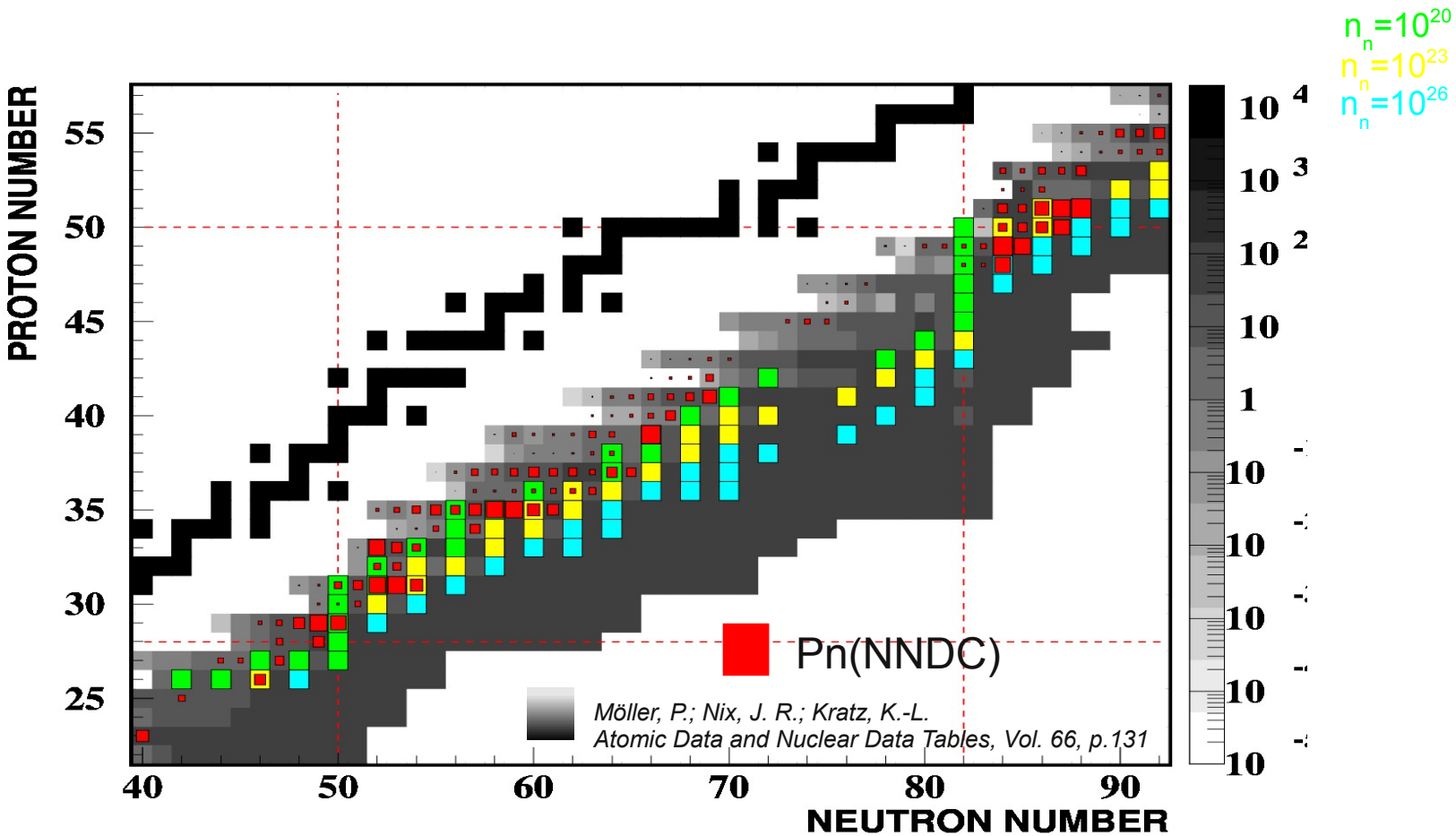
BETA DELAYED NEUTRON EMISSION – NEW PERSPECTIVE ON R-PROCESS NUCLEI WITH VERSATILE ARRAY OF NEUTRON DETECTORS AT LOW ENERGY (VANDLE)

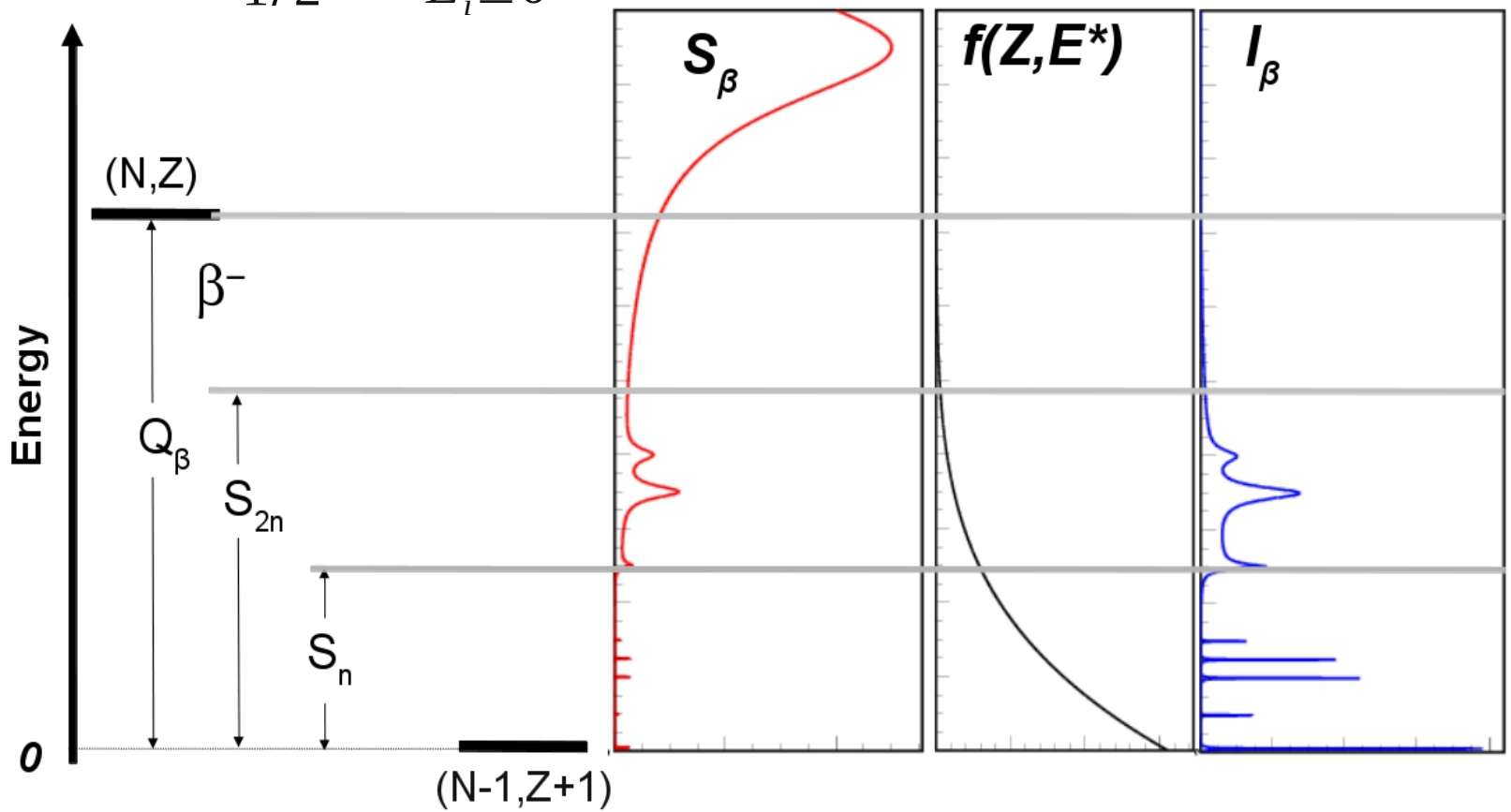
Increase of decay energies far from stability enables complex decay channels



All of the r-process waiting point nuclei are beta-delayed neutron emitters

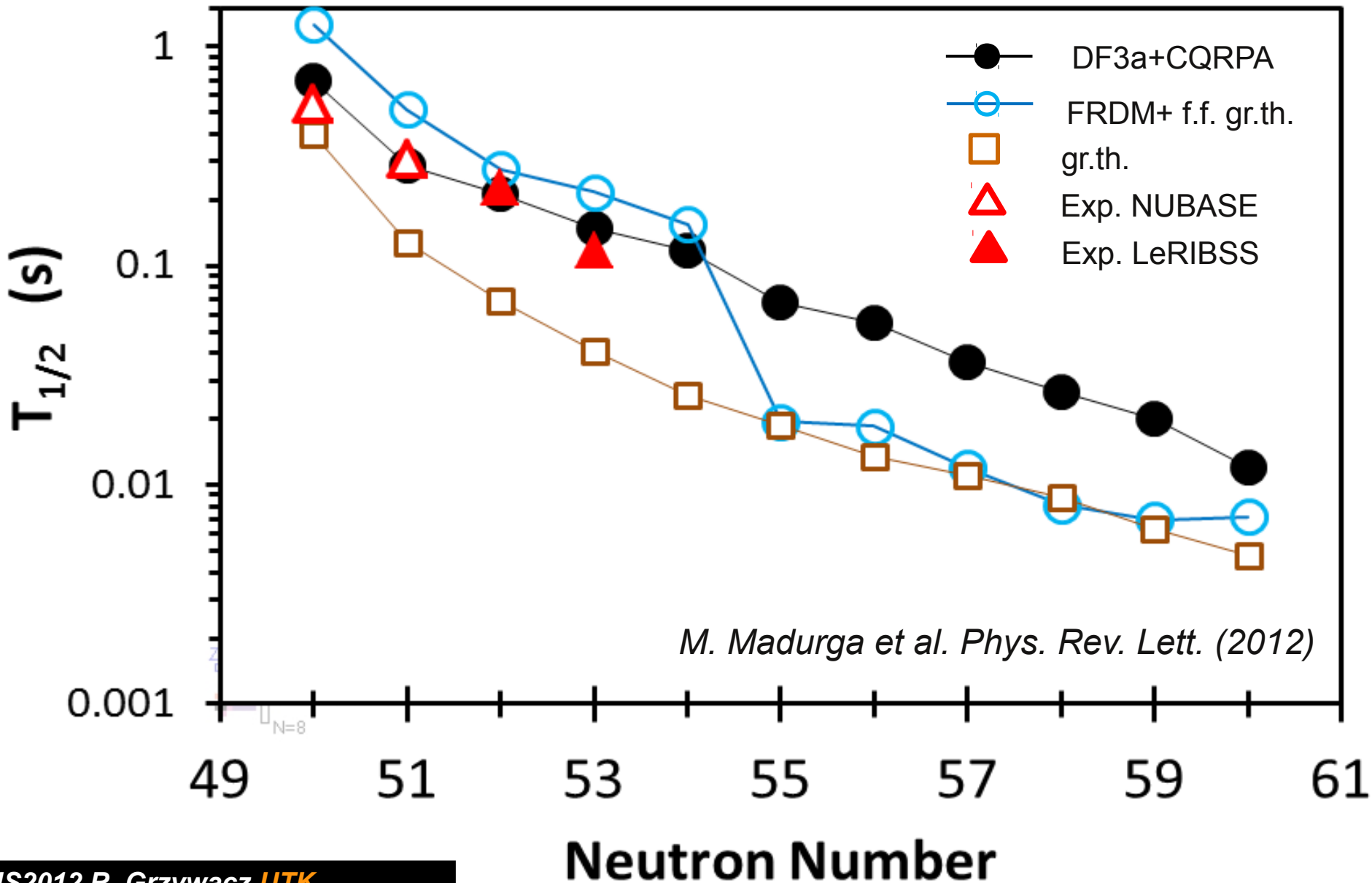
Nuclear lifetimes
$T_{1/2}$ and the nuclear structure

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



Essential features of S_β – reliable extrapolations into unknown

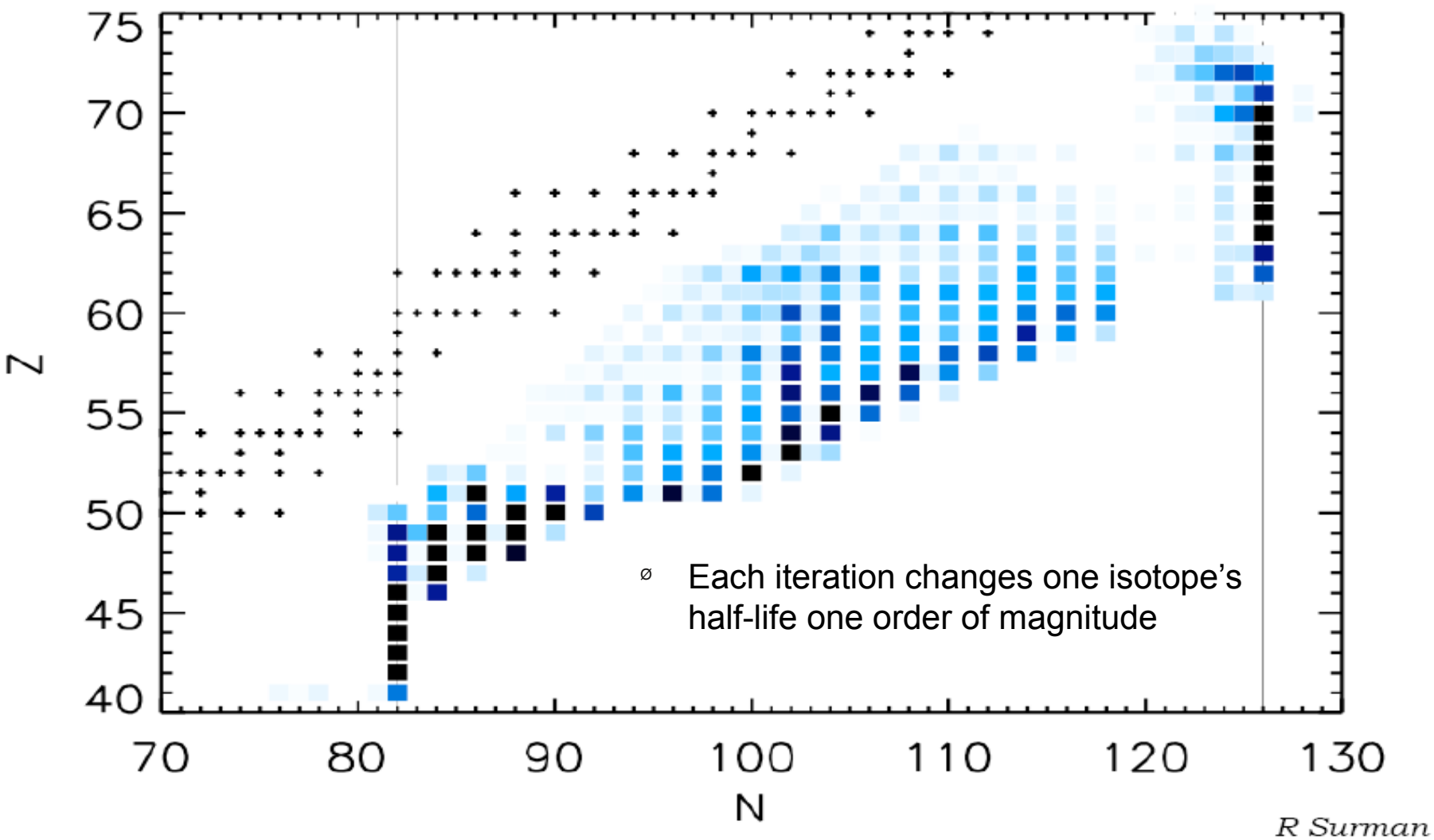
Benchmarking theoretical predictions: Zn half-lives



β-decay in hot r-process

Beta decay rate sensitivity study

J. Cass, G. Passucci, R. Surman, A. Aprahamian

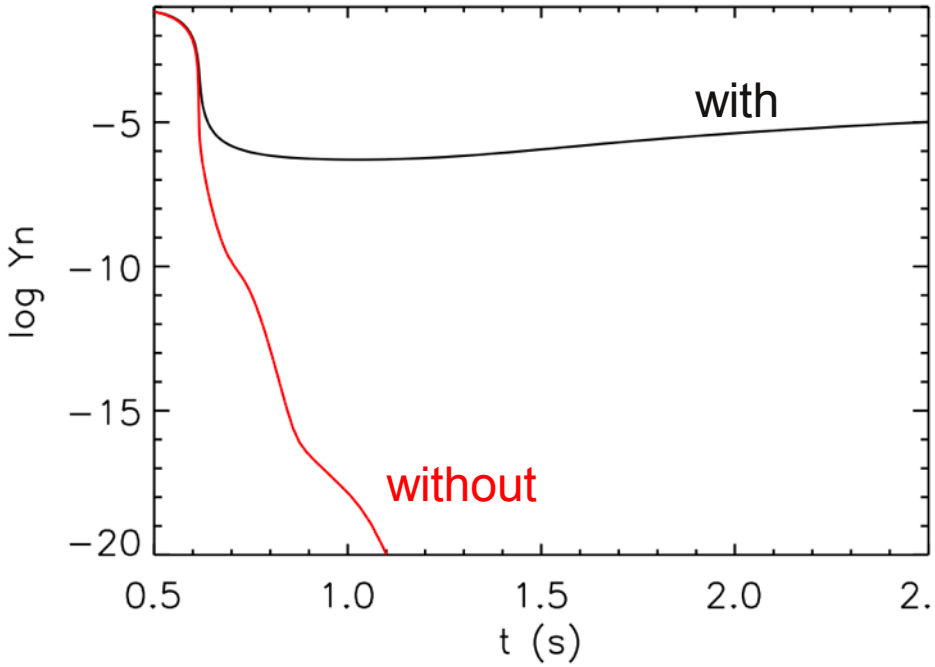


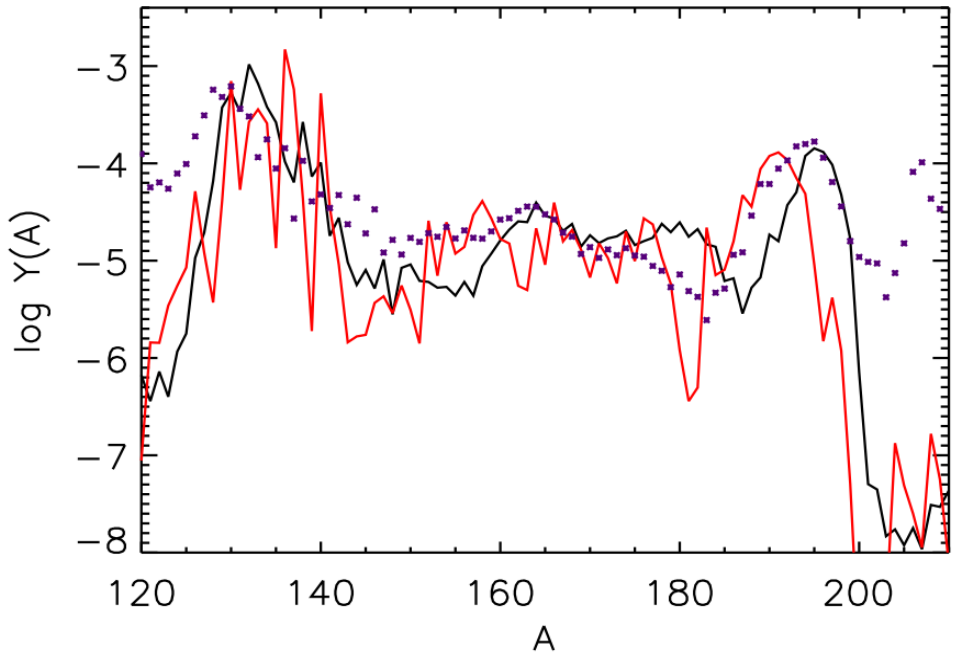
- Each iteration changes one isotope's half-life one order of magnitude

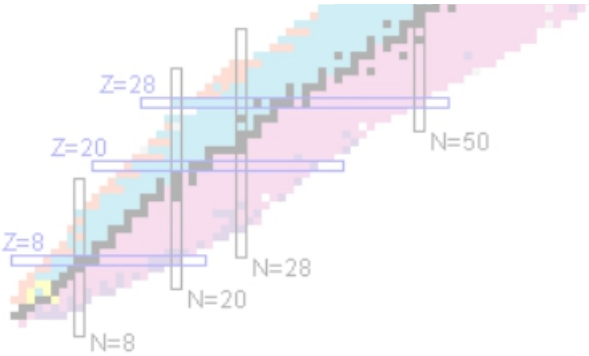
β-delayed neutron emission in a cold r-process

