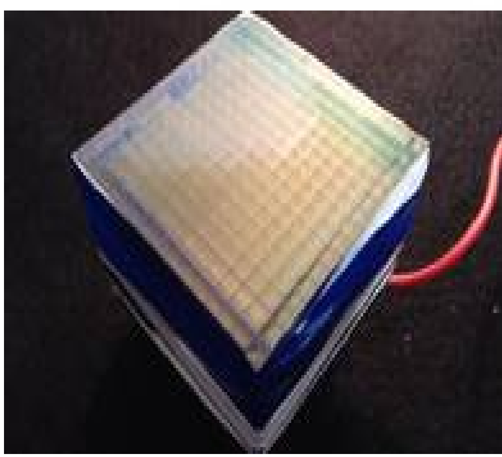


86Ga: neutron b+n+g spectrum
K. Miernik et al. Phys. Rev. Lett, 2013 Phys Rev Lett. 111(2013),132502.
RILIS : Y. Liu et al., Nucl. Instrum. Methods Phys. Res., Sect. B 298, 5 (2013).

VANDLE – a multipurpose neutron detector for decay and reaction studies



New trigger detectors
(fragmentation and ISOL experiments)



VANDLE – first fully digital array for energy resolved neutron spectroscopy

Survey of ~30 isotopes in a HRIBF campaign with VANDLE

Completed VANDLE data analysis for ^{83,84}Ga.

- Intense neutron peaks attributed to Gamow-Teller decays
- Data consistent with simplified shell-model calculations based on ^{78}Ni core decay.
- Ongoing work on more complete SM calculations.

VANDLE improved for future experiments

1m TOF configuration with larger bars

New TOF start detectors

Higher gamma detection efficiency ($LaBr_3$ array HAGRID).

Complementary Total Absorption Spectroscopy !