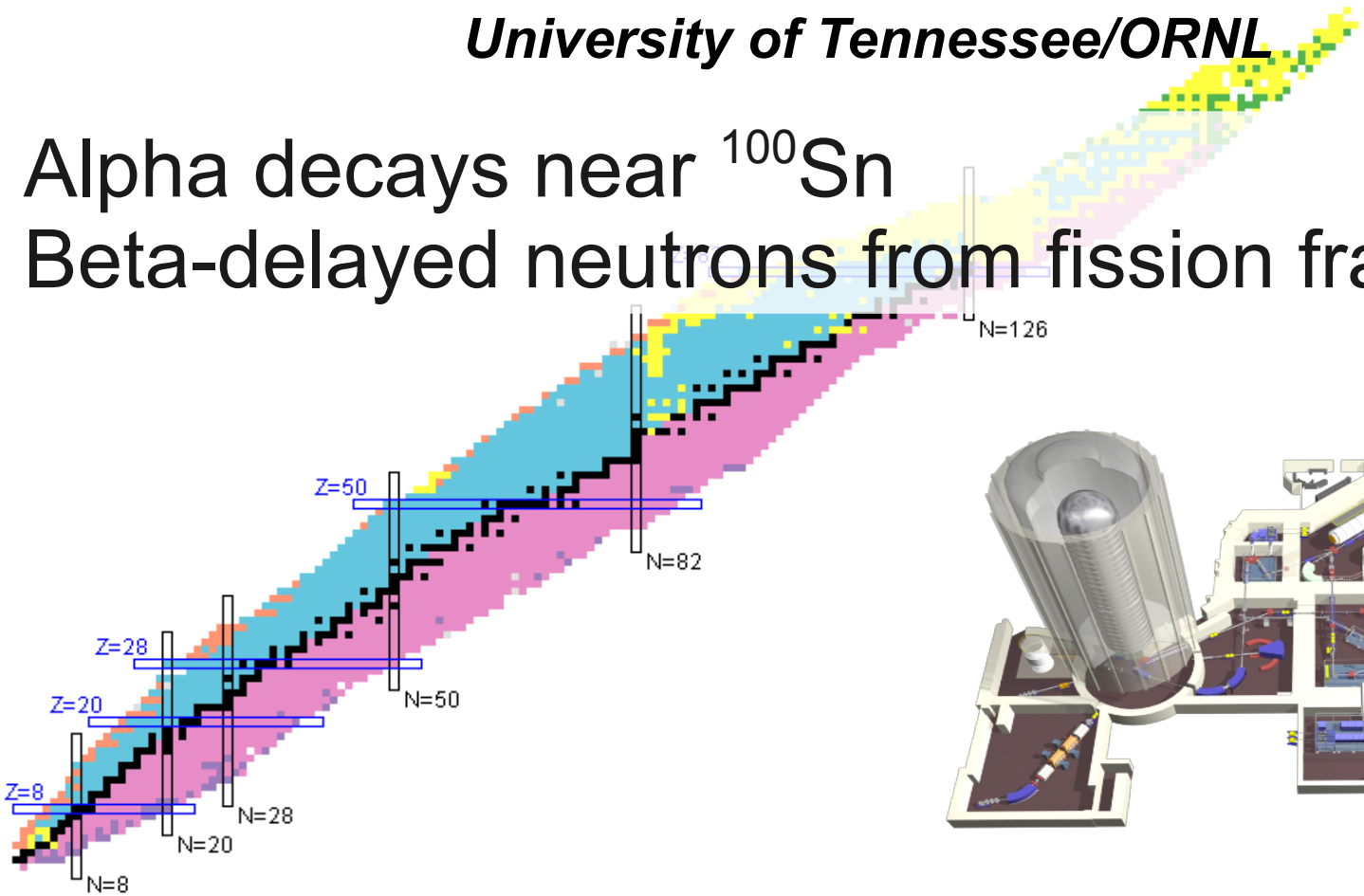
Hard to measure nuclear decays: Digital spectroscopy of nuclei far from stability.

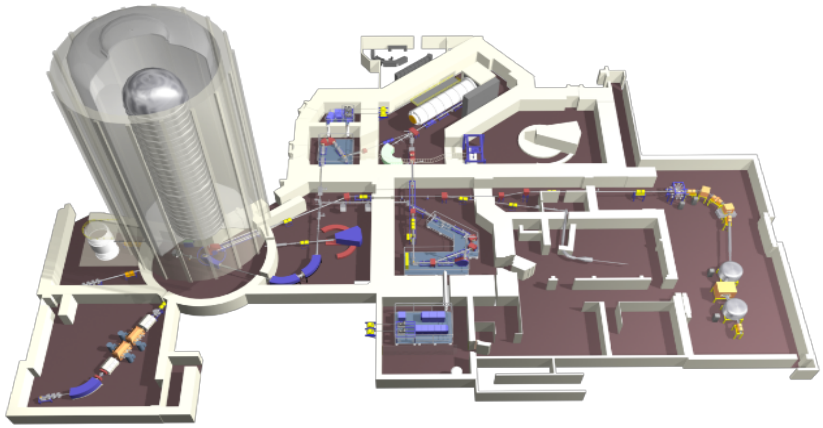
Robert Grzywacz

University of Tennessee/ORNL

Alpha decays near ^{100}Sn

Beta-delayed neutrons from fission fragments





The digital magic...

Signal is processed with numerical algorithms operating on its discrete represention.

- Signals exist as digital data streams
- Digital information can be stored and retrieved without losses
- Single data stream can be multiplied and each stream processed independently
- Correlations between separate data streams can be made on arbitrary time scale
- Decisions can be made with a preferred, user defined, numerical algorithm

The essential components of the real-time DSP system

60 MB/s/channel

total system load 5.8 GB/s

Analog

Digital

Field Programmable Gate Array

sampling ADC (40 MHz-100 MHz)

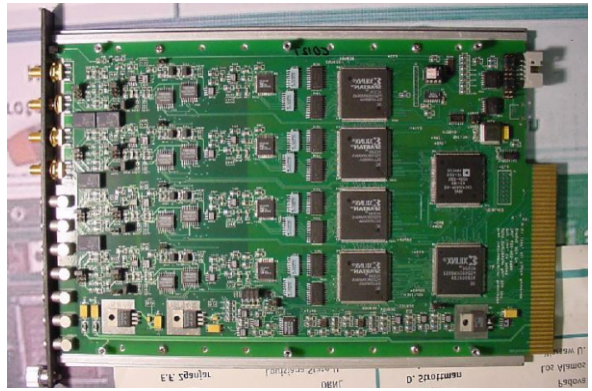
Selective triggering (0.3Mb/s)

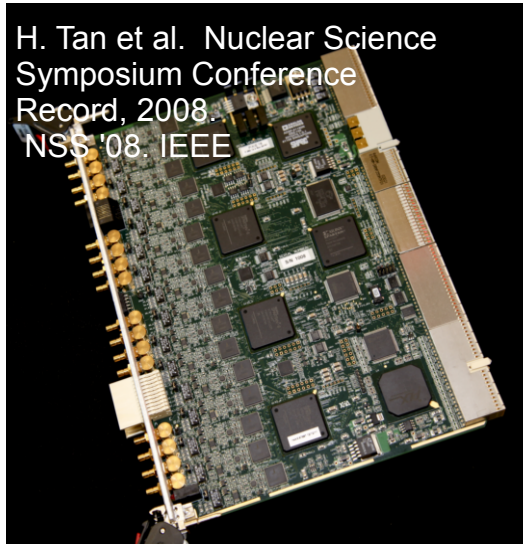
Digital filters implemented in real-time operations on-board and in post-processing.

Experiments enabled by Digital Data Acquisition

Uniform hardware (DGF4c, Pixie16) with any detector system ...

Summary Reviews:
R. Grzywacz et al. , Proc. of ENAM01 Conference 2001, p 453
R. Grzywacz et al., NIM. B 204, 649 (2003)
R. Grzywacz et al.,NIM B 261, 1103 (2007)
Selected articles: (DGF4C)
W. Królas et al., Phys. Rev. C 65, 031303 (2002)
M. Pfützner et al., NIM A 493 (2002) 155 (GSI)
M. Karny et al. Phys. Rev. Lett. 90, 012502 (2003)
R. Grzywacz et al. Eur. Phys. J. A 25, s1.145-s1.147 (2005)
S.N. Liddick et al., Phys. Rev. Let., 97, 082501 (2006)
C. Mazzocchi et al., Phys. Rev. Let. 98, 212501 (2007)
M. Karny et al., Phys. Let. B 664, 52 (2008)
J.A. Winger et al., Phys. Rev. Lett. 102, 142502 (2009)
I.G. Darby et al., Phys. Rev. Lett. 105, 162502 (2010)
*S.N. Liddick, I.G. Darby and R.K. Grzywacz NIM A **669**, 70 (2012)*
Pixie 16
*S. Ilyushkin et al. Phys. Rev. C **80**, 054304 (2009)*
*M. Madurga et al. AIP Conf. Proc., **1336,** 586 (2010)*
*S. Padgett et al. Phys. Rev. C **82**, 064314 (2010)*
D.T. Miller et al. GSI Scientifig Report (2011)
*L. Cartegni et al. Phys. Rev. C **85**, 014312 (2012)*
*M.M. Rajabali et al. Phys. Rev. C **85**, 034326 (2012) (NSCL)*
*S. Liddick et al. Phys. Rev. C **85**, 014328 (2012) (NSCL)*
*A. Korgul et al. Phys. Rev. C **86**, 024307 (2012)*
*M. Madurga et al. Phys. Rev. Lett. **109**, 112501 (2012)*
*C. Mazzocchi et al. Phys. Rev. C **87,** 034315 (2013)*





Many of those experiments were possible only with digital system !

Alpha decay island near ^{100}Sn

Enhanced alpha decays (N~Z)

"Superallowed" alpha decay

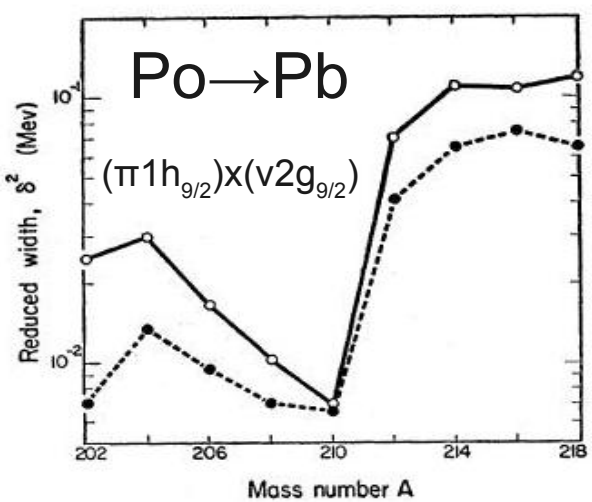
MacFarlane and Siivola, PRL 14,114,1965

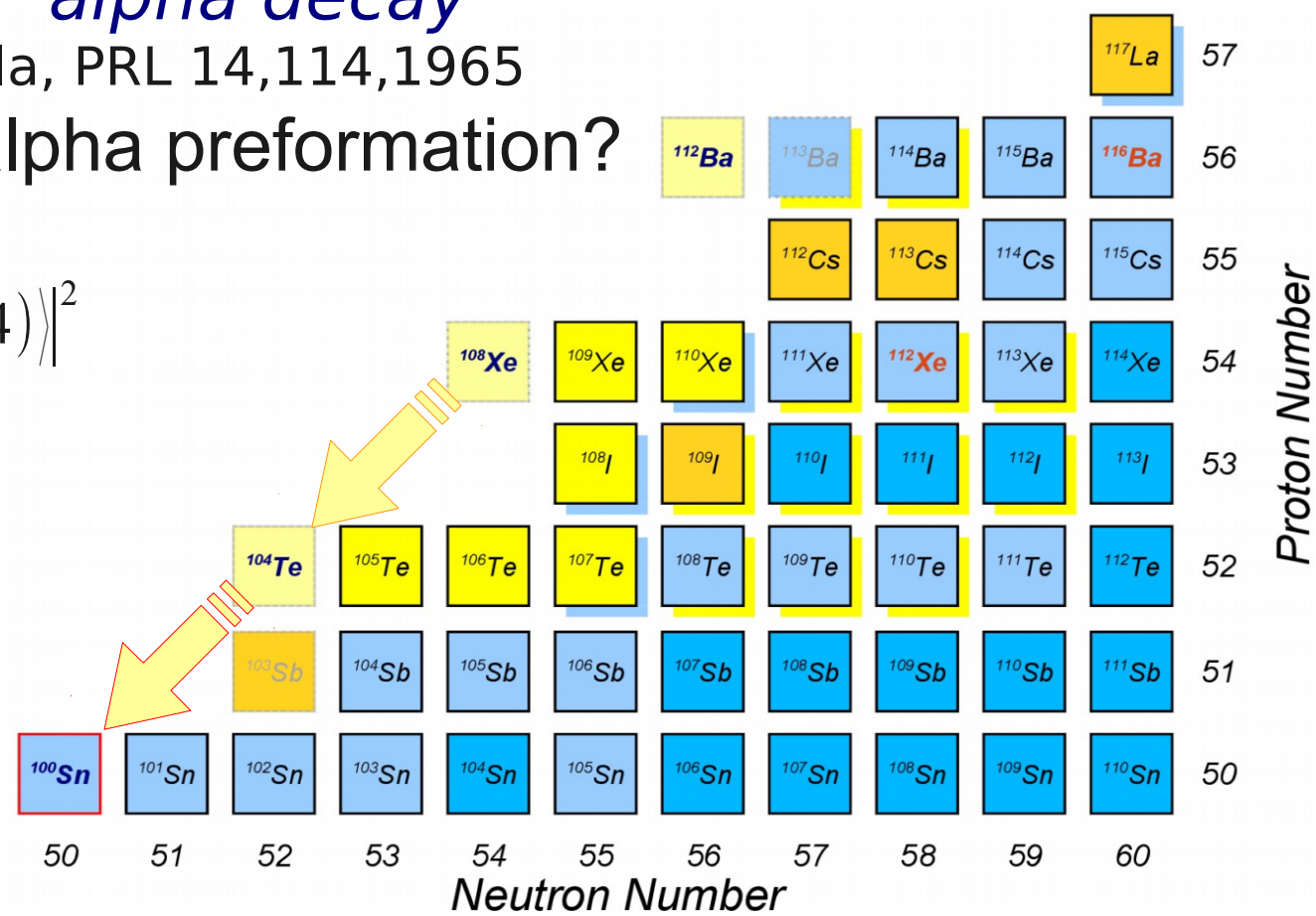
Do we understand alpha preformation?