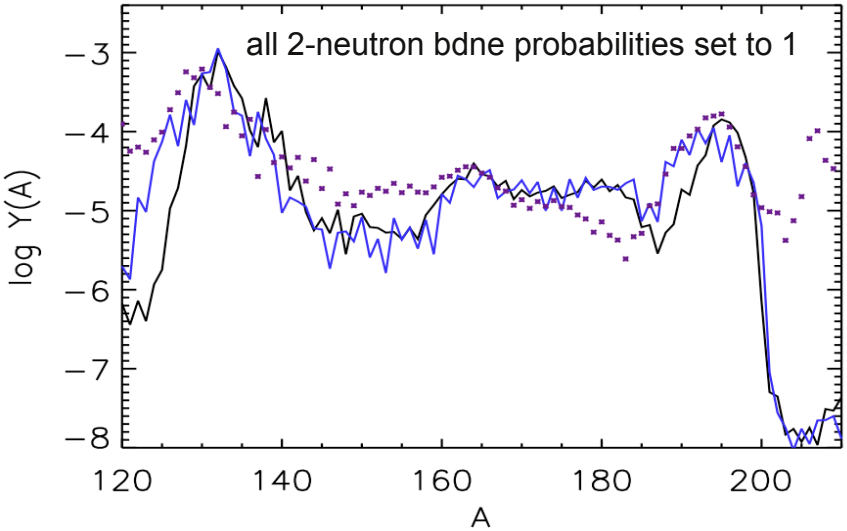
R. Surman

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



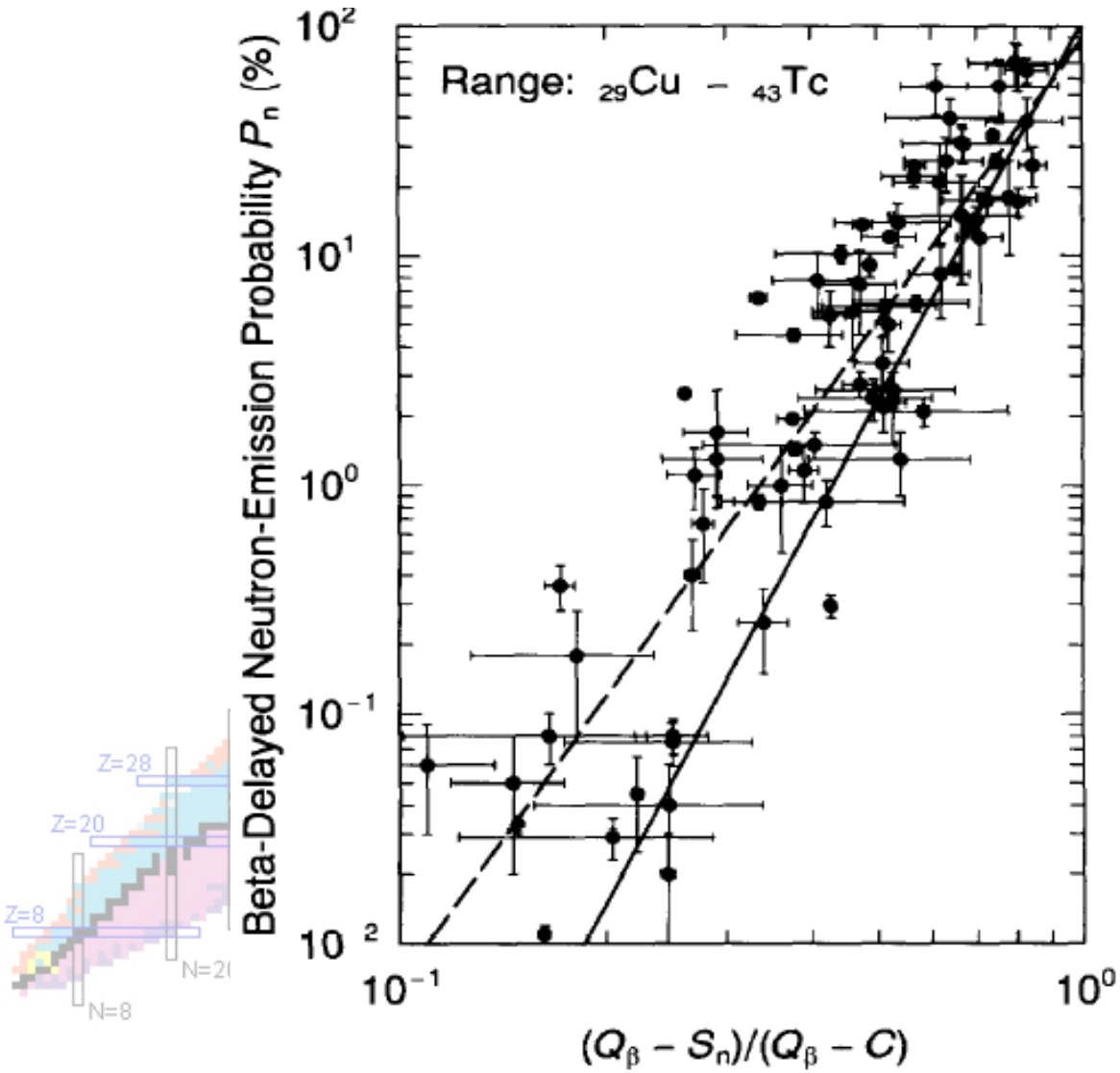






Predicting neutron branching ratios

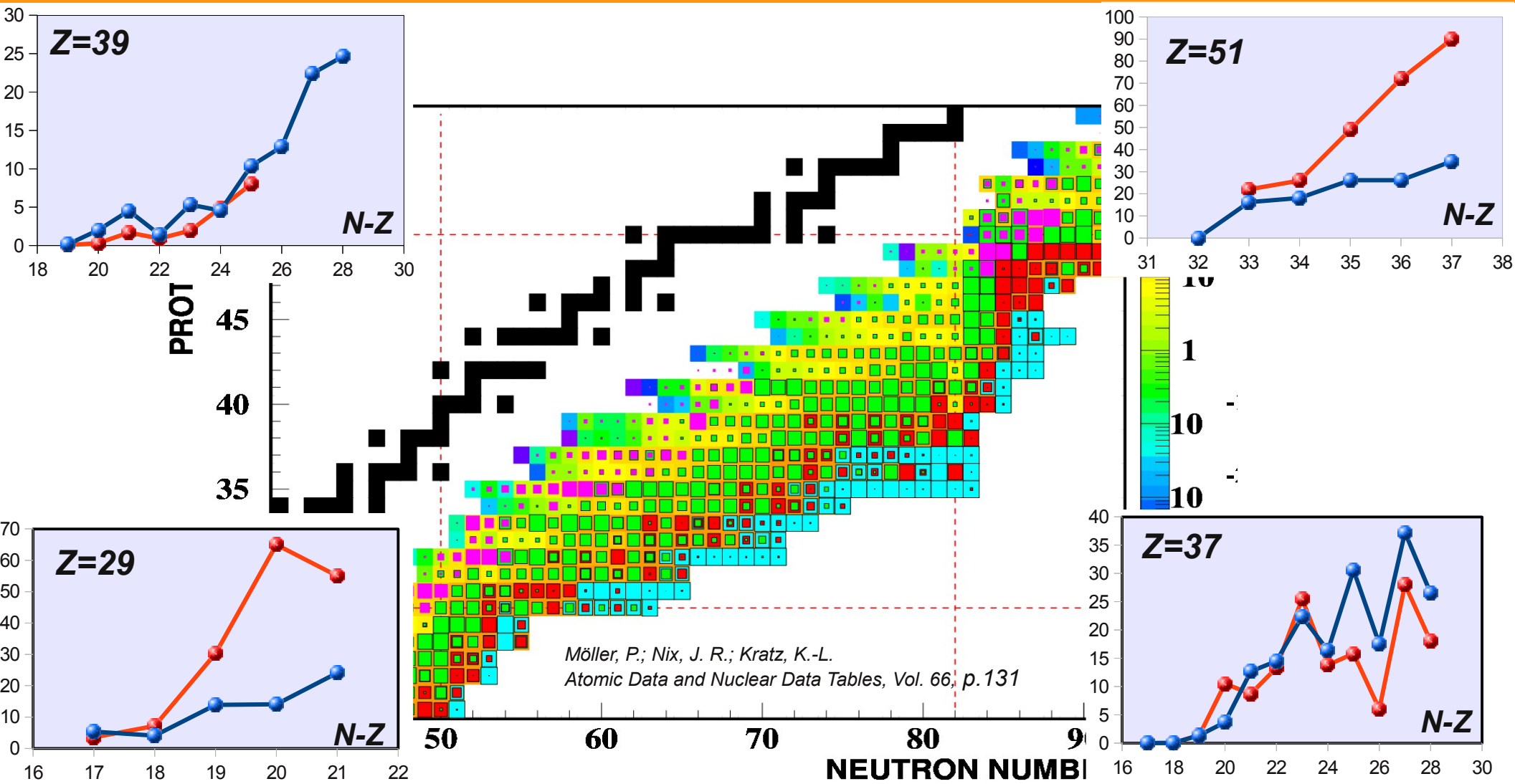
Kratz – Herrmann formula "average nucleus"



Progress in Nuclear Energy 41 p39 (2002)
B. Pfeiffer, K.L. Kratz

Predicting neutron branching ratios

Kratz – Hermann formula "average nucleus"



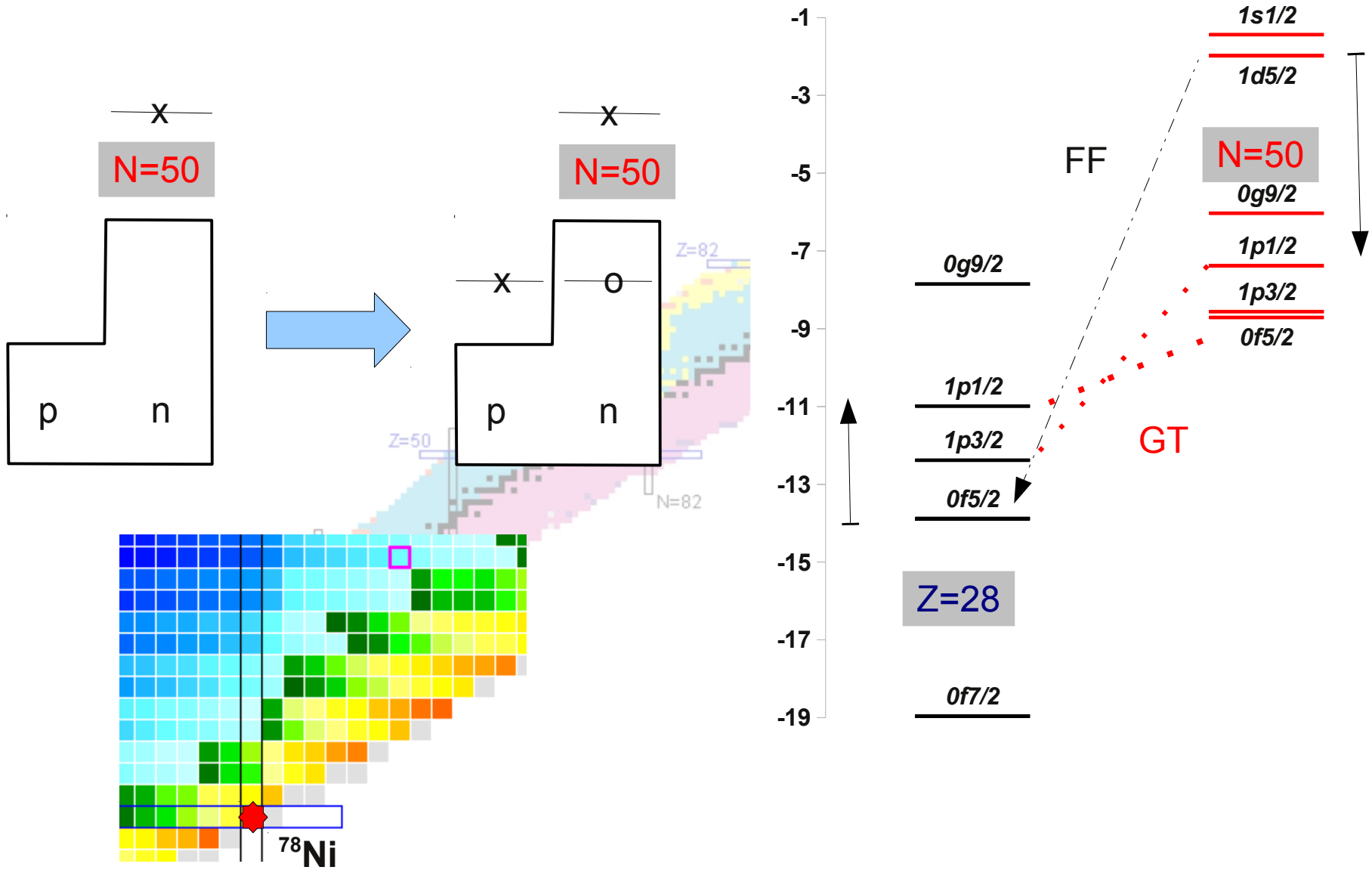
βn β2n β3n

Exp. (NNDC)

Kratz-Herman formula

Exp. (NNDC)

Beta decay of neutron rich nuclei
Allowed (GT) and “forbidden” transitions

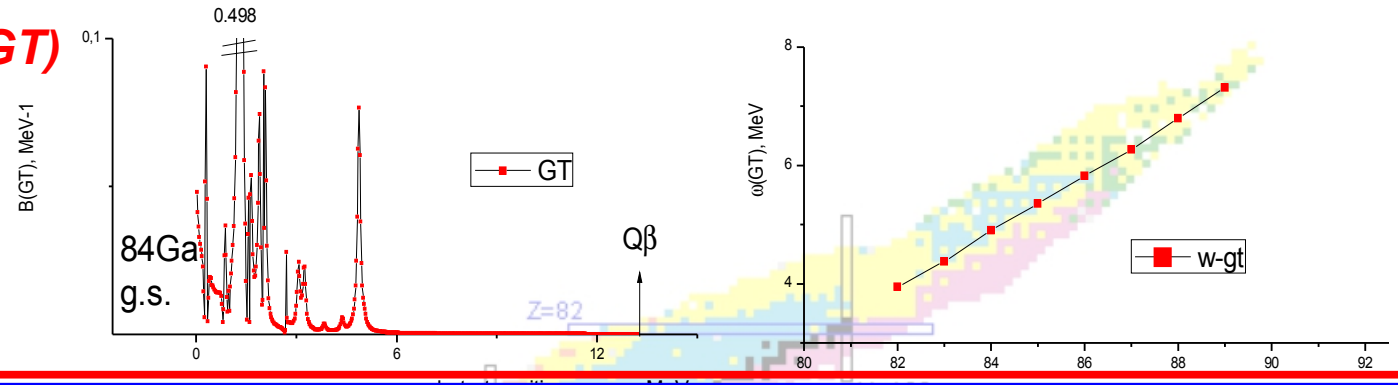


Neutron energy measurement GT

Allowed (GT) and "forbidden"FF strength from theory (^{84}Ga)

ALLOWED (GT)

GT: ω= 4.875 MeV
log(ft)=4.601

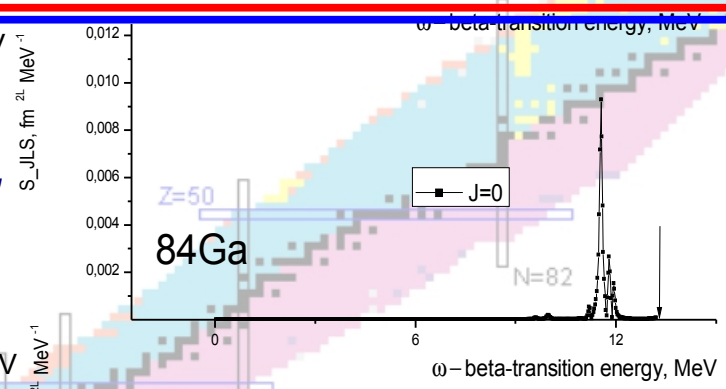


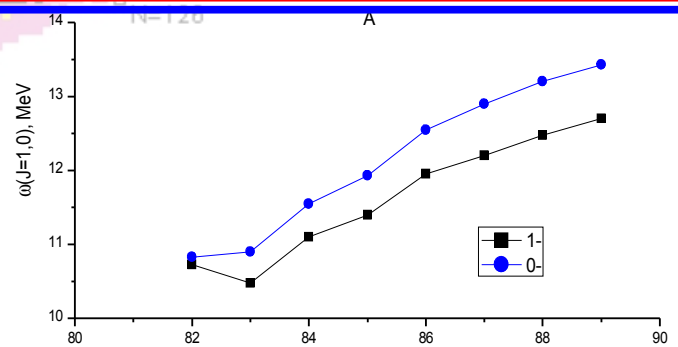
J=1: ω= 11.550 MeV
log(ft)=6.557

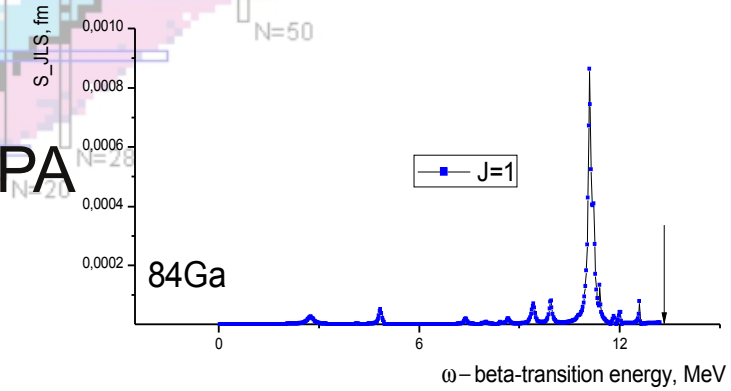
"FIRST FORBIDDEN"

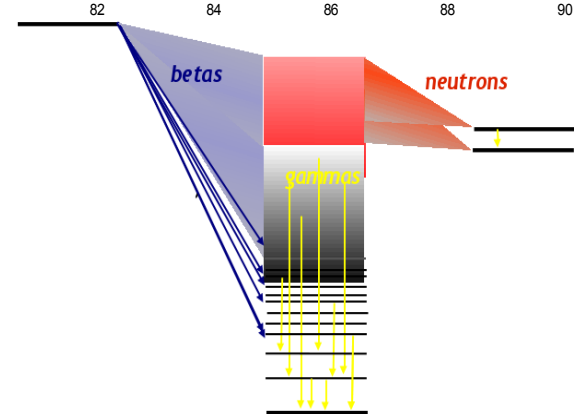
J=0: ω= 11.150 MeV
log(ft)=5.524

DF3a+QRPA
I. Borzov



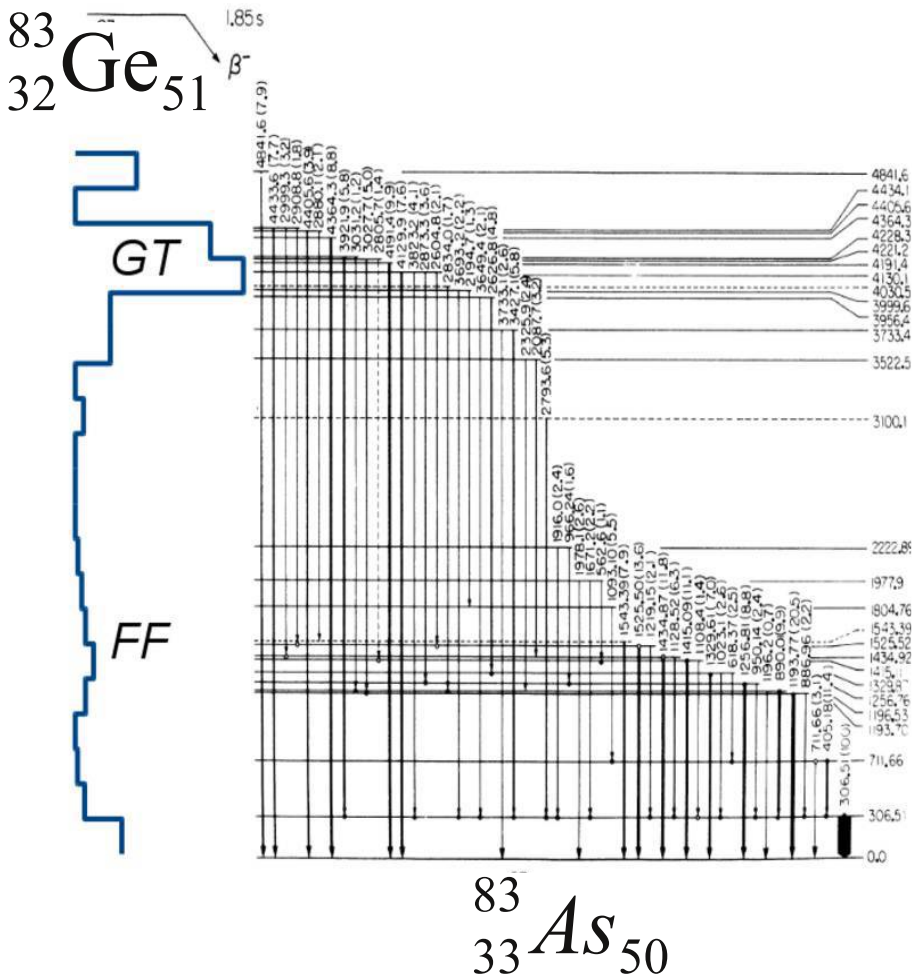


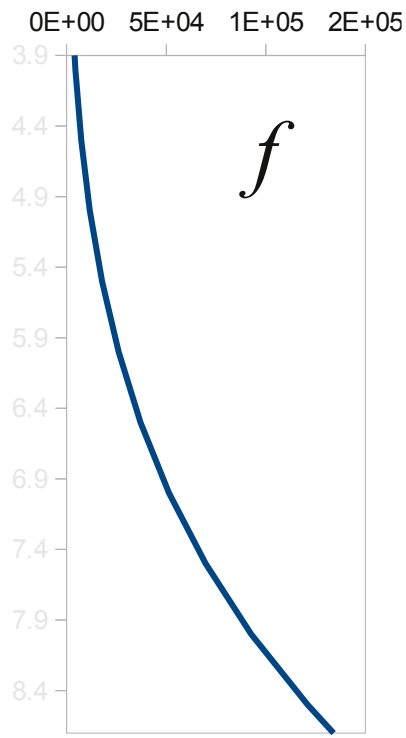


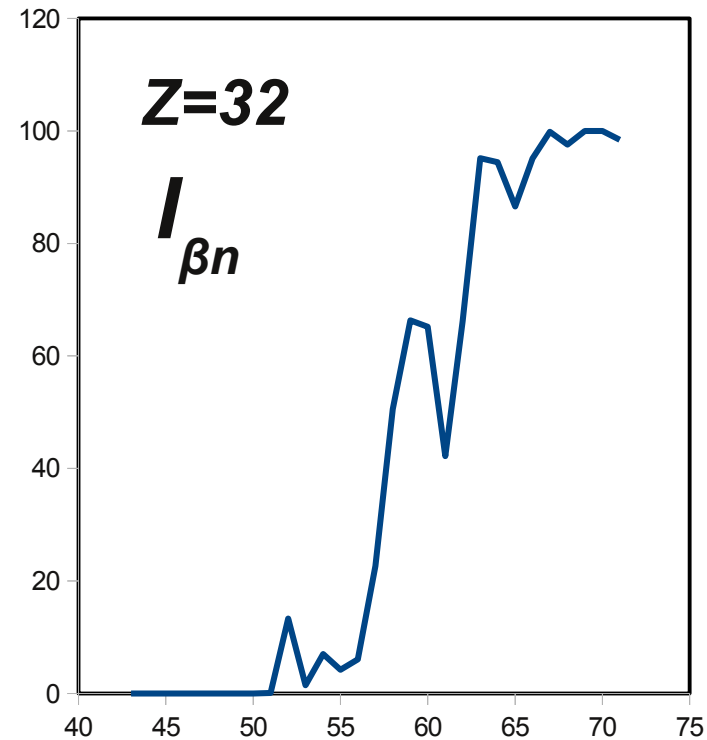


Beta decay strength distribution – allowed and forbidden transitions
"Threshold" nature of beta delayed neutron emission

*J. Winger et al., PRC **38**, 285 (1988)*







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

- First forbidden decays may influence $I_{\beta n}$
- Indicates that one may no longer observe βγ only βn/βnγ

Beta-delayed neutrons from ^{238}U fission fragments (1970-1990)

Experiments limited by experimental reach of the production and separation techniques and detector properties (long lifetimes, small Q_β-S_n)

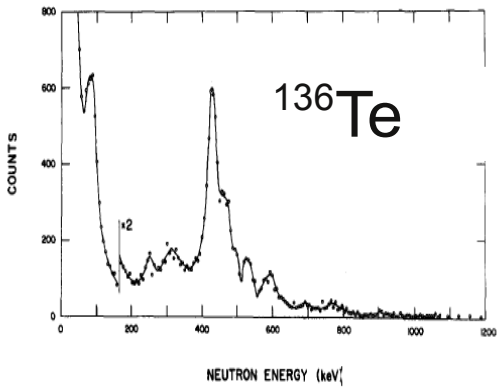
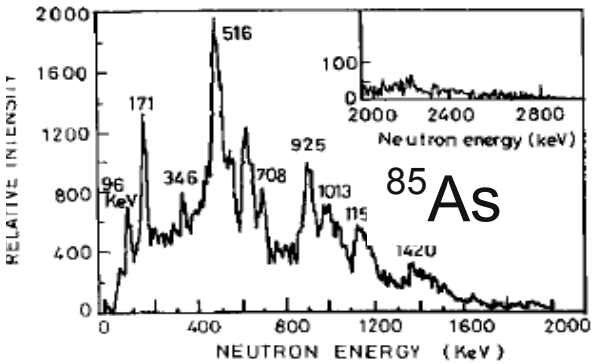


Fig. 9. The pulse height spectrum of delayed neutrons from the precursor ^{136}Te.



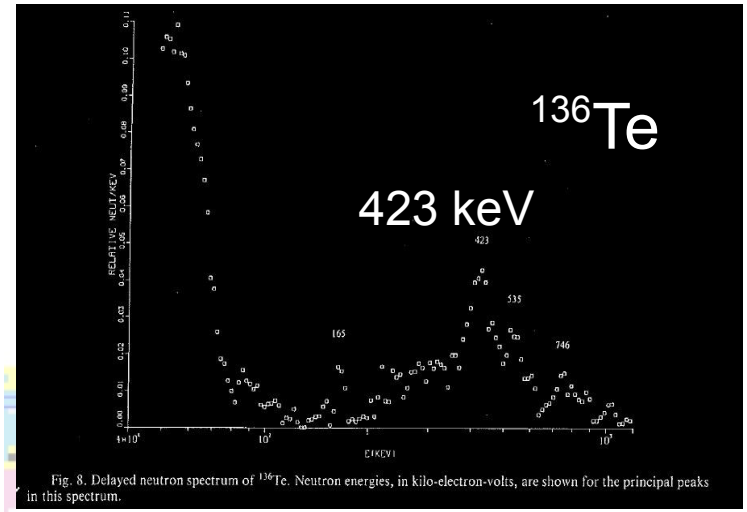
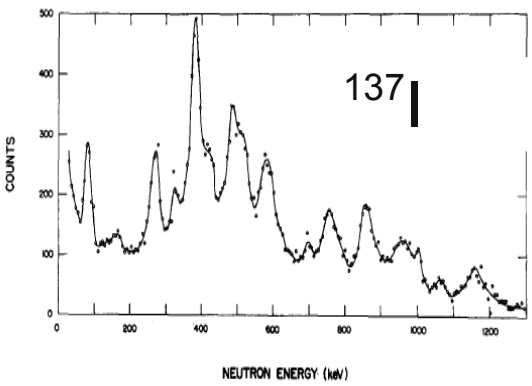
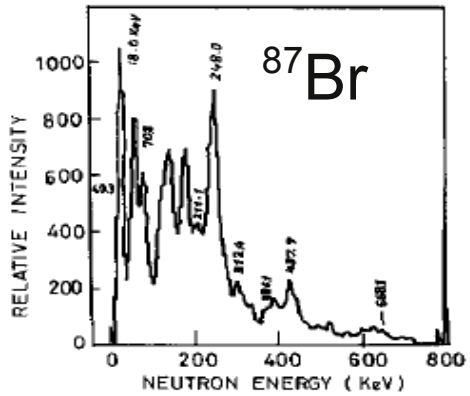


Fig. 8. Delayed neutron spectrum of ^{136}Te. Neutron energies, in kilo-electron-volts, are shown for the principal peaks in this spectrum.

R.C. Greenwood (Brookhaven, TRISTAN)



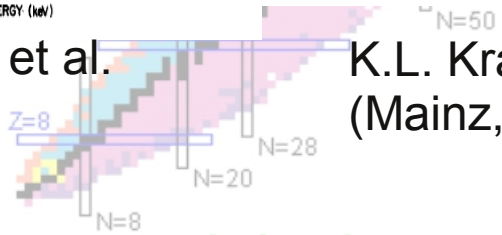


G. Rudstam et al. (Studsvik)

K.L. Kratz et al. (Mainz,ISOLDE)

^{3}He ionization chambers
H_2 and CH_4 proton-recoil proportional counters
Good resolution
Low threshold
Very low intrinsic efficiency
(NOT very usefull for exotic nuclei)

Focus mainly on reactor physics
No gamma-ray detection

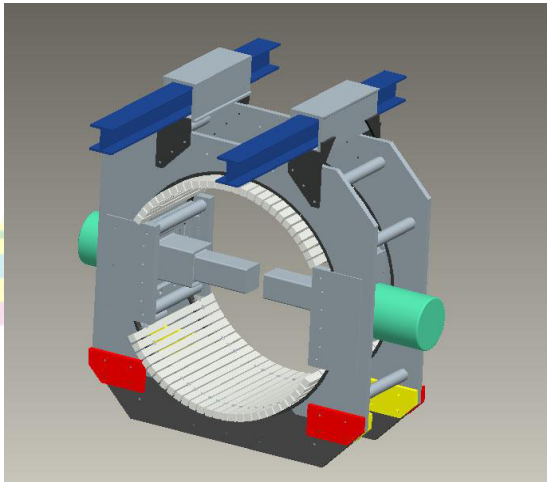


r-process nuclei – large Q values, short lifetimes
broad energy range of neutron energies (E> 100 keV)

True challenge –measure energy of the neutrons !
VANDLE - neutron time of flight detector

Center of Excellence for Radioactive Ion Beam Studies for Stewardship Science

Maximize the detection efficiency in the broad energy range

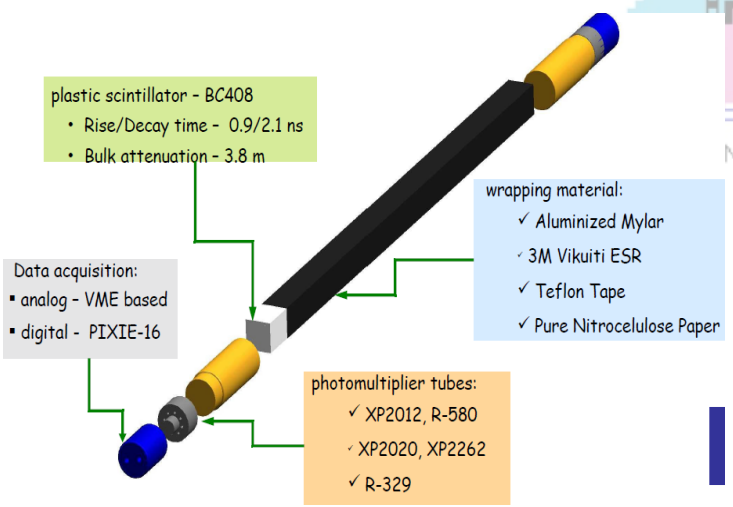


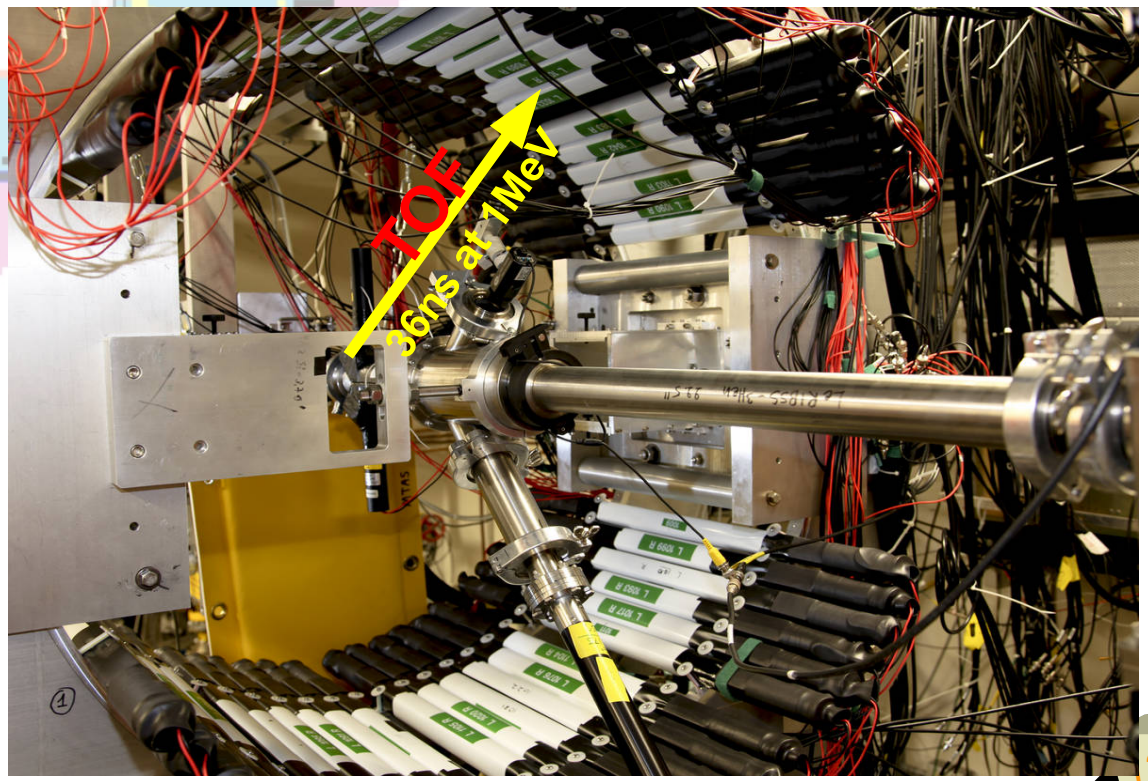
Neutrons (inelastic scattering off the scintillator material)