$$\lambda = A_\alpha^2 fP$$

$$A_\alpha^2 = \left| \langle \psi_i(A) | \psi_f(A-4)\varphi(4) \rangle \right|^2$$

H. Mang PRC 119(1960) 1069





R. IdBetan and W. Nazarewicz
Phys. Rev. C 86, 034338 (2012)
α decay in the complex-energy shell model

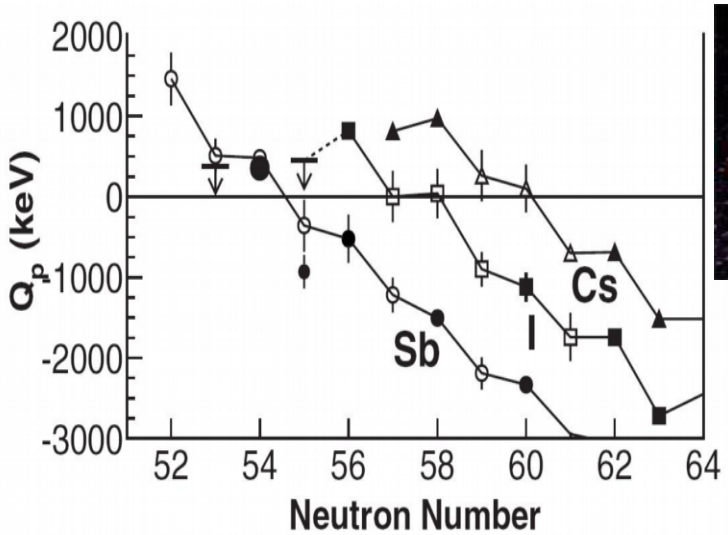
P. Mohr Eur. Phys. J. A 31, 23–28 (2007)
Super-allowed α decay above
doubly-magic of 104Te = 100Sn ⊗ α

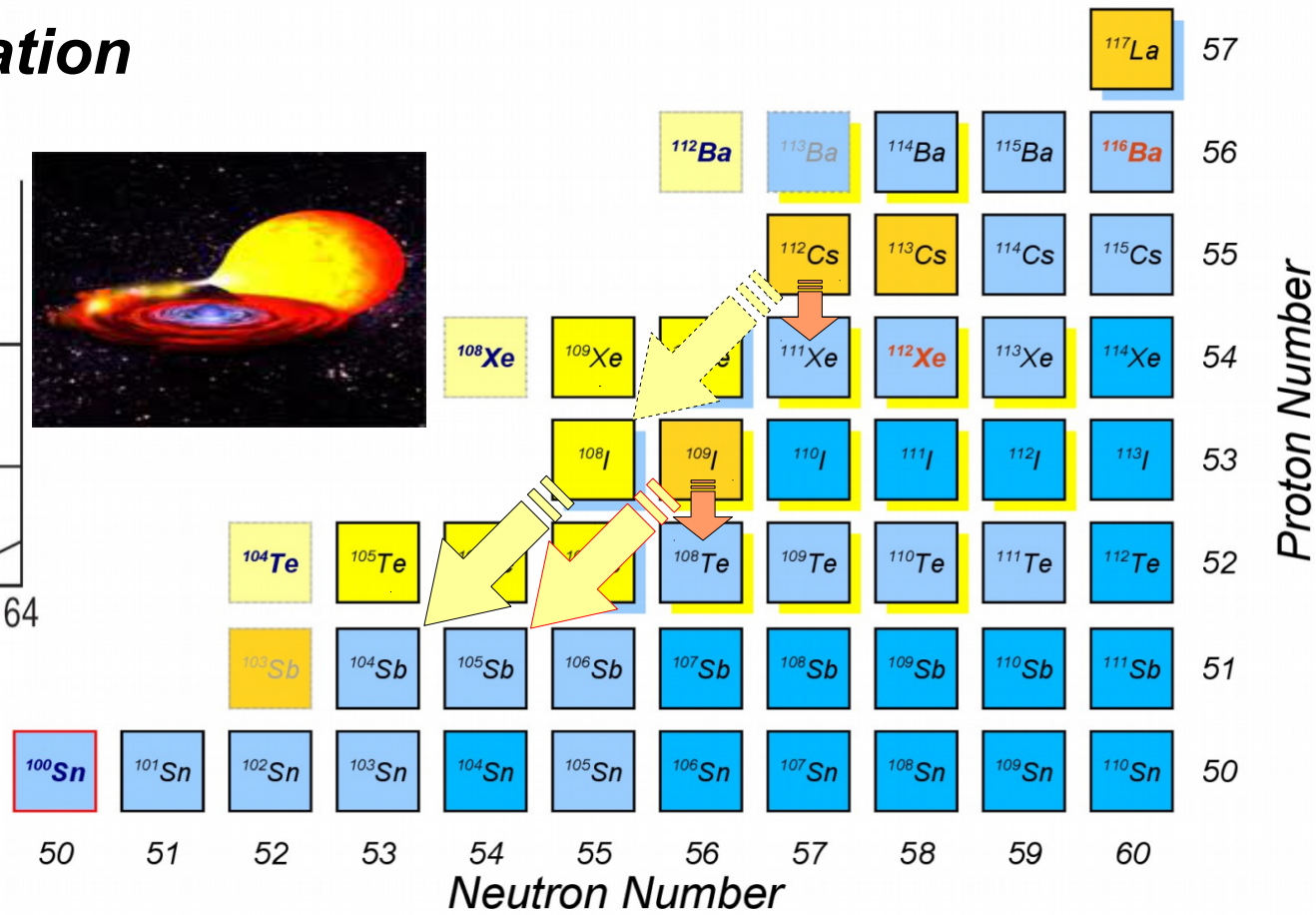
Phys. Rev. C 74, 037302 (2006)
Half lives of α-emitters approaching the N = Z line
Chang Xu and Zhongzhou Ren

Alpha decay island near ^{100}Sn

Odd-even effect for S_p

pn interactions
rp-process termination



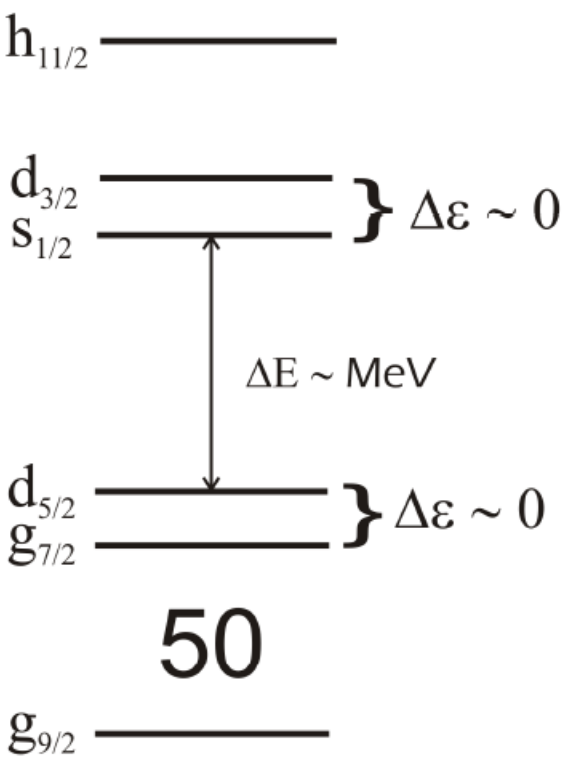


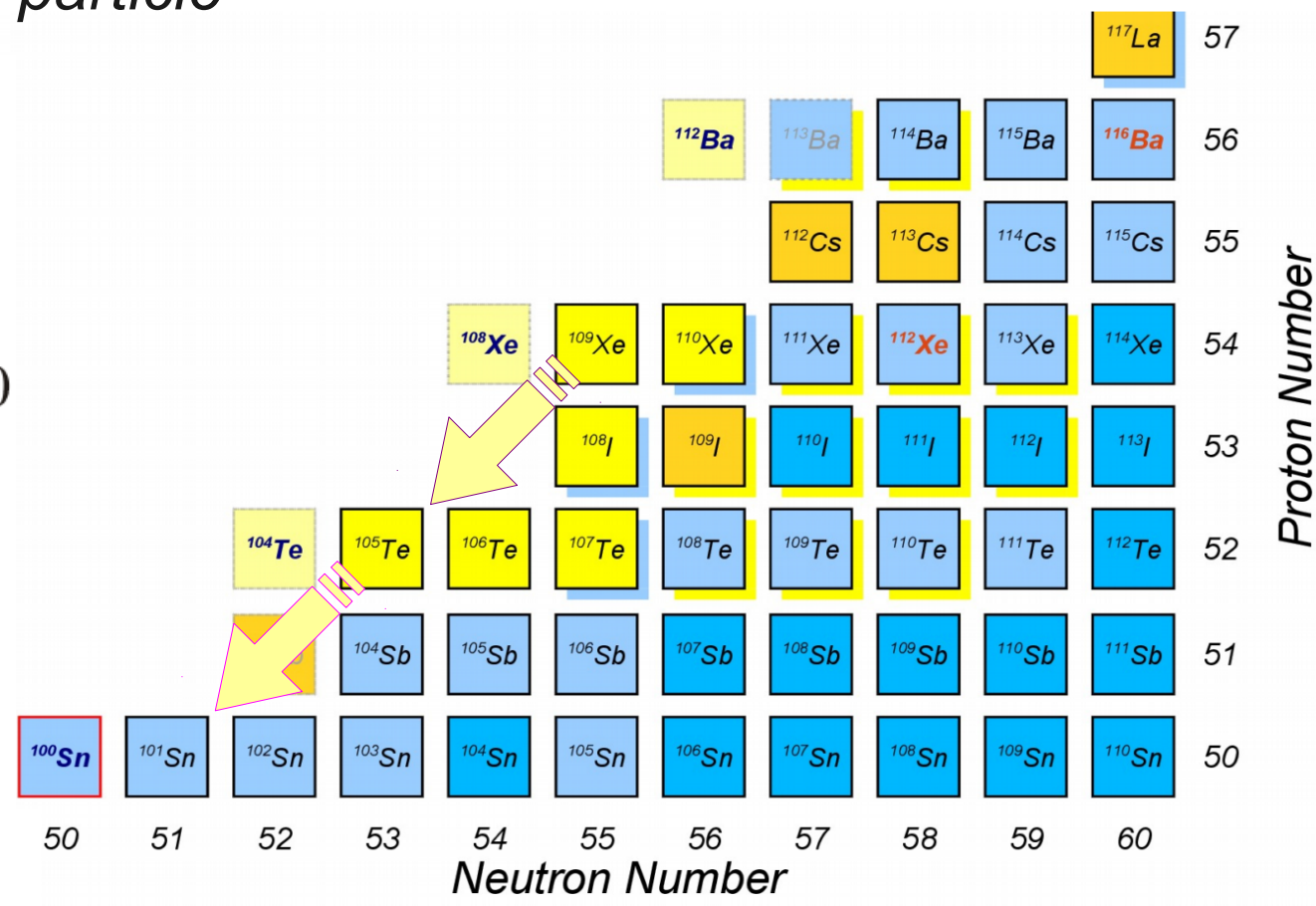
C. Mazzocchi et al., Phys. Rev. Lett. 98 (2007)
L. Cartegni et al. Phys, Rev. C *85, 014312 (2012)*