- **48 bars 3x3 x 60 cm^3**
- **Ω = 26% of 4π**
- **12% total efficiency @ 1MeV**
- **50 cm TOF radius**
- **40-60% efficiency "START"**

Gamma rays:

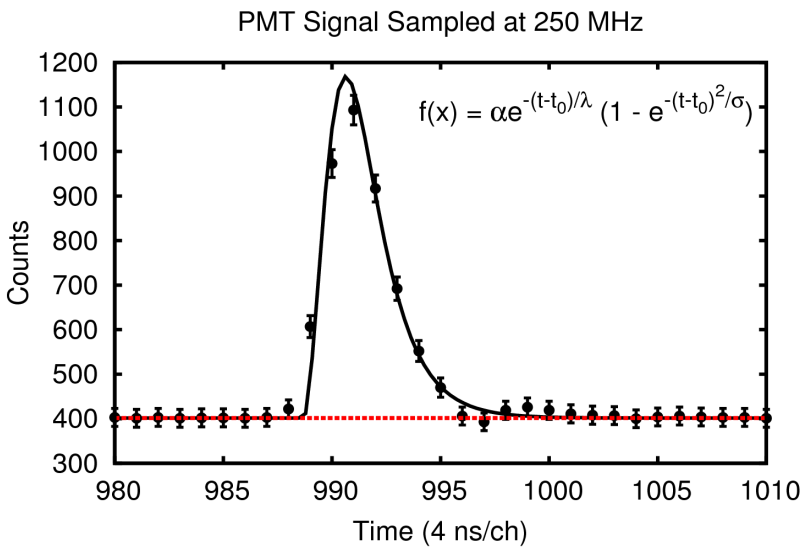
- **2 clovers, 3% efficient @ 1MeV**



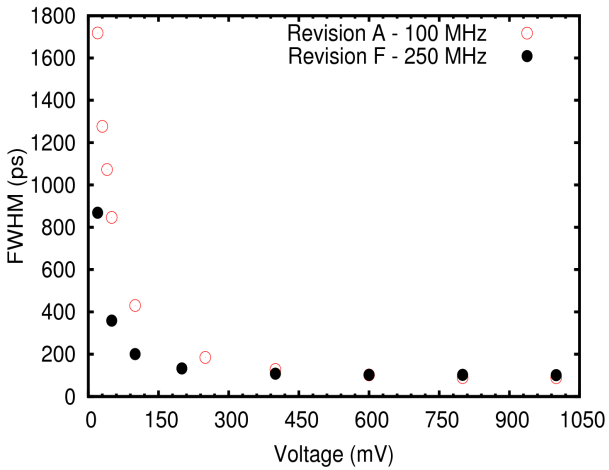


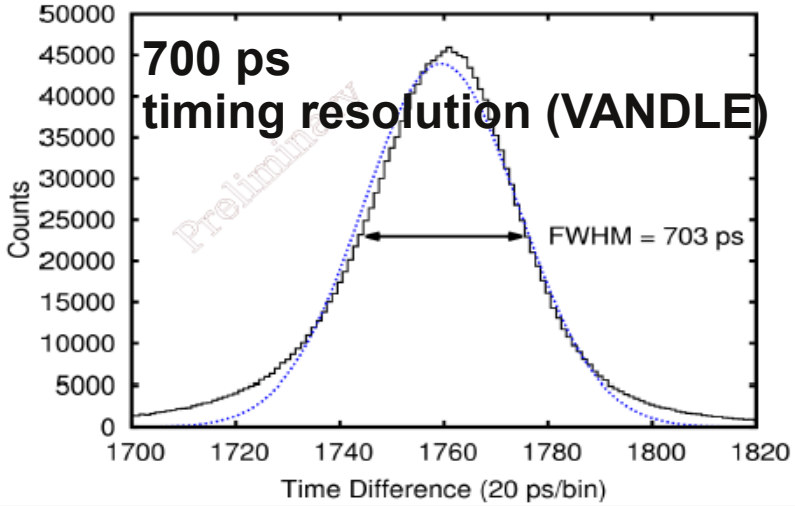
Low threshold/high efficiency digital electronics for VANDLE

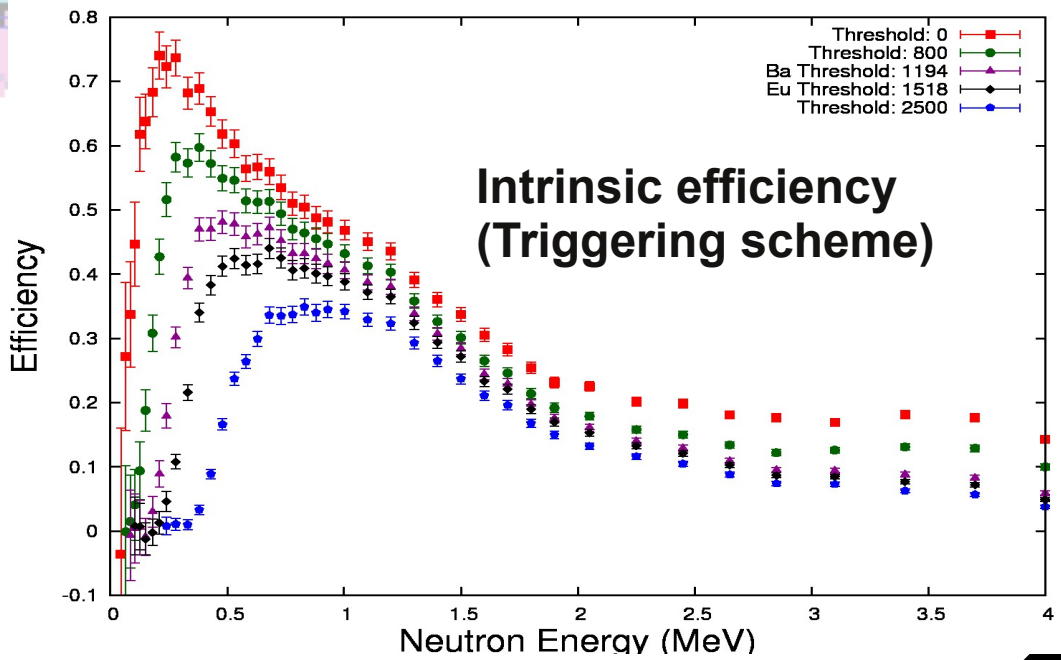
250 MSPS (4ns) digitizer
Pulse shape analysis



100 ps
timing resolution (digitizer)



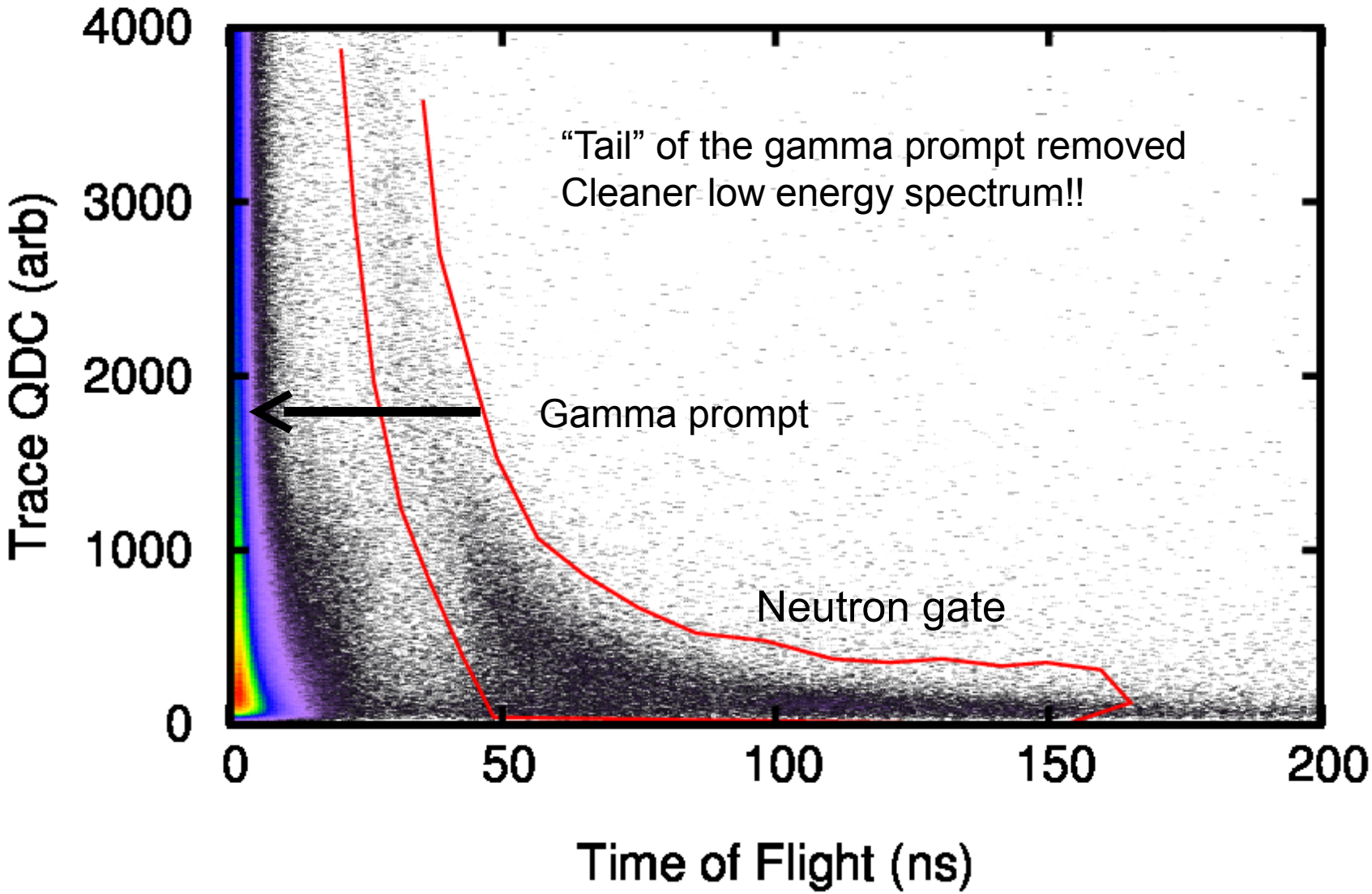




Holifield Radioactive Ion Beam Facility: accelerators and experimental areas

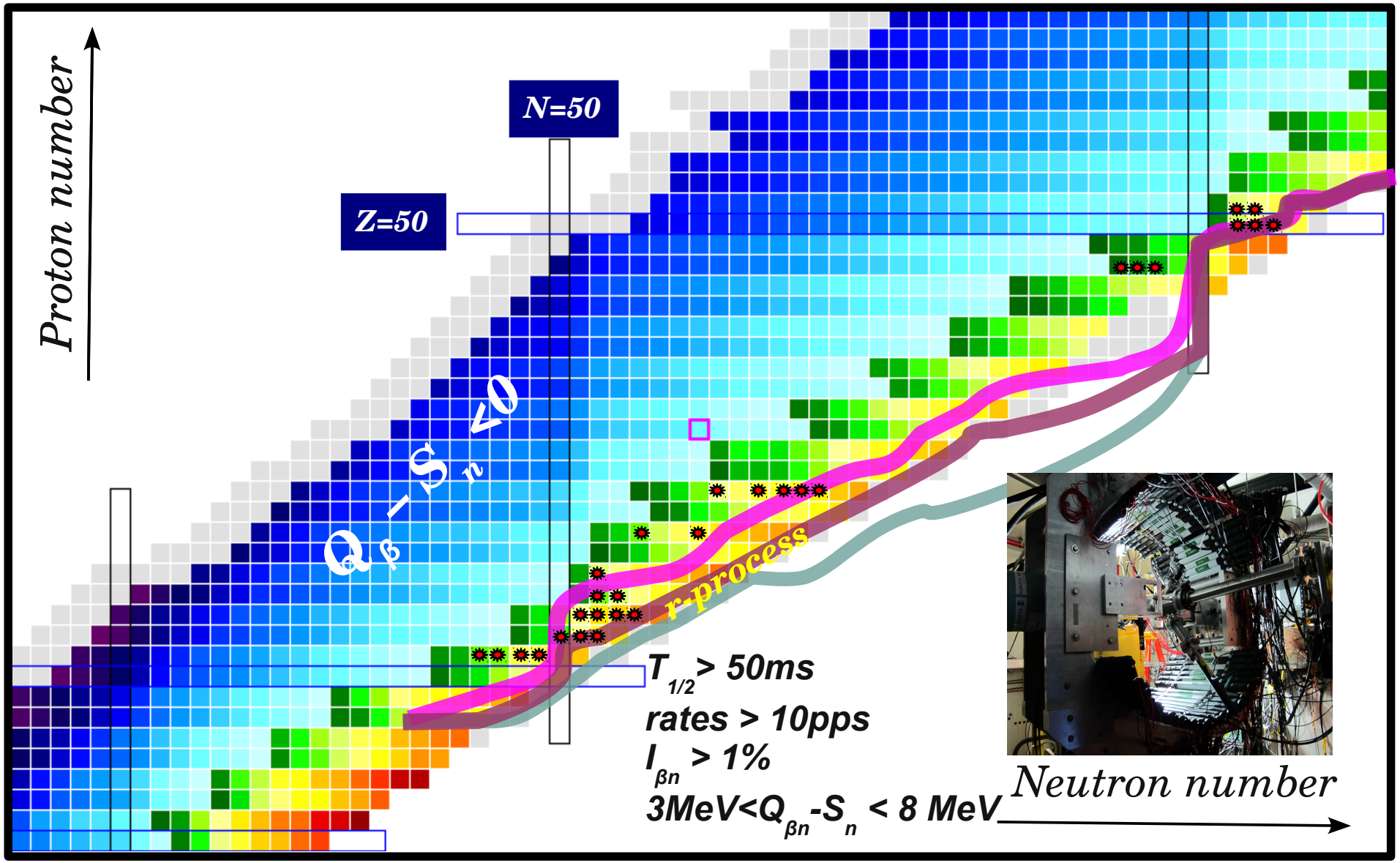
Intense beam (~10 μA) of (50MeV) protons on UCx targets
Isobar separation essential for success of the experiments !
IRIS-1/IRIS-2 platforms, negative and positive ions.