Alpha decay island near ^{100}Sn

Excited states in light Sn isotopes

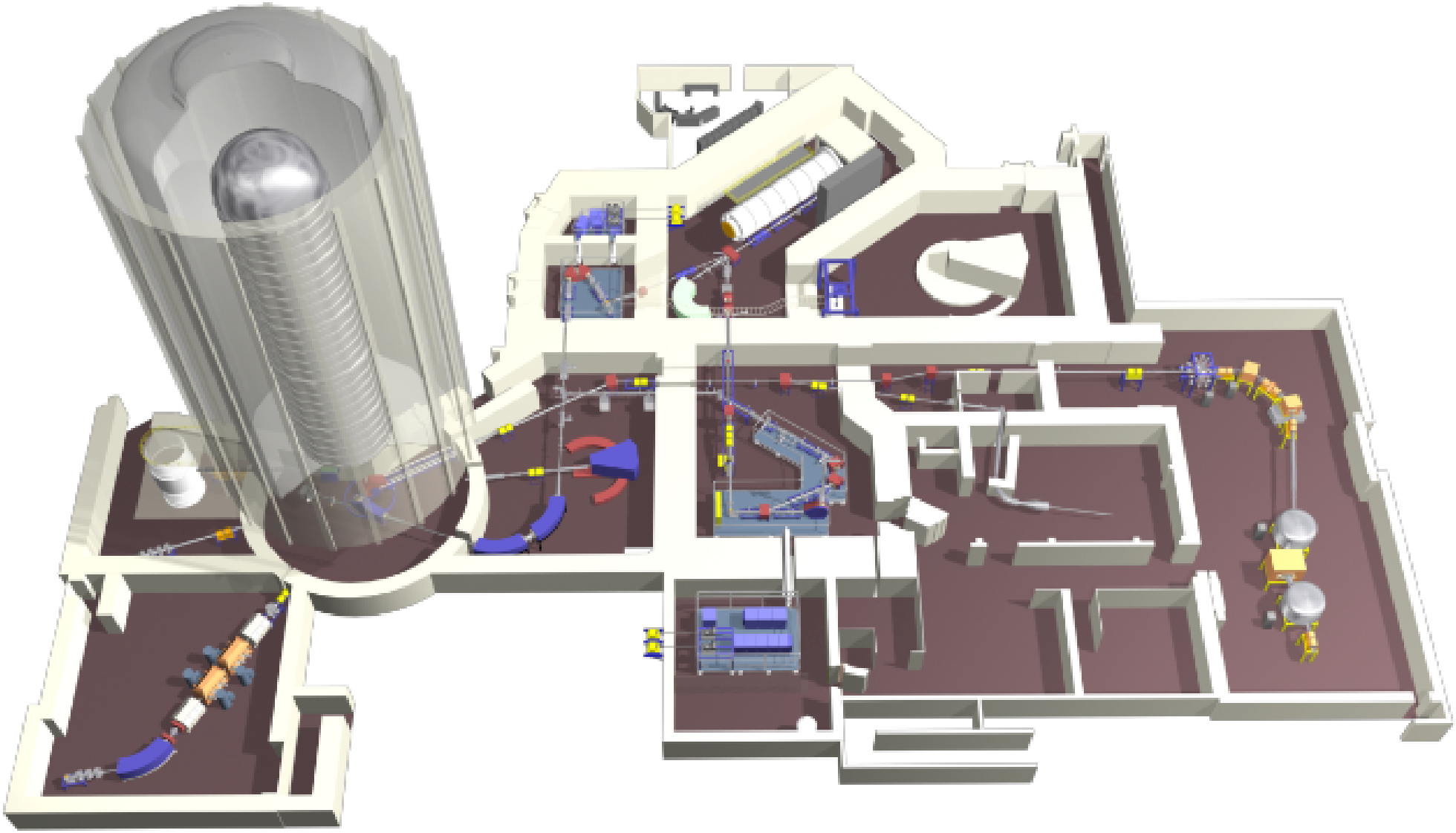
pairing vs single particle



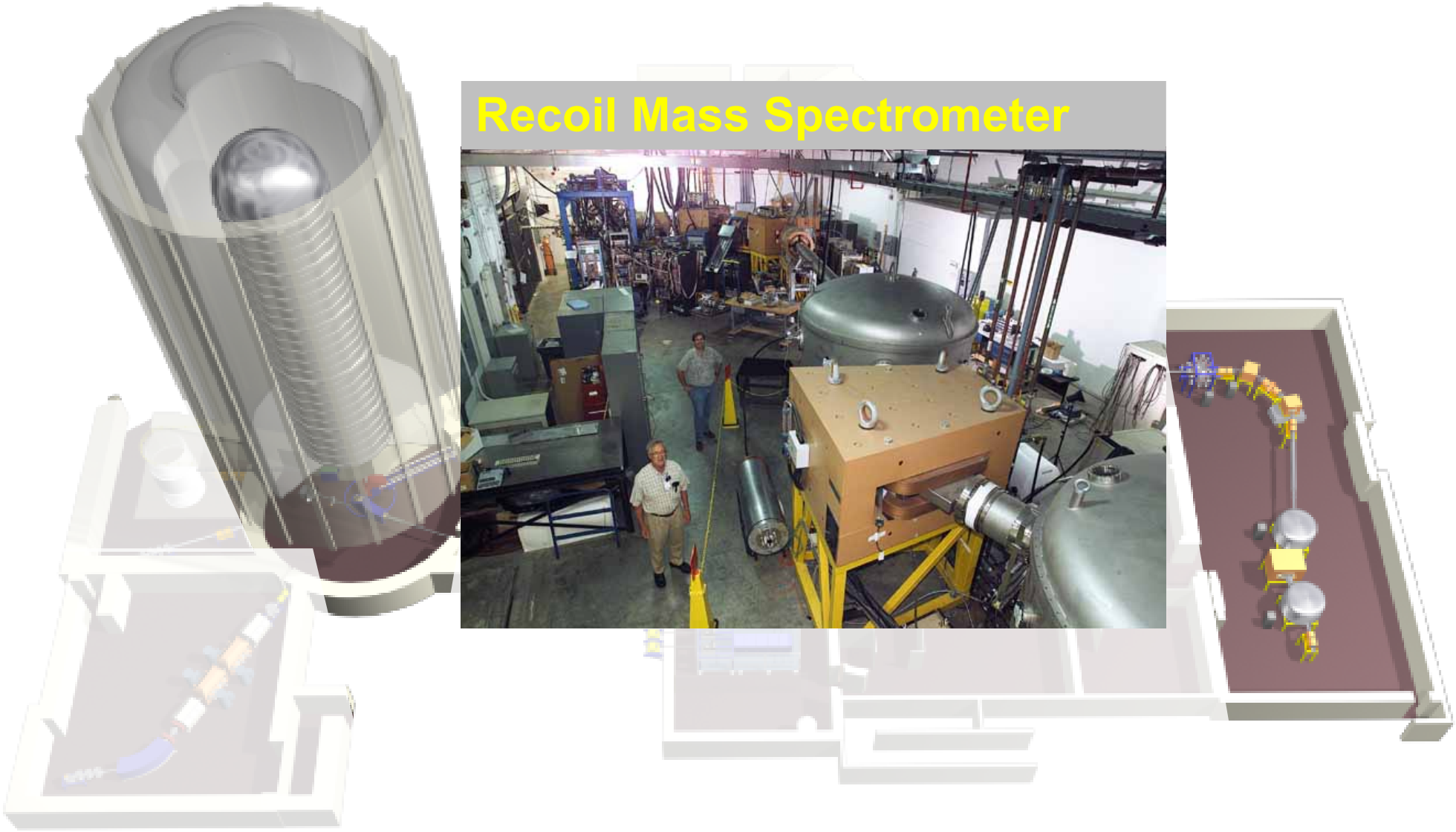


I.G. Darby et al., Phys. Rev. Lett. 105, 162502 (2010)

EXPERIMENTS
Holifield Radioactive Ion Beam Facility



EXPERIMENTS
Holifield Radioactive Ion Beam Facility



HRIBF Experimental Setup

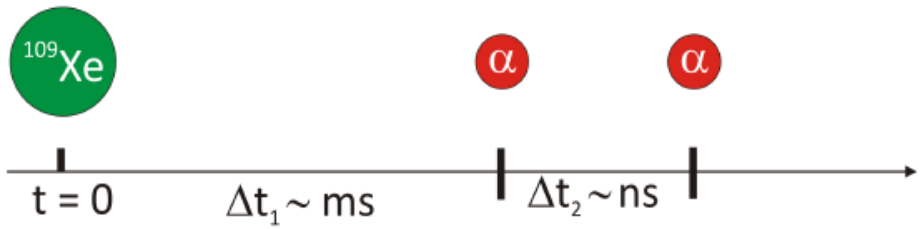
$$^{54}Fe + ^{58}Ni \rightarrow ^{112}Xe^{*}(3n)^{109}Xe$$

Recoil Implant

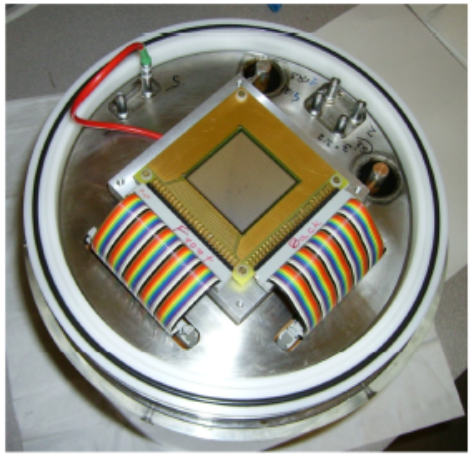
$E_{dep} > 9.2MeV$

Consecutive Decay Events

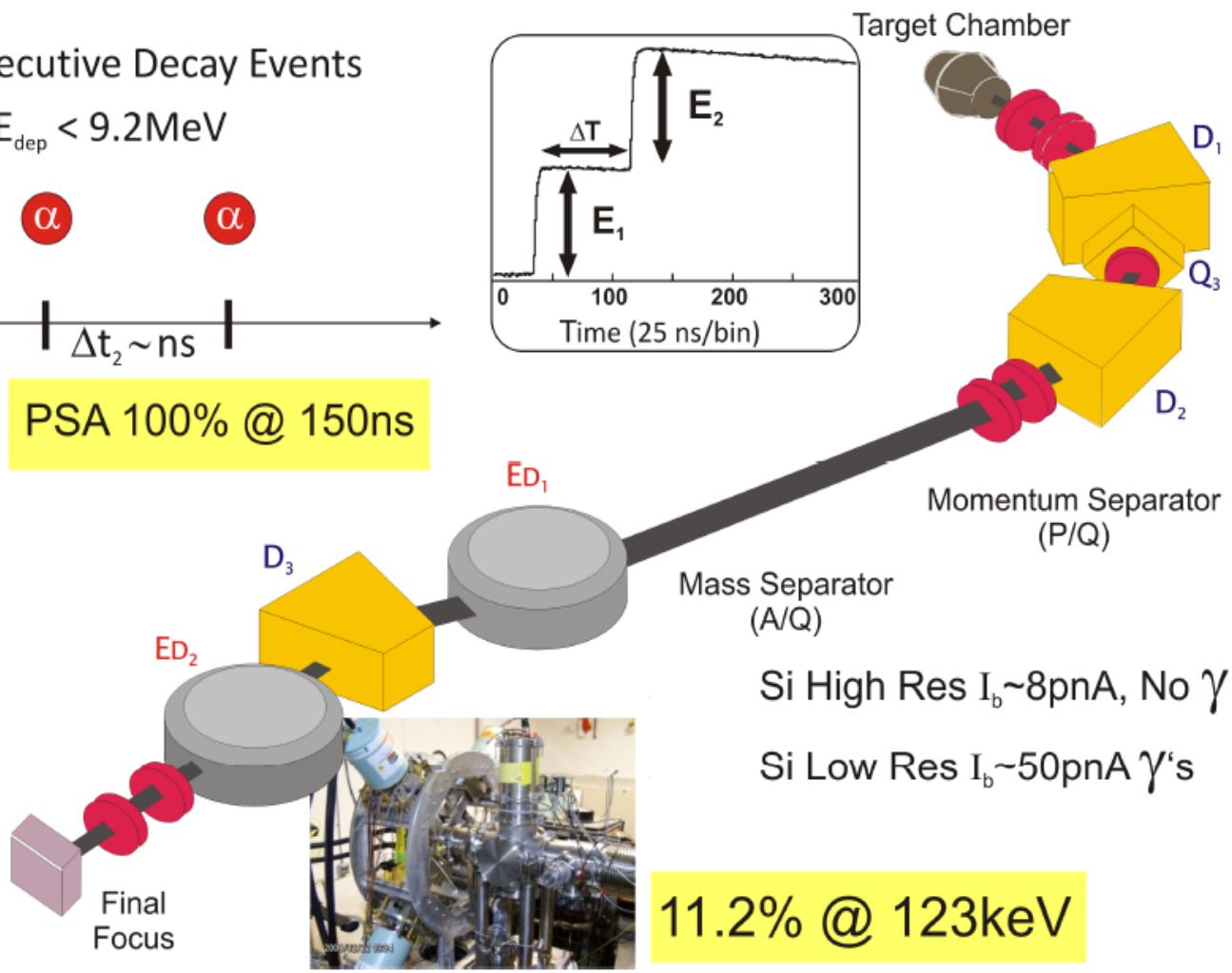
$E_{dep} < 9.2MeV$



PSA 100% @ 150ns



40 strip 65μm



Si High Res I_b~8pnA, No γ

Si Low Res I_b~50pnA γ's

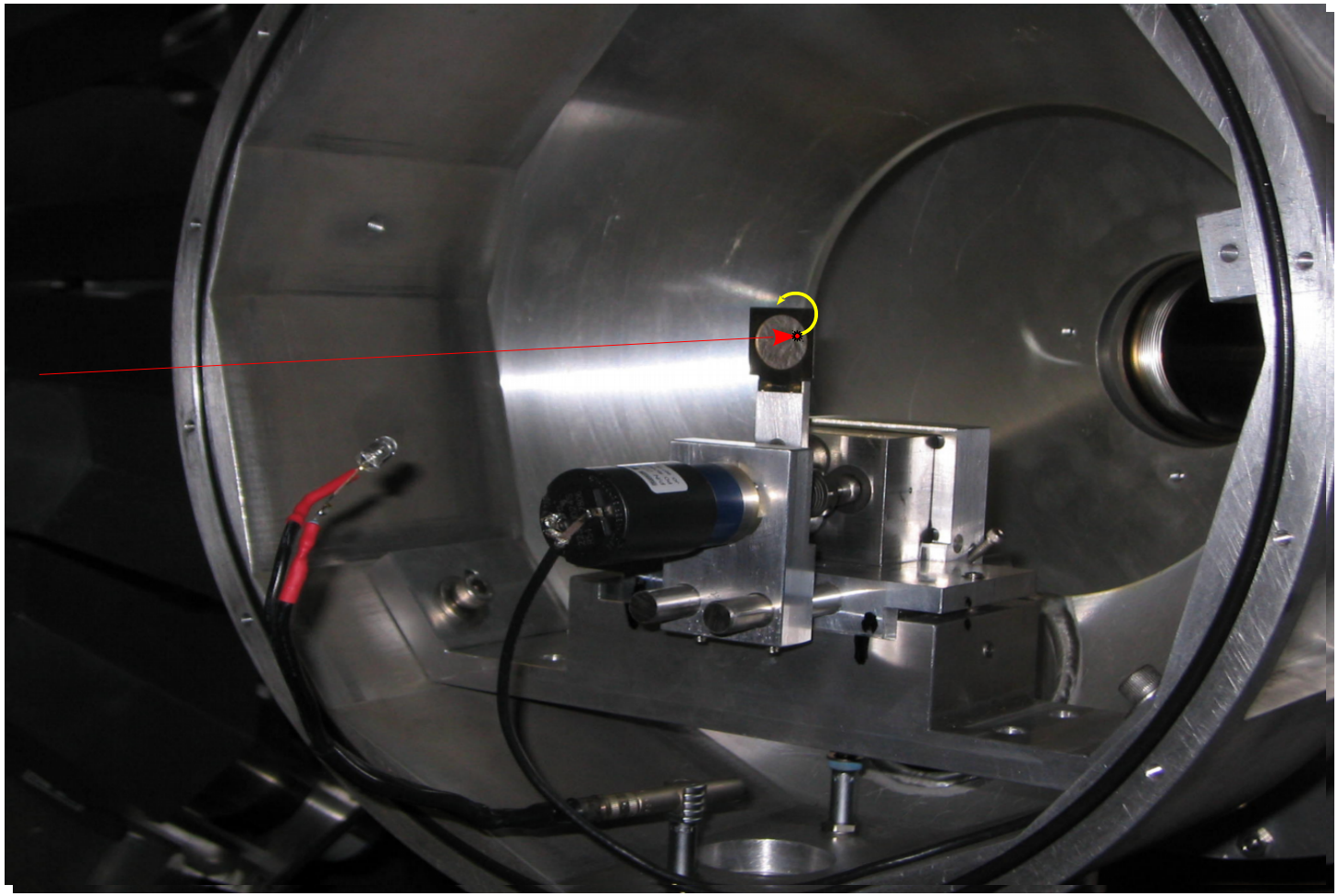
11.2% @ 123keV

Small cross section problem:

Oscillating target tested up to 50 pnA

(J. Johnson et al. ORNL/UTK)

$^{54}_{26}Fe_{28} + ^{58}_{28}Ni_{30}$



Where is the digital trick ?

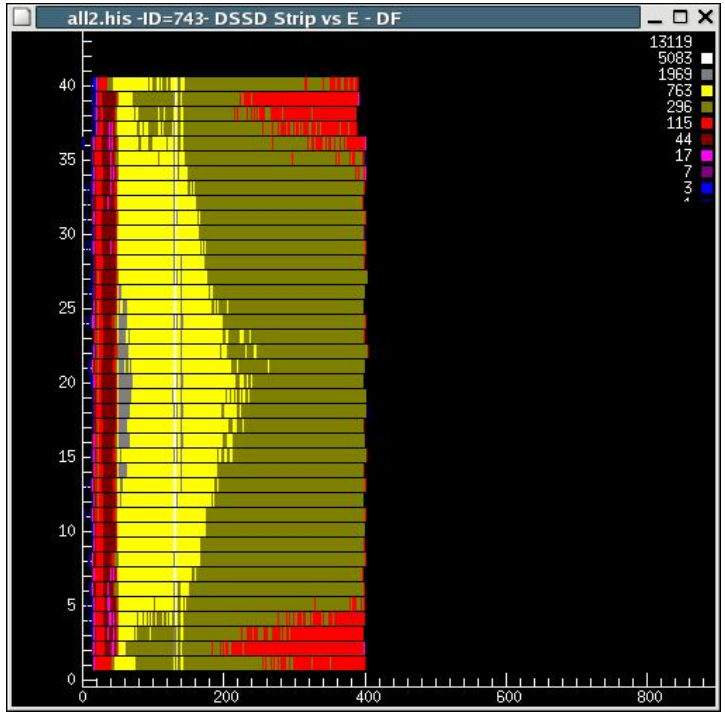
Energy based self-triggering scheme reduces the volume of the data !

R. Grzywacz et al. Nuclear Instruments and Methods B **261**,(2007) p. 1103-1106

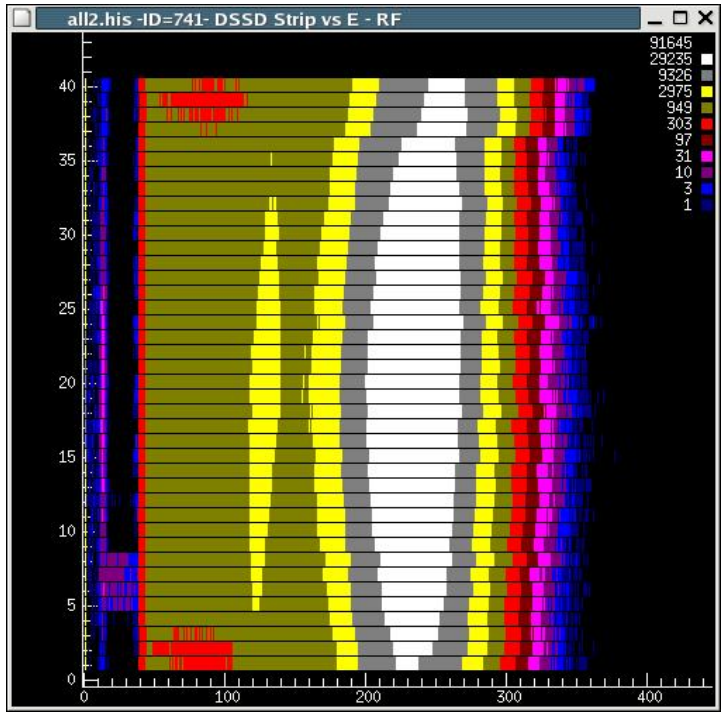
DECAYS ~ 1-10 Hz
Pulse shapes
~ 1 kB per event

RECOILS 1-10 kHz
Energy and time only
10 bytes

strip number



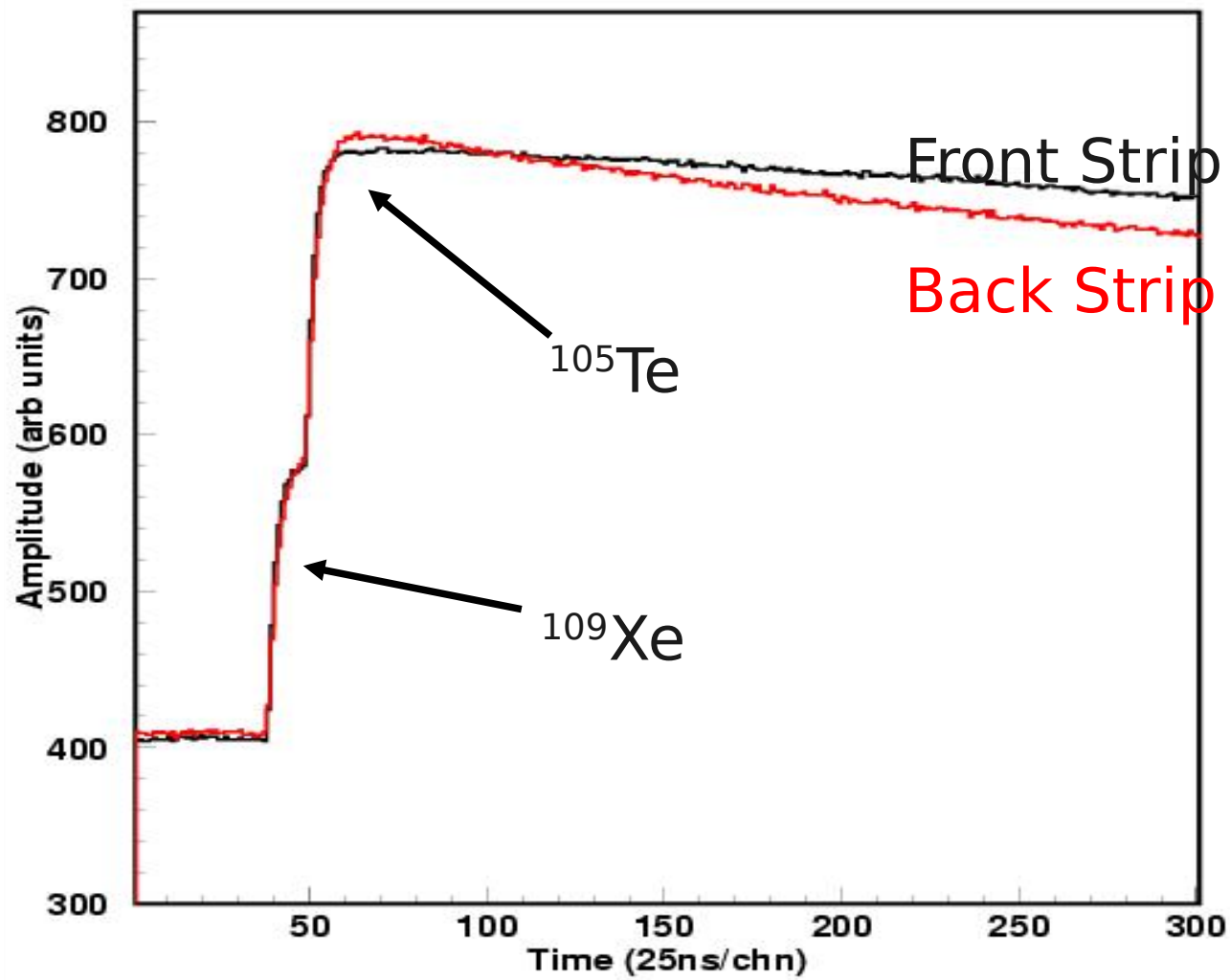
E < 12 MeV



E~80 MeV

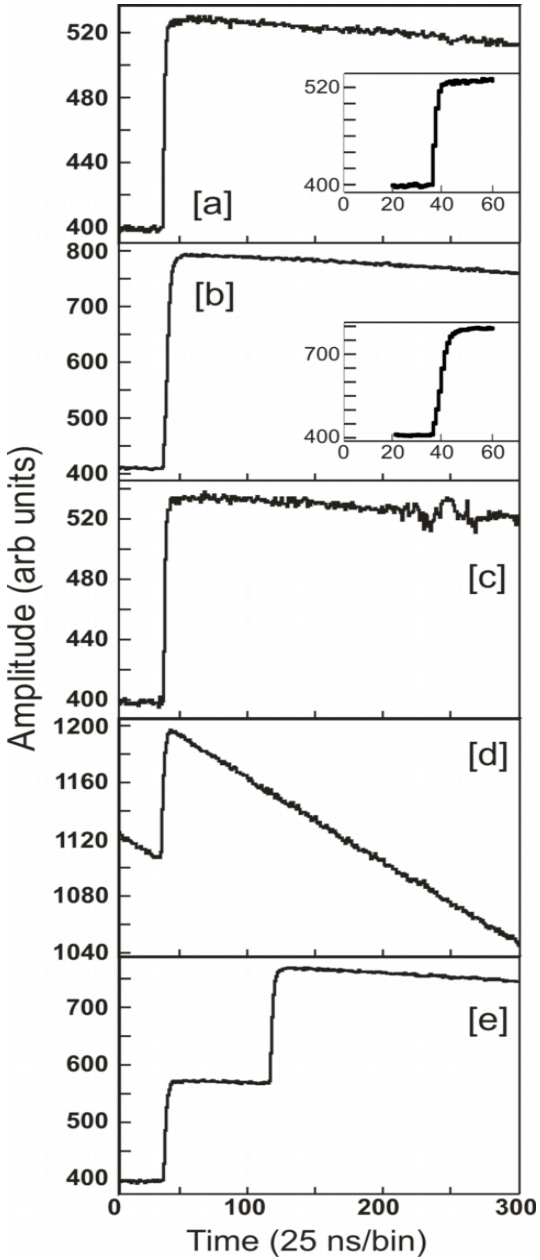
$^{109}Xe \rightarrow {}^{105}Te \rightarrow {}^{101}Sn$