Light output vs time of flight: Neutron gate



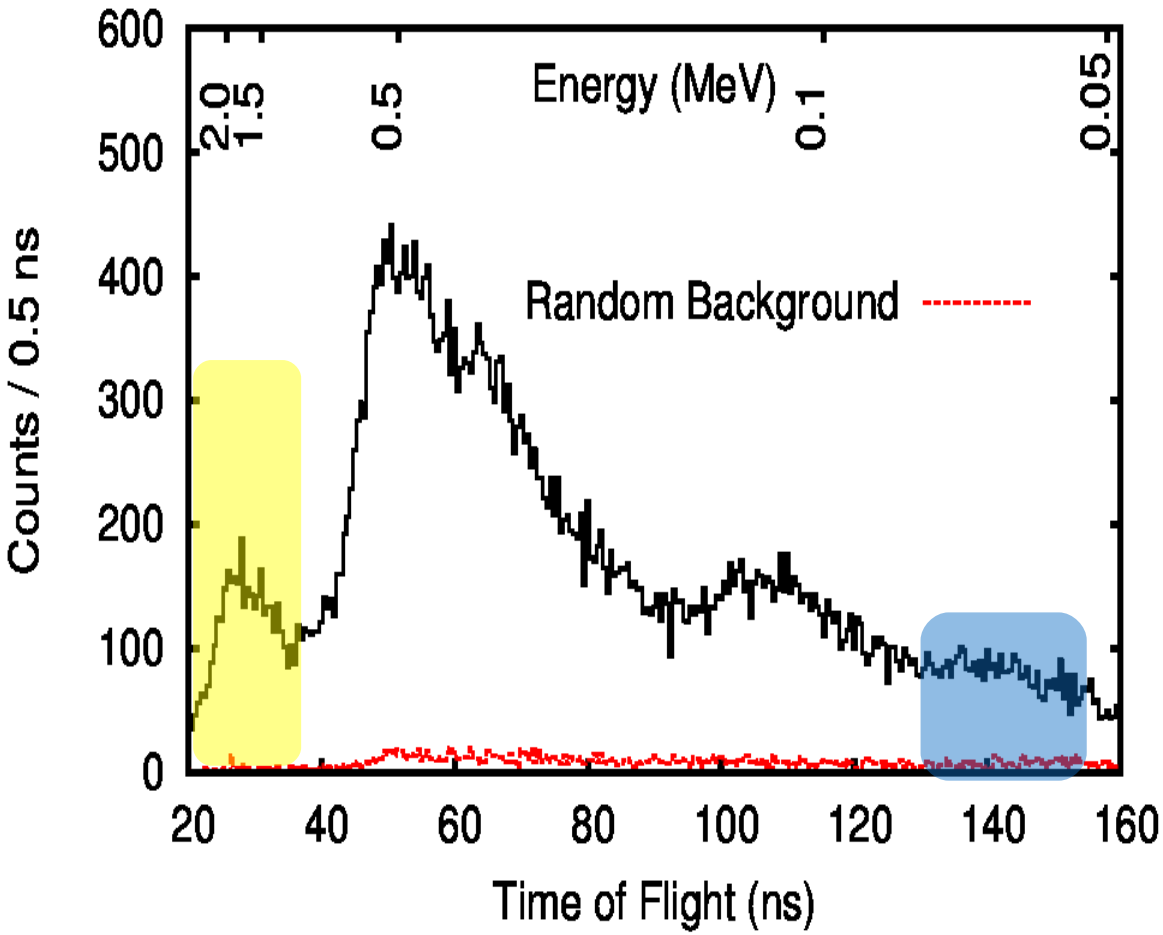
The Versatile Array of Neutron Detectors at Low Energy

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



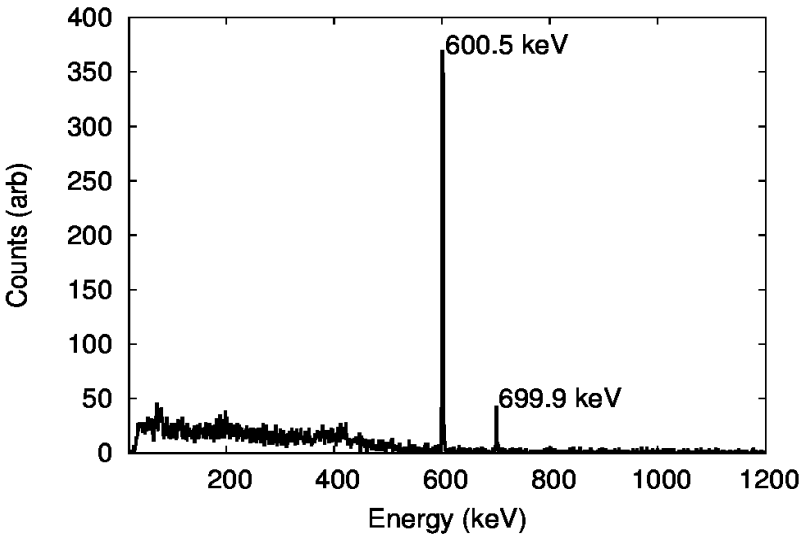
VANDLE highlights
Low/high energy neutrons from ^{77}Cu

$Q_\beta - S_n = 5.5$ MeV, $P_n = 30.3(20)\%$



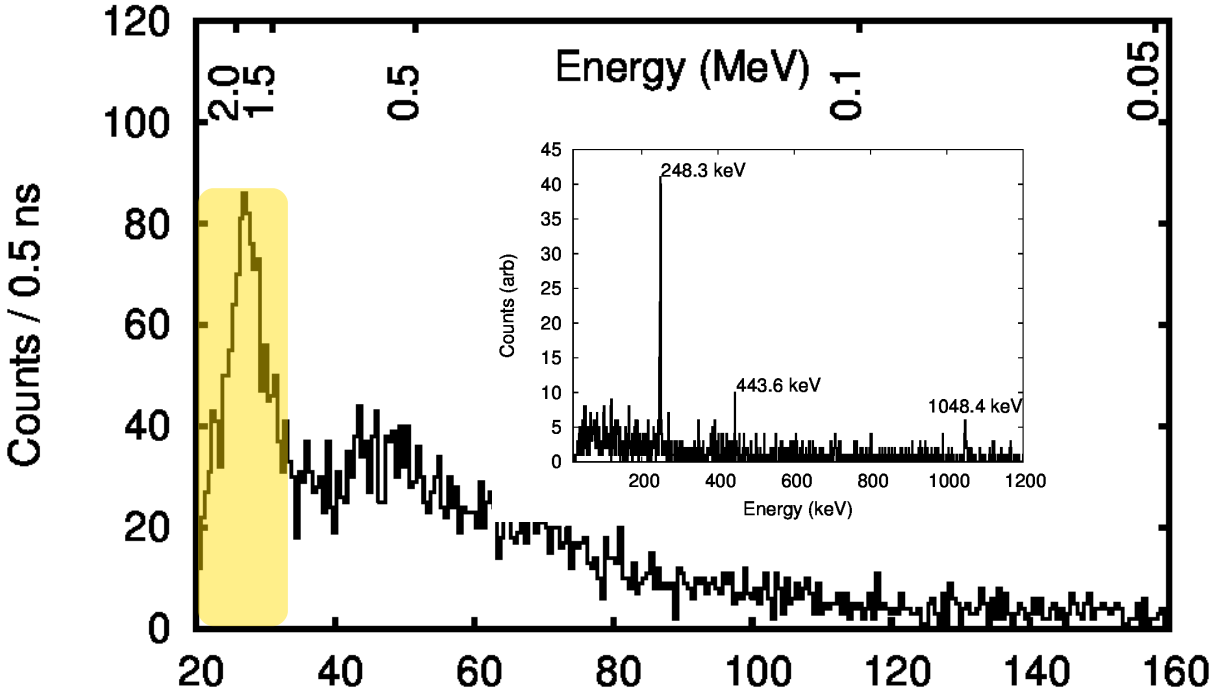
- Gamow-Teller decays at 0.5 and 2 MeV above Sn
- 100 keV neutrons detected!
- ~70 keV neutrons?
- Level 50 keV above Sn previously observed @ LeRIBSS

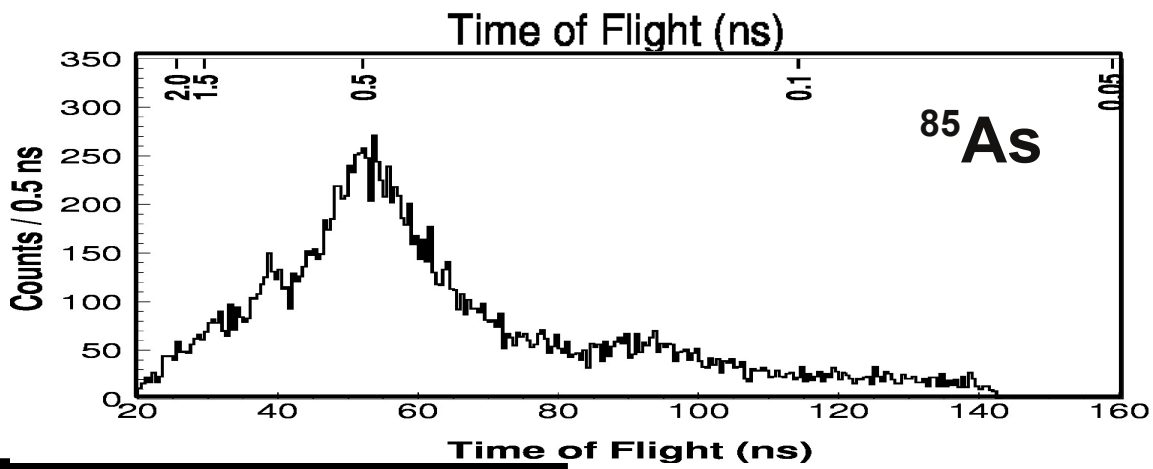
S.V Ilyushkin et al. PRC 80, 054304 (2009)



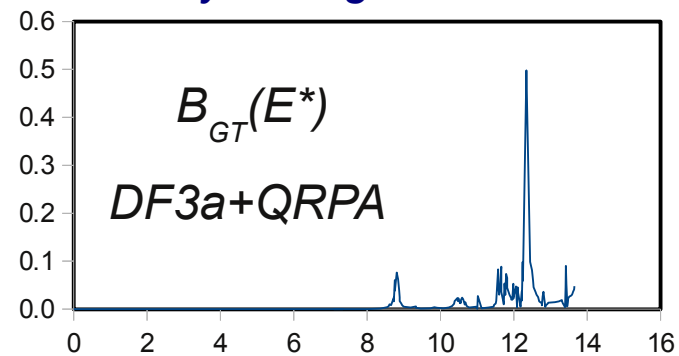
VANDLE highlights
"Resonant" decay of ^{84}Ga

$Q_{\beta\text{-}n}$ = 8.6 MeV, P_n = 74(14)%

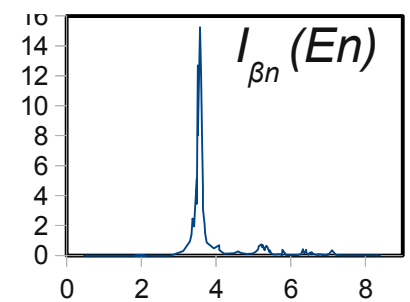




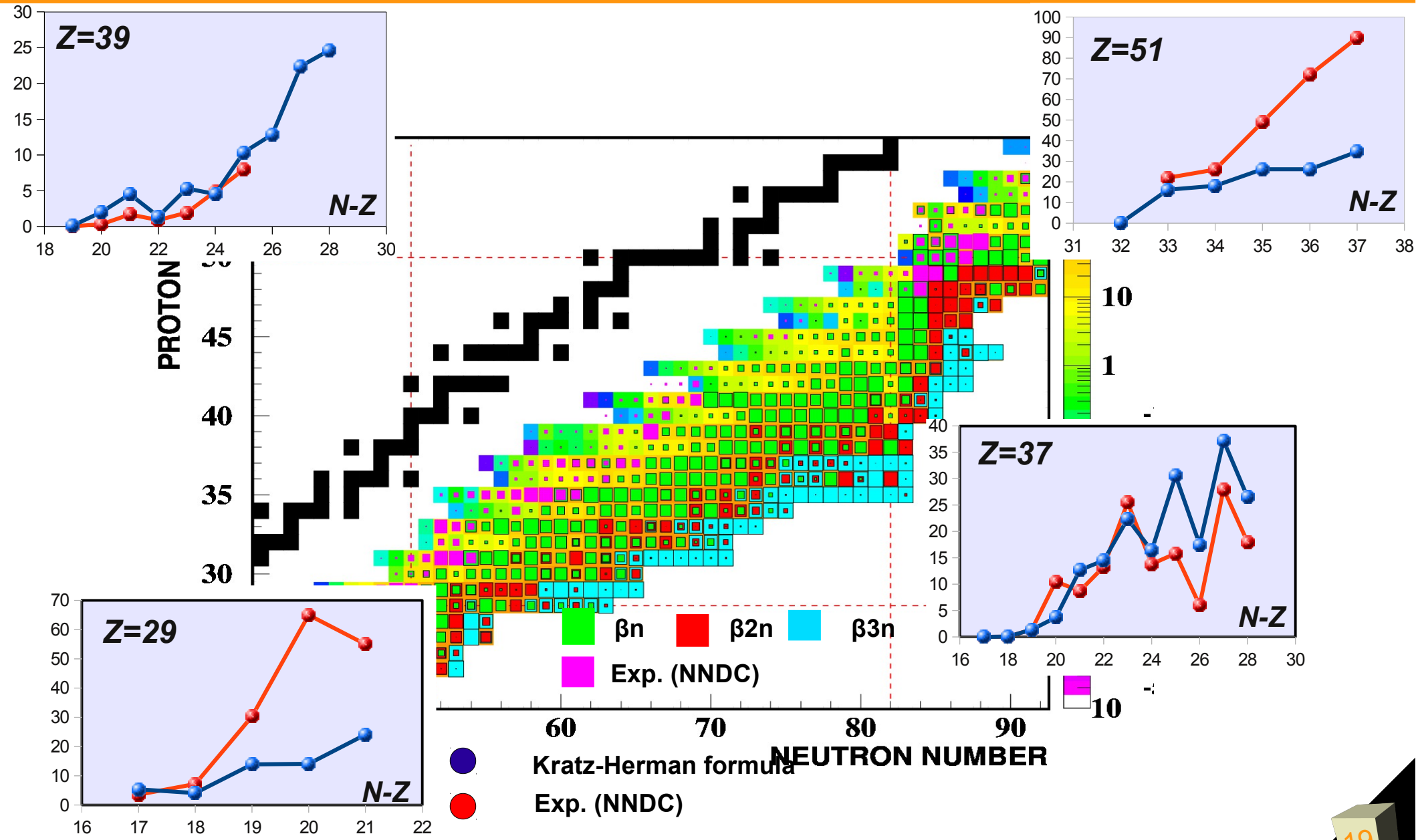
Decay strength



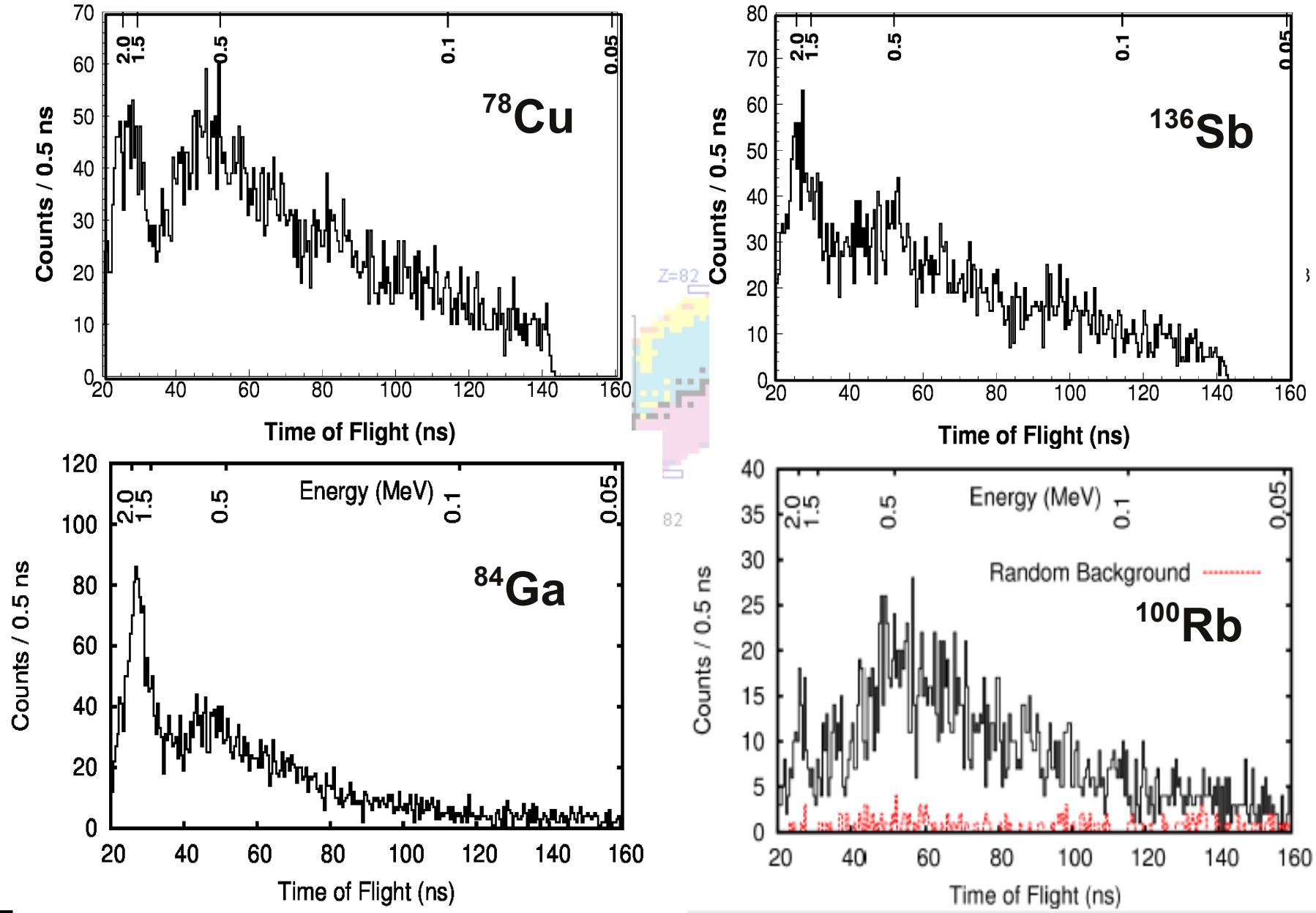
Branching ratio



Kratz-Herrmann predictions



High energy neutrons



VANDLE campaign summary

- VANDLE array commissioned in “decay” configuration
- Digital electronics enabled low energy threshold
- Survey of 30 isotopes in HRIBF campaign

Decay strength at high excitation energy
will affects nuclear lifetimes and branching ratios (βn, β2n,β3n)
“Pandemonium”, Gamma-rays following neutrons

- Analysis in progress (TOF resolution, background,theory...)
- Continue decay studies on r-process nuclei
- Complementary Total Absorption studies
- VANDLE is getting ready for “reactions” experiments

THANK YOU !

D. W. Bardayan, C. Gross, C. Jost, A.J. Mendes II,
K. Rykaczewski, D. Stracener, K. Miernik, M. Wolinska-Cichocka, *ORNL*
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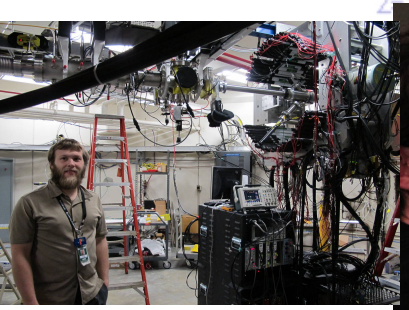
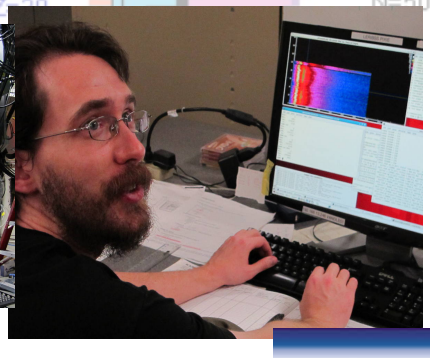
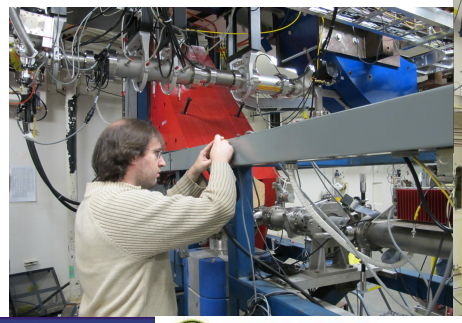
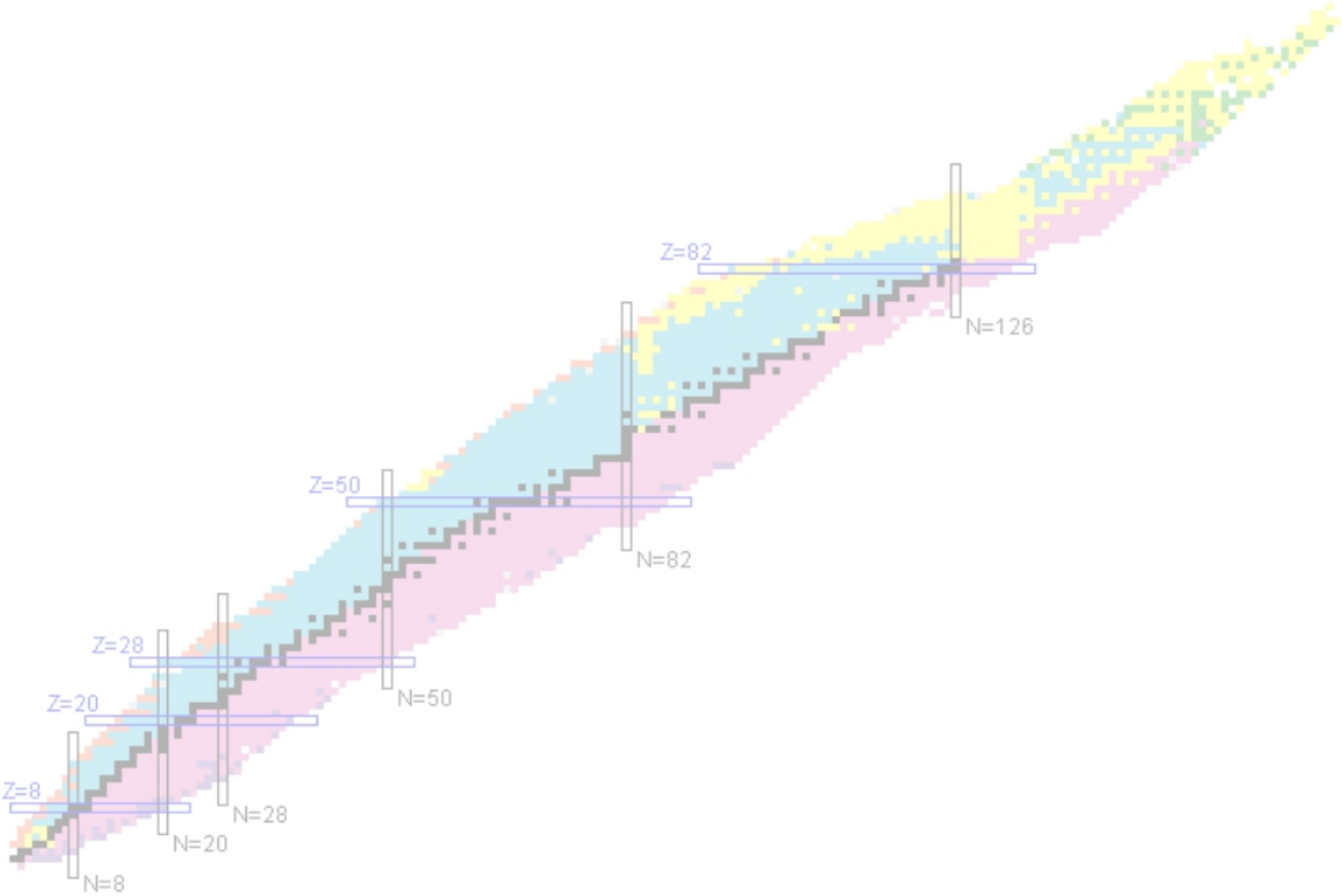
J.C. Batchelder, S. Liu, C. Matei and I. Spassova, *ORAU*
N. Brewer, J.K. Hwang, *Vanderbilt*
P.D. O'Malley, M. Howard, B. Manning,
E. Merino, and J. Cizewski, *Rutgers U.*
C. Brune and T. Massey, *Ohio U.*
S. Ilyushkin, F. Raiola, D. Walter,
and F. Sarazin, *Colorado School of Mines*
J. Blackmon, E. Zganjar, *Louisiana State U.*
P.A. Copp, *WUL*