Example of α–α pile-up traces

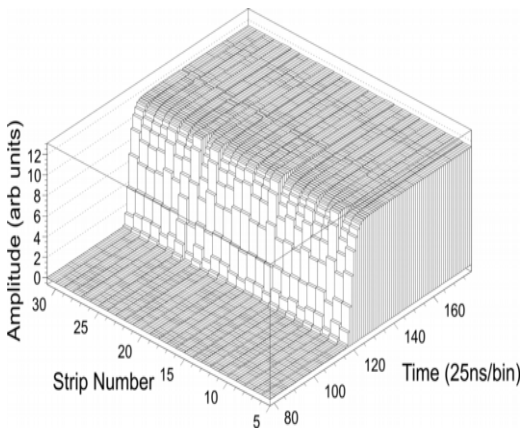


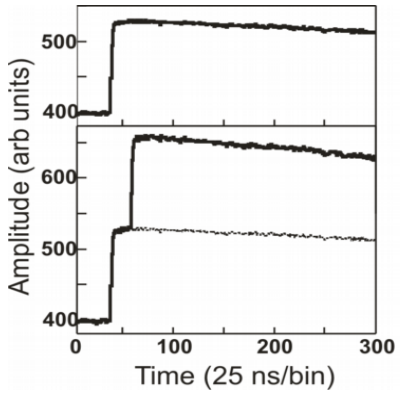
“alpha catcher” (software)

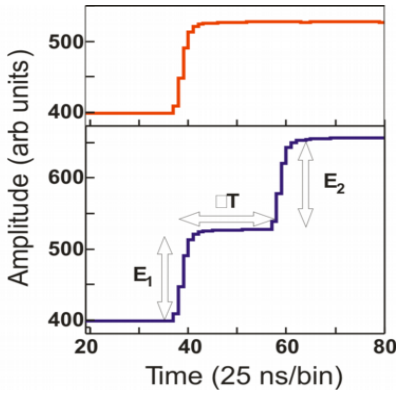
(I. Darby, S.N. Liddick, RG. Nuc. Instr. Meth.)

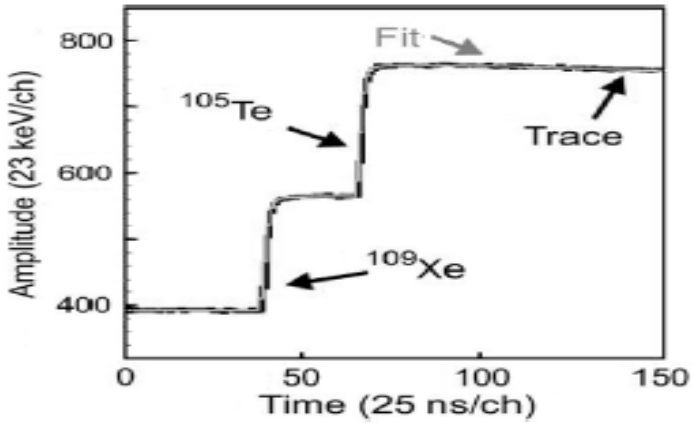


Generate super-pulse data base

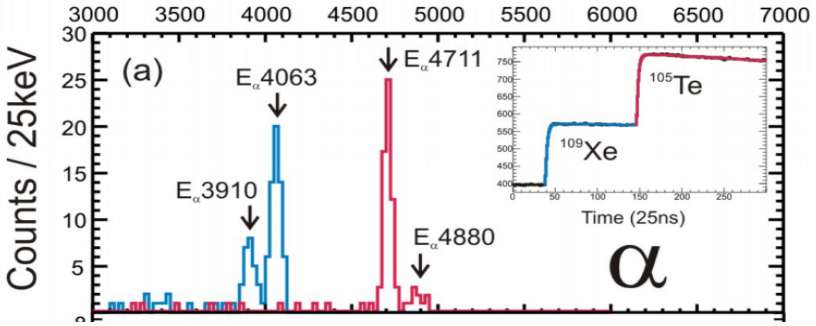








Search using single or double “super-pulse” fit



”Superheavies firmware”

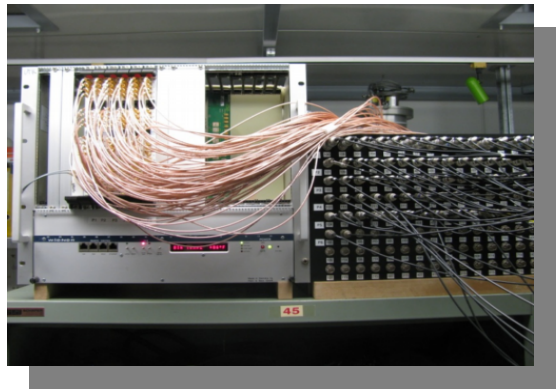
New operating mode of the firmware:
- save energies and times for all signals
- save traces ***only*** for pile-up signals

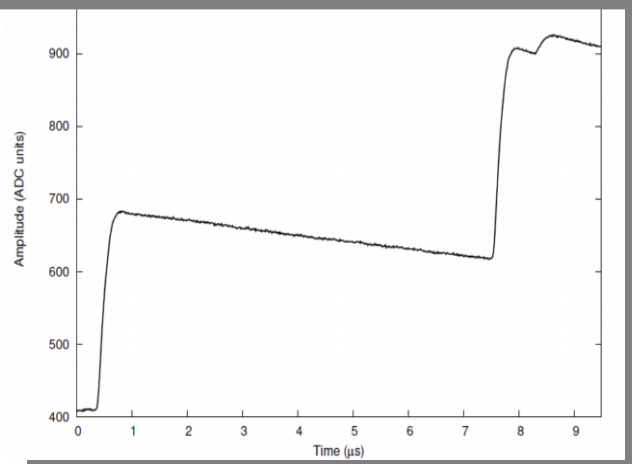
System is:
- **Efficient**
- **Dead time free**

Applied recently at SHIP(GSI)

Z=120 in the ^{248}Cm + ^{54}Cr reaction

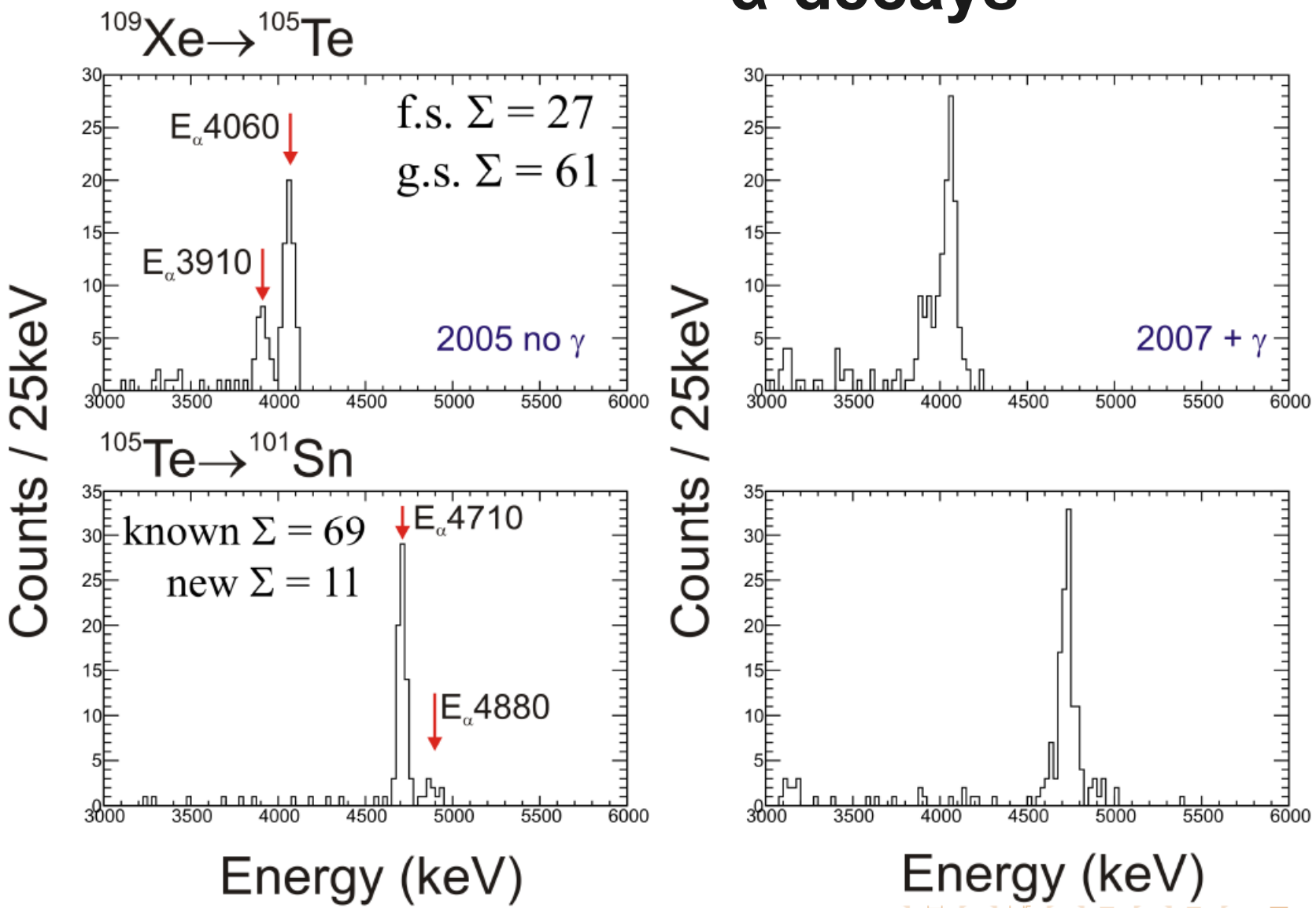
1 month of very reliable (remote) operation !