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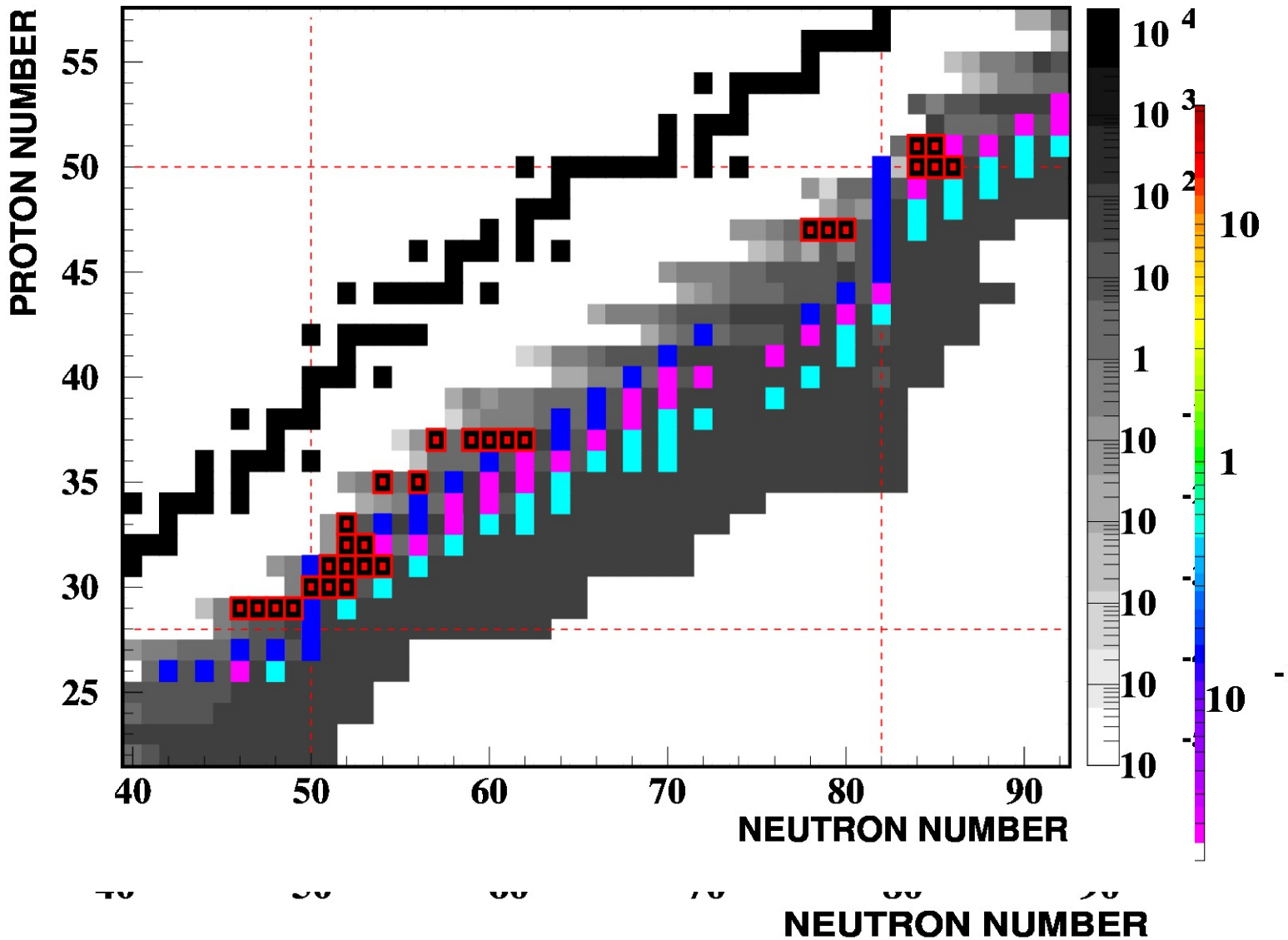
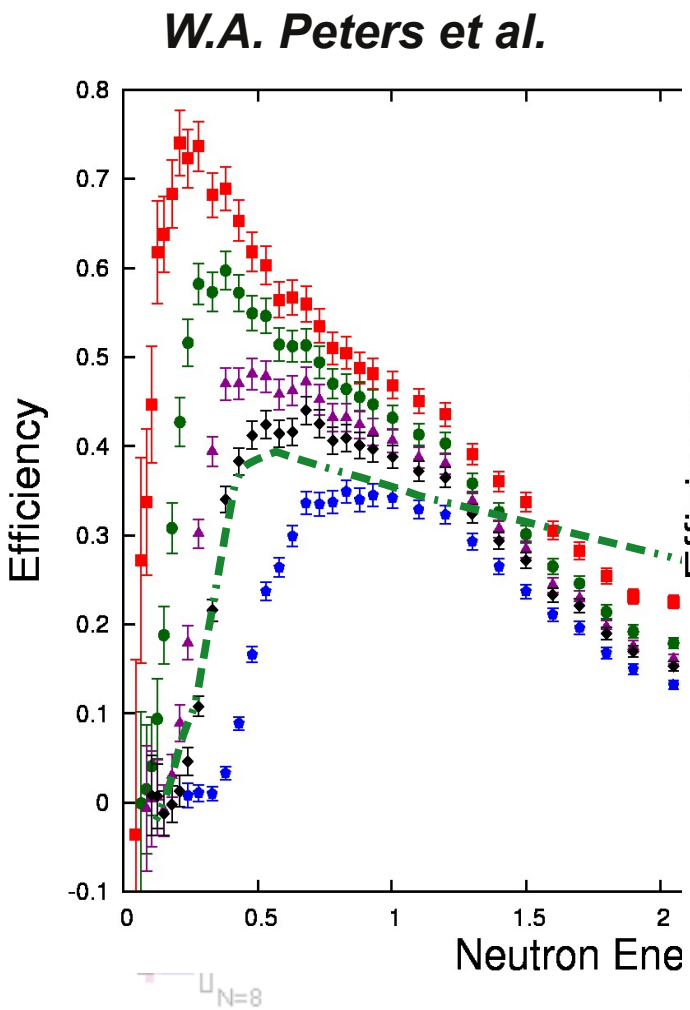
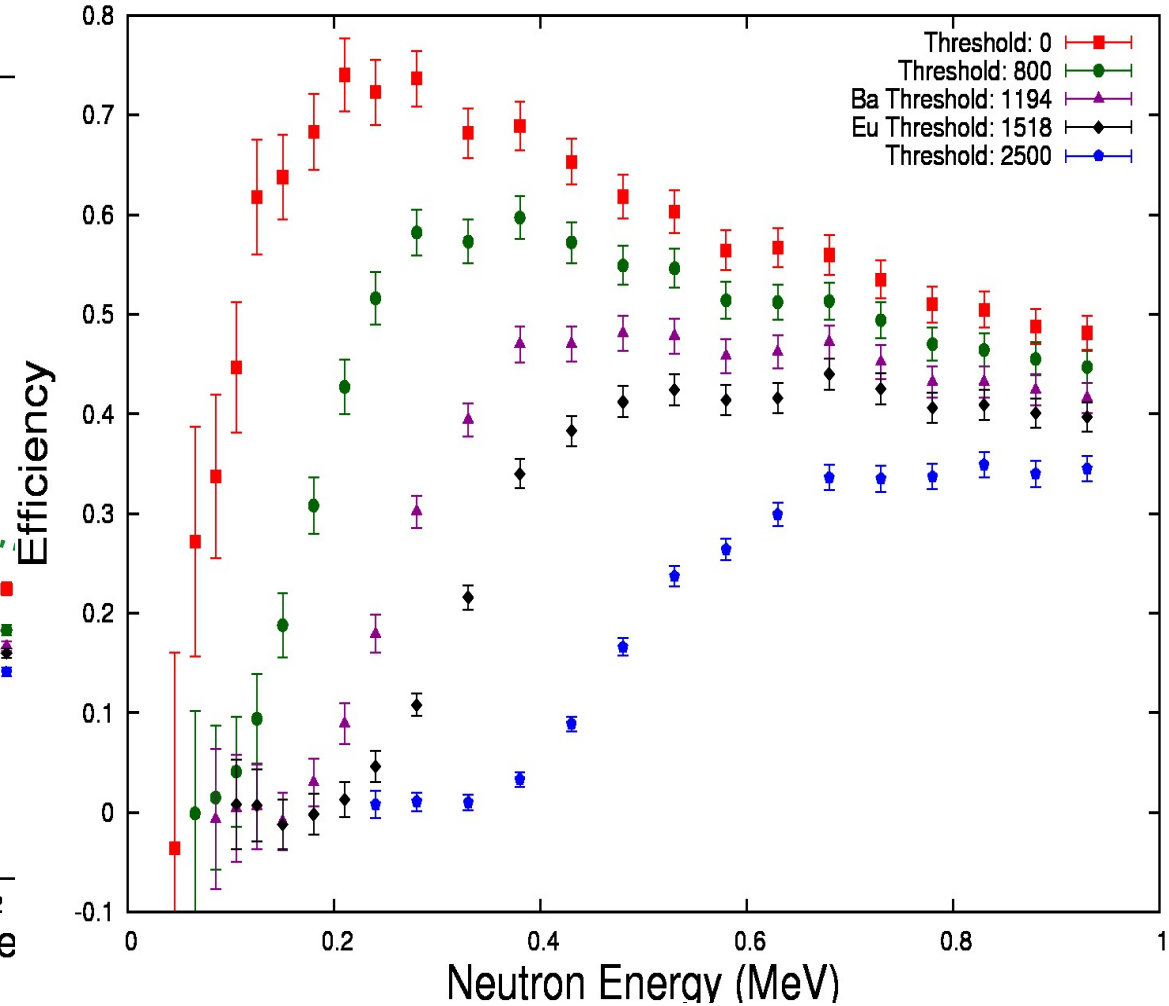
Z=50
N=82
Z=28
N=50
Z=20
Z=8
N=28
N=20
N=8


PROTON NUMBER
55
50
45
40
35
30
25
40
50
60
70
80
90
NEUTRON NUMBER
NEUTRON NUMBER

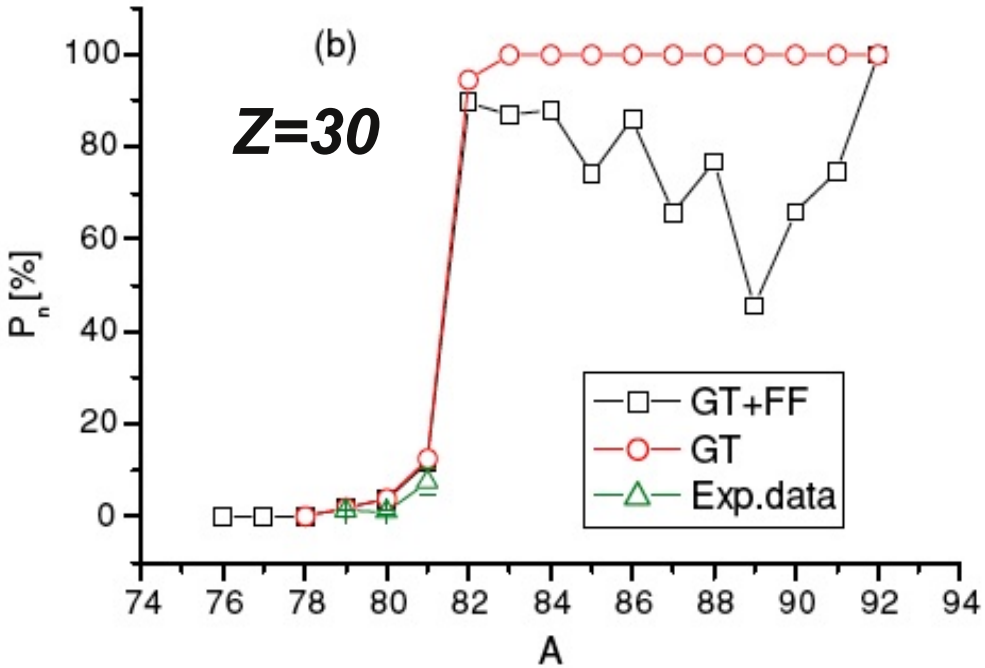
Intrinsic neutron detection efficiency
Small VANDLE bar

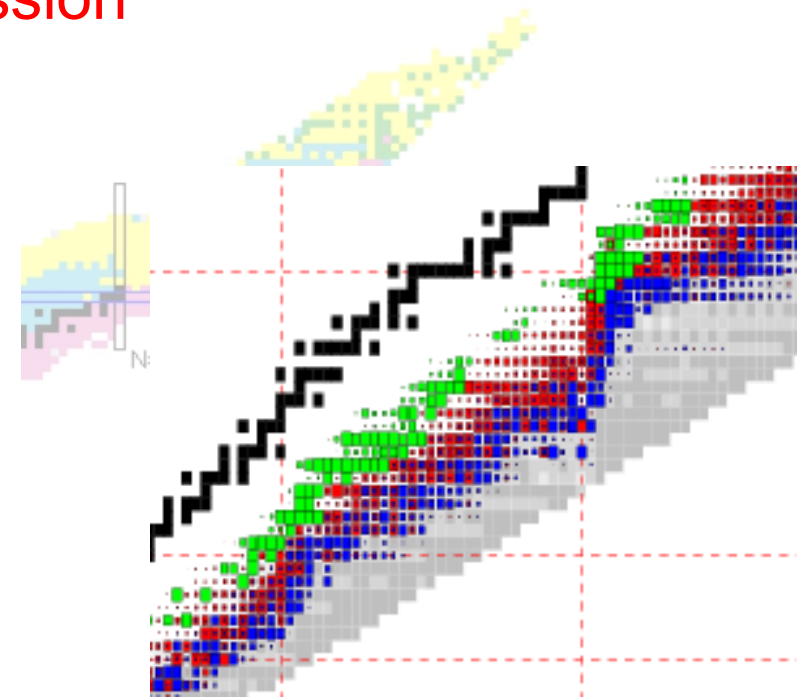




Beta delayed neutron branching ratios Isotopes with N>50

Threshold character of the beta-n emission position of GT vs. Q_β window





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- First forbidden decays may influence $I_{\beta n}$
- Indicates that one may no longer observe βγ only βn/βnγ