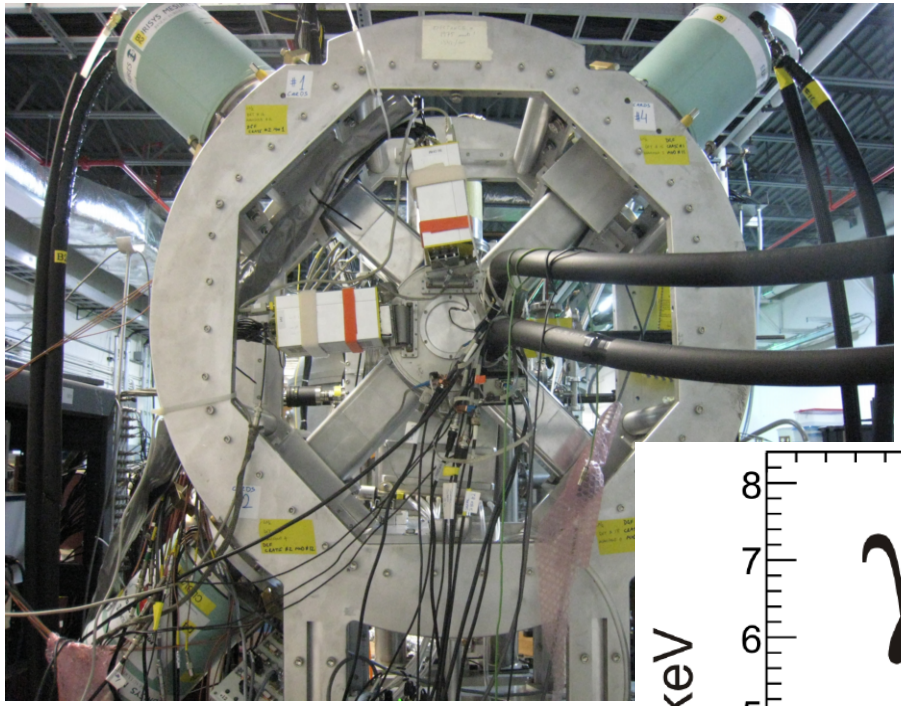


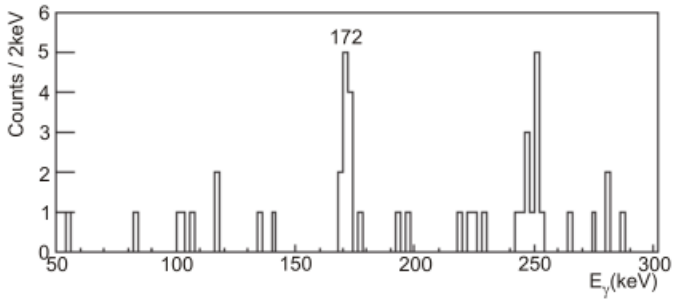
Back to ^{101}Sn
Experimental results :

α-decays

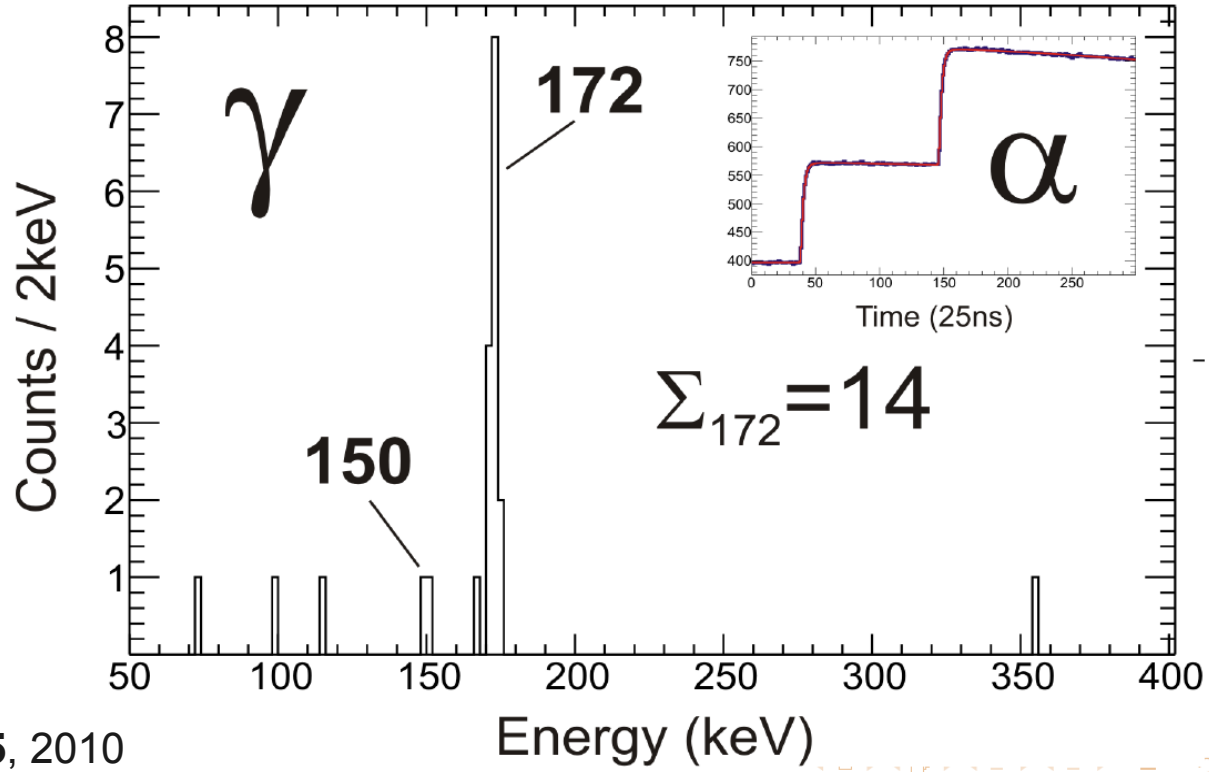


The 172 keV gamma line !





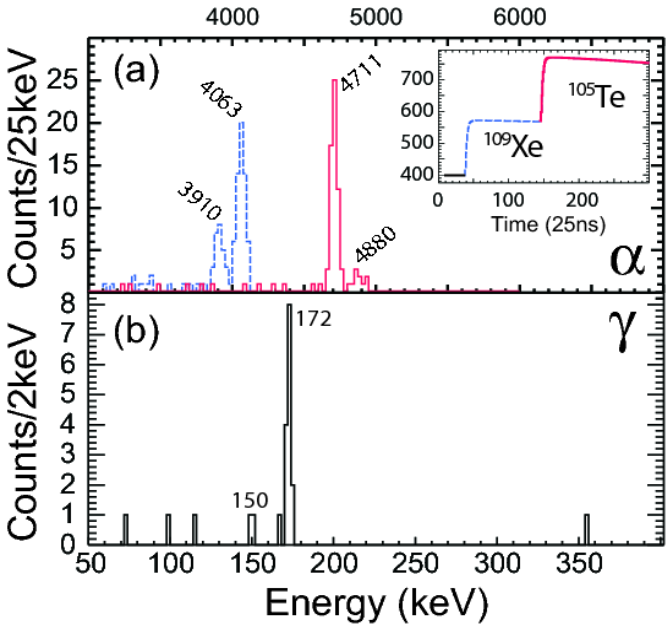
Seweryniak *et al.*, PRL **99** (2007)



I.G. Darby et al, Phys. Rev. Lett. **105**, 2010

What does it really mean ?

Experimental results
Main decay path: $^{105}Te \rightarrow {}^{101}Sn^{*}$



13ms

$^{109}Xe_{55}$

E_α = 3910 keV

b_α = 31%

$\Delta l = 0$

E_α = 4063 keV

b_α = 69%

$\Delta l = 2$

E_γ = 150 keV

0.62μs

$^{105}Te_{53}$

E_α=4711(4)(10) keV

$\Delta l = 0$

b_α = 89%

E_γ = 172 keV

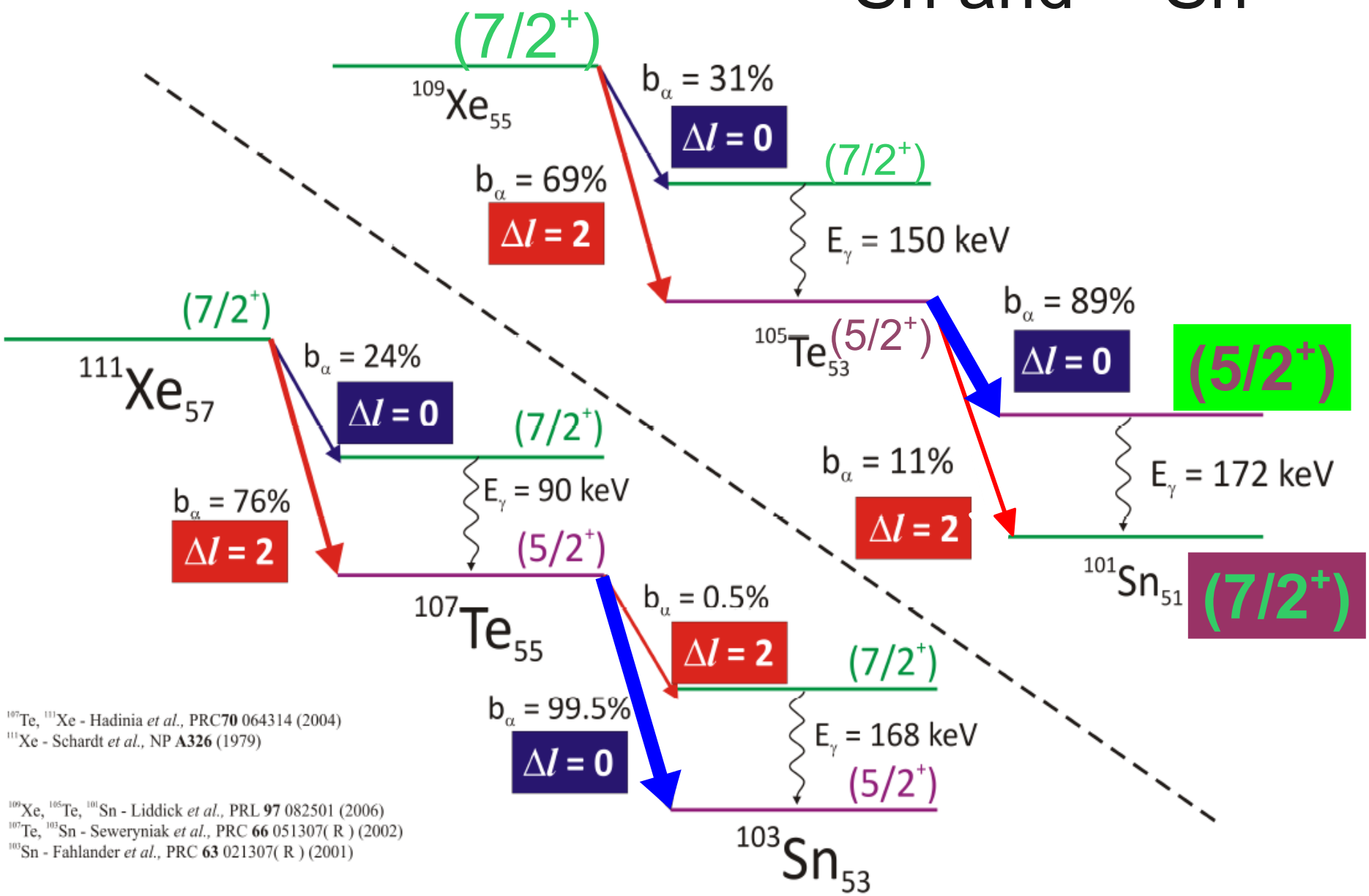
E_α = 4880(12)(10) keV

b_α = 11%

$\Delta l = 2$

$^{101}Sn_{51}$

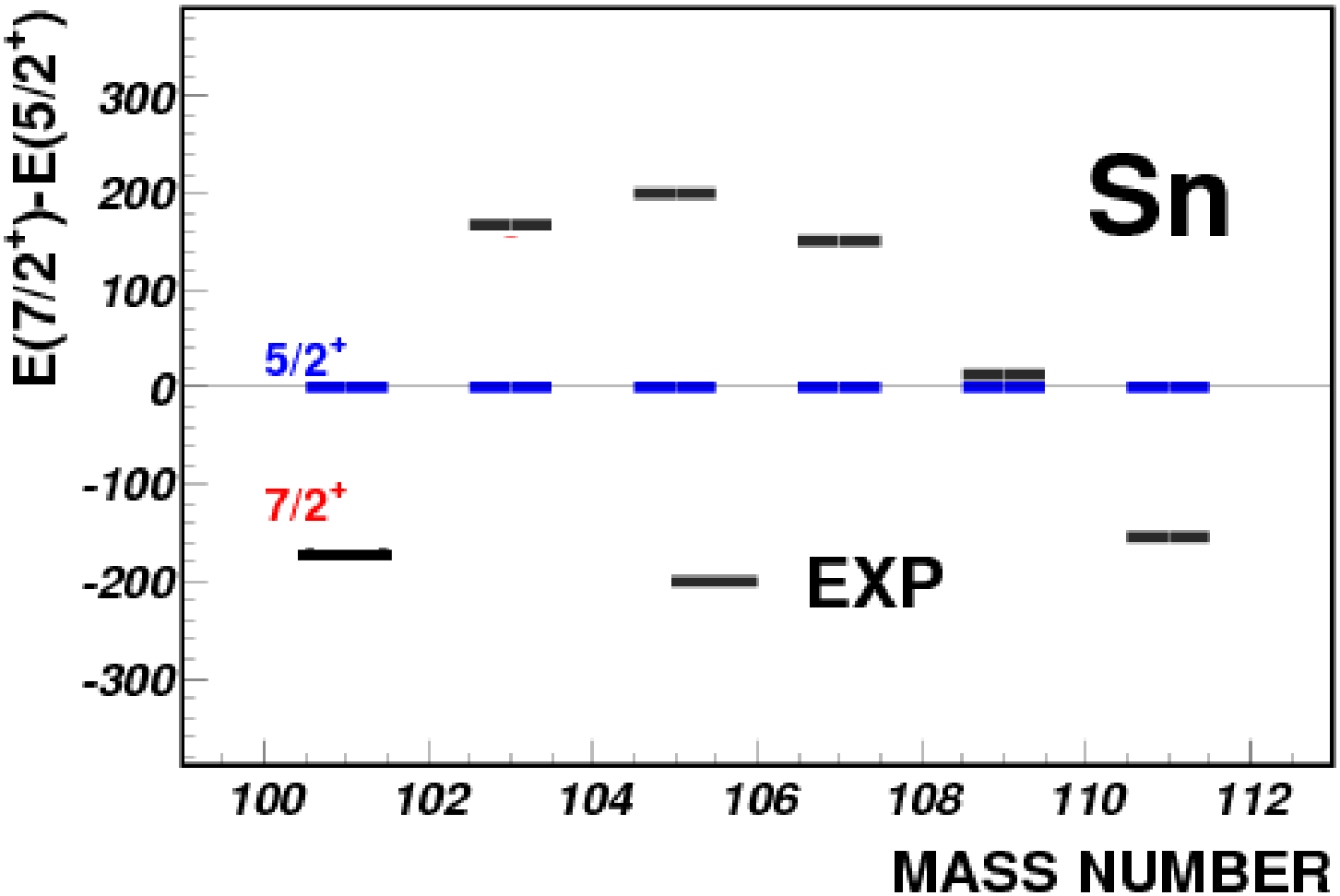
Ground state spin-switch between ^{103}Sn and ^{101}Sn



^{107}Te, ^{111}Xe - Hadinia *et al.*, PRC**70** 064314 (2004)
^{111}Xe - Schardt *et al.*, NP **A326** (1979)

^{109}Xe, ^{105}Te, ^{101}Sn - Liddick *et al.*, PRL **97** 082501 (2006)
^{107}Te, ^{103}Sn - Seweryniak *et al.*, PRC **66** 051307(R) (2002)
^{103}Sn - Fahlander *et al.*, PRC **63** 021307(R) (2001)

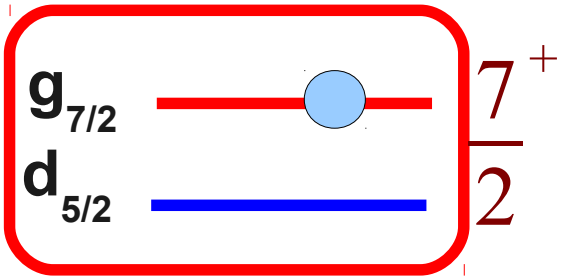
The $I^{\pi}=5/2^{+}$ becomes ground state of $^{103\text{-}109}Sn$ …
$I^{\pi}=7/2^{+}$ is the ground state of ^{101}Sn

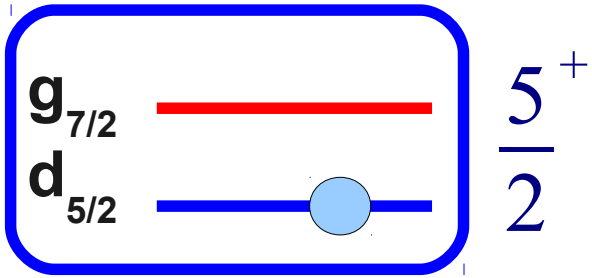


...and this is not business as usual.

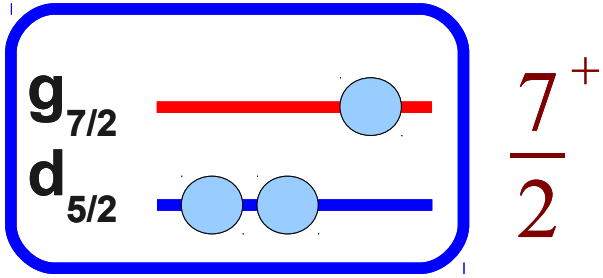
Dominant configurations in ^{101,103}Sn "traditional"

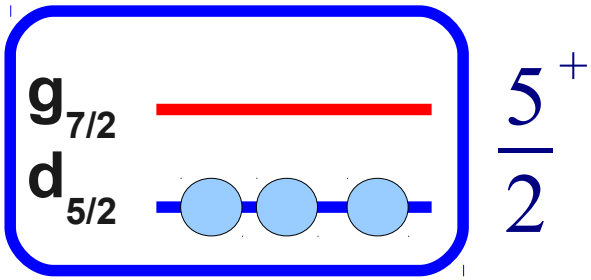
^{101}Sn

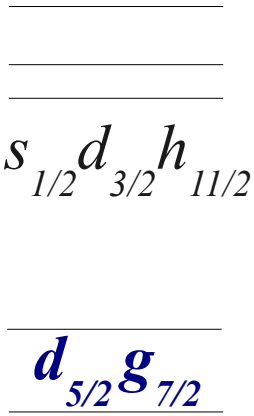




^{103}Sn







Nuclear Shell Model: ^{100}Sn core,

$\pi\ \nu$ $d_{5/2}$, $g_{7/2}$, $s_{1/2}$, $d_{3/2}$, $h_{11/2}$ orbitals

THEORY

FROM NN INTERACTIONS TO SHELL MODEL WITH RESIDUAL INTERACTIONS

- Modern Realistic Effective Interactions derived from free NN-scattering potentials *(AV18,N3LO,CD-Bonn)*

NOT ADJUSTED TO EXPERIMENTAL DATA

Shell-model should be accurate for few valence particles !!!

SM, TBME M. Hjorth-Jensen et al., Phys. Rep. 261(1995) 125
N3LO D.R. Entem and R. Machleidt, Phys. Rev. C, 68, 041001(R),(2003)
CD-Bonn R. Machleidt, Phys. Rev. C, 63,024001, (2001)
AV18 R.B. Wiringa,V.G.J Stoks and R. Schiavilla, Phys. Rev. C, 51,38 (1995)

"Pairing" two body matrix elements (TBME)

$$(d_{5/2})^2_{J=0} \text{ vs } (g_{7/2})^2_{J=0}$$

Seniority scheme:
TBME(J=0) ~ (2j+1)

$$(d_{5/2})^2_{J=0} = -0.75 \text{ MeV}$$

$$(g_{7/2})^2_{J=0} = -1.0 \text{ MeV}$$

$$\frac{-1.0}{-0.75} = \frac{8}{6} = 1.33$$

M.Goeppert- Mayer
Phys. Rev. 78 (1950)22

Modern interactions:
AV18,N3LO potentials

$$(d_{5/2})^2_{J=0} = -0.7 \text{ MeV}$$

$$(g_{7/2})^2_{J=0} = -1.12 \text{ MeV}$$

$$\frac{-1.12}{-0.7} = 1.6$$

M. Hjorth-Jensen et al.
Phys. Rep. 261(1995)125

Orbital dependent pairing !

(Exceeds the usual 2j+1 scaling.)

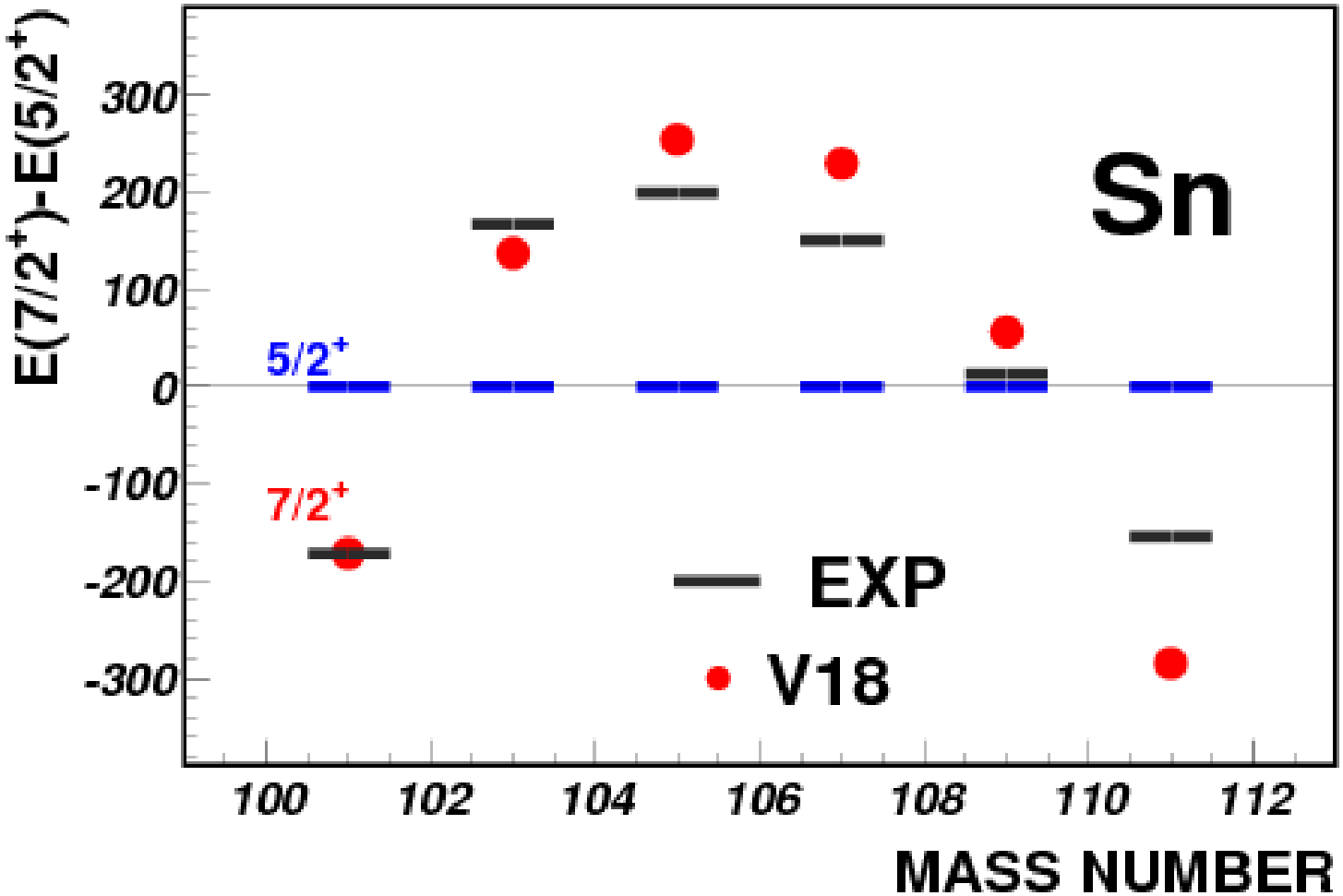
Microscopic origin of the strong $(g_{7/2})^2_{J=0}$ pairing matrix element.

M. Hjorth-Jensen

Nearly 90% of the pairing matrix element is due to the core polarization effect induced by tensor forces.

In medium effect due to virtual ph excitations generated by the interaction between spin-orbit partners $g_{9/2}$ and $g_{7/2}$.

The $I^{\pi}=5/2^{+}$ becomes ground state of $^{103\text{-}107}Sn$ ...



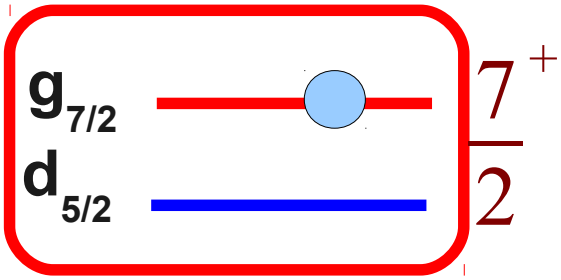
Realisitc effective interaction for nuclear system
M. Hjorth-Jensen, T.T.S. Kuo and E. Osnes, Phys. Rep 261 125-270 (1995).
Accurate nucleon-nucleon potential with charge-independence breaking
R.B. Wiringa, V.G.J. Stoks and R. Schiavilla, Phys. Rev. ***C 51****, 38 (1995)*

Residual interaction derived from Argonne V18 nucleon-nucleon potential.

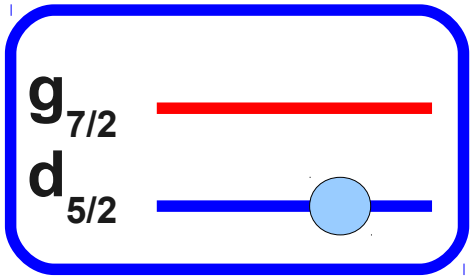
M. Hjorth-Jensen

Dominant configurations in $^{101,103}Sn$ "traditional"

^{101}Sn

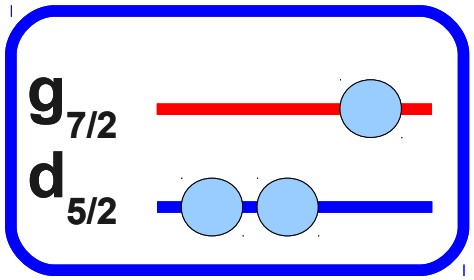


$\frac{7}{2}^+$

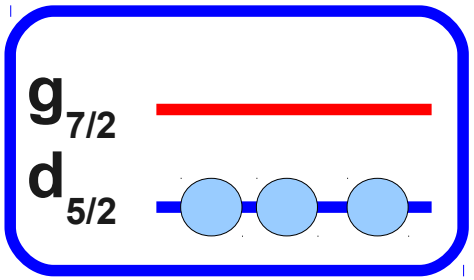


$\frac{5}{2}^+$

^{103}Sn

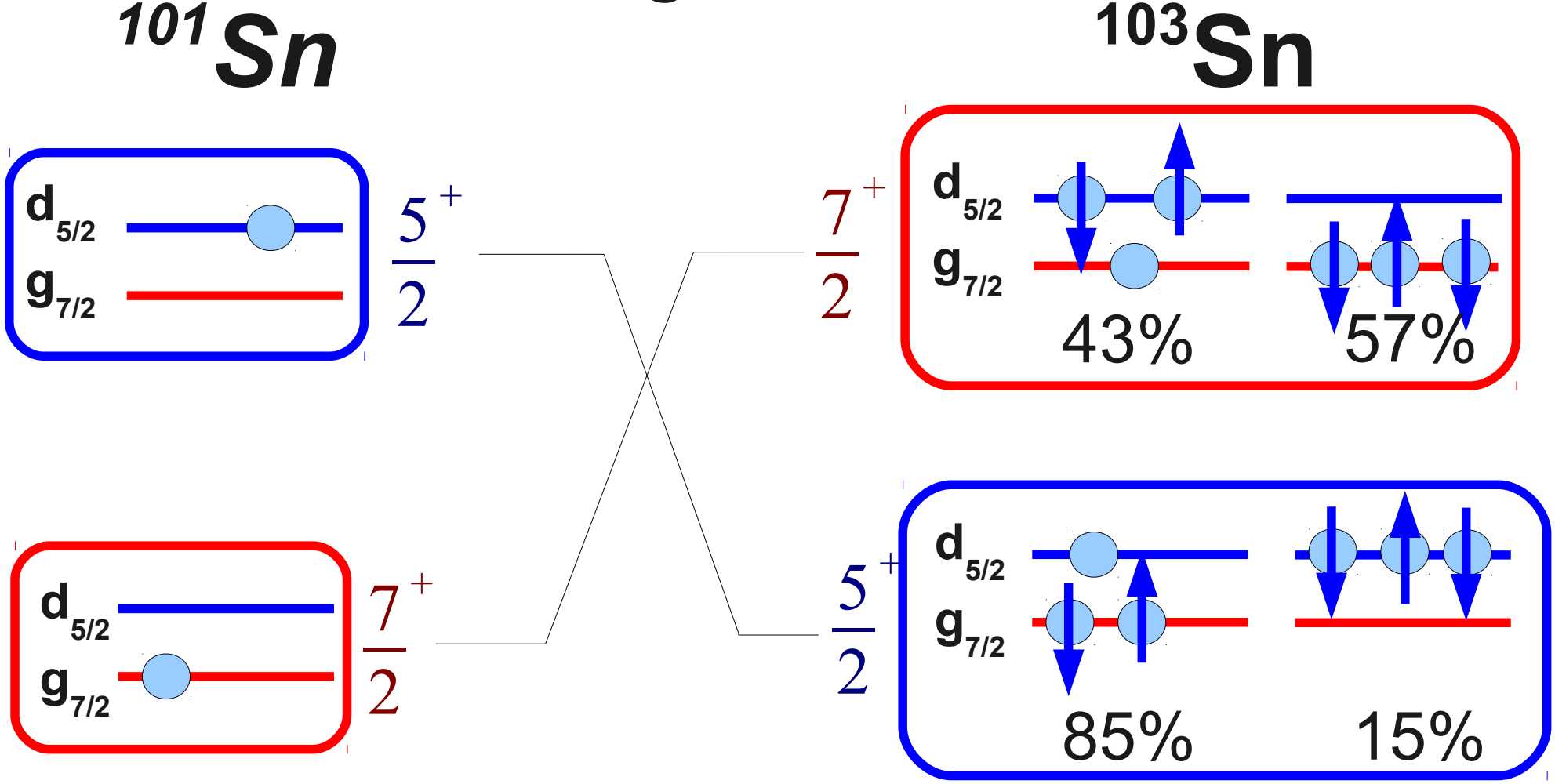


$\frac{7}{2}^+$



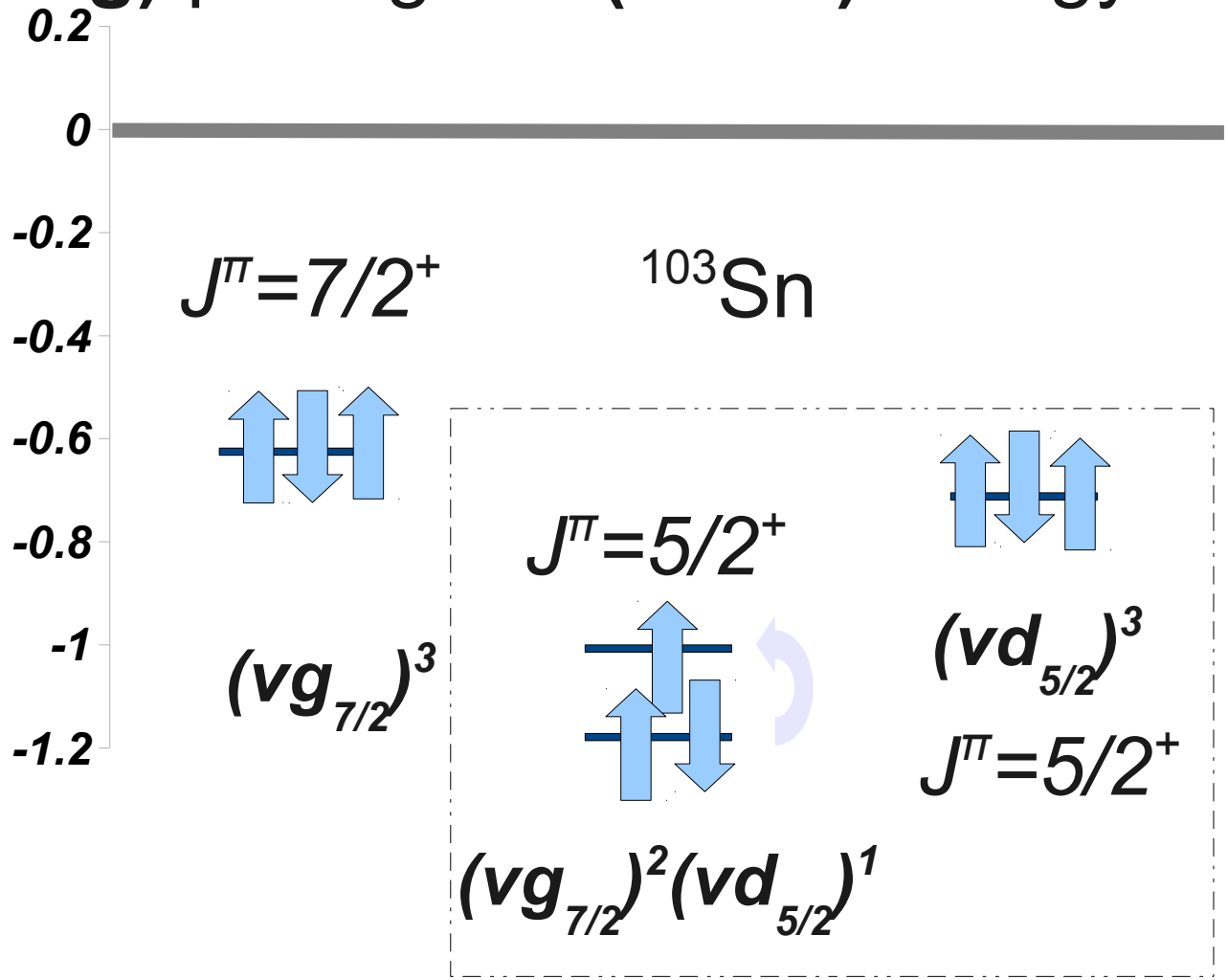
$\frac{5}{2}^+$

How to switch spins ?
Dominant configurations in ^{101,103}Sn



Strong pairing ($J=0^+$) TBME for the $(g_{7/2})^2$!!

Three particle configurations
(strong) pairing v.s. **(small)** energy difference



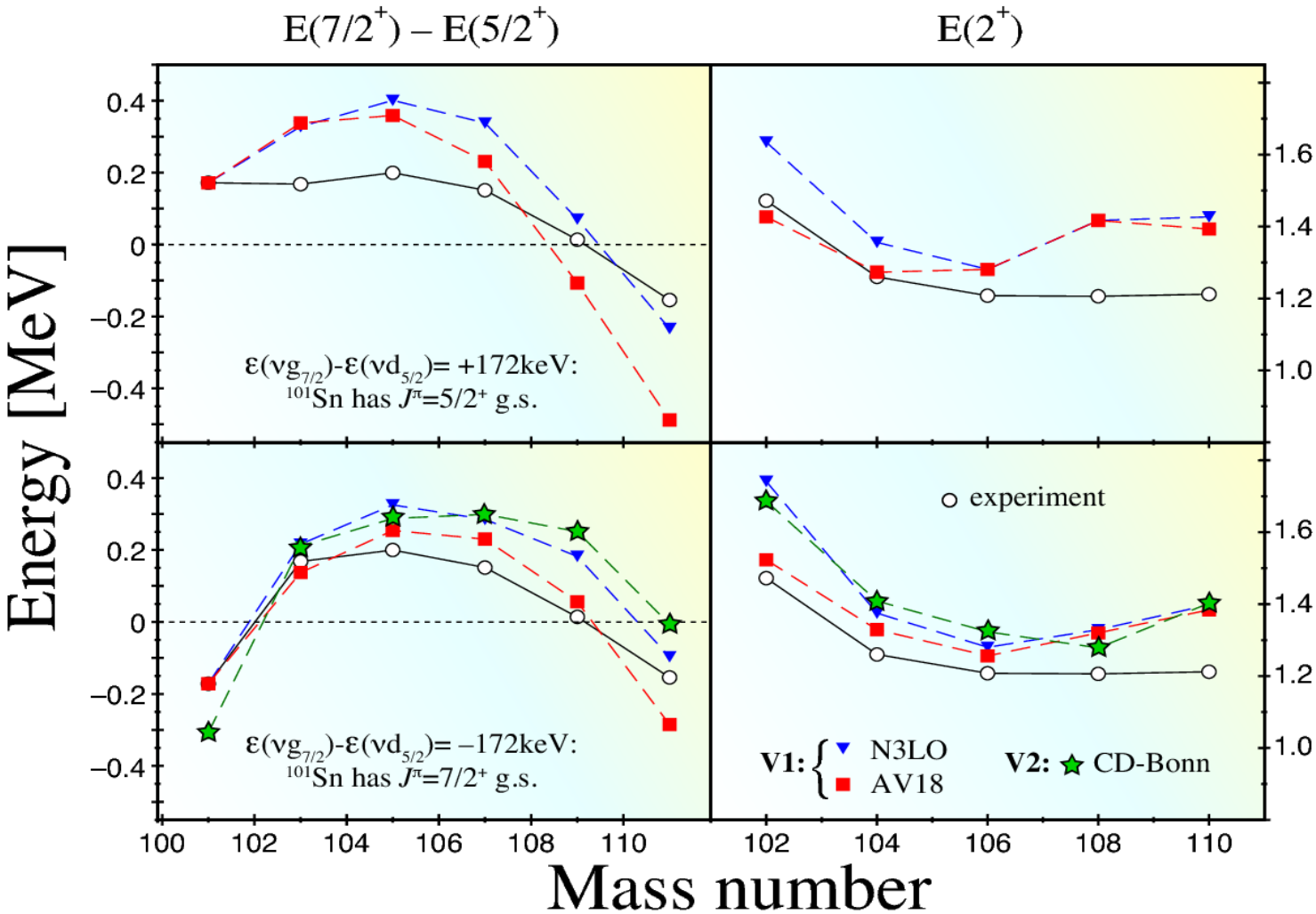
$$E(\nu g_{7/2})^3 = f(V_{J=0}, V_{J=2}, V_{J=4}, V_{J=6})$$

Wave function has to be antisymmetric !

I. Talmi and I. Unna, Ann. Rev. Nuc. Sci. 10 (1960) 353

Is there an independent method to establish g.s. spins of odd-A isotopes of tin ?

D. Seweryniak et al. PRL 99(2007)
I. Darby et al. PRL 105(2010)



Spectroscopic studies close to ^{100}Sn using neutron knockout reactions.

K.L. Jones +R.G. et al.

^{108}Sn→ ^{107}Sn and ^{106}Sn→ ^{105}Sn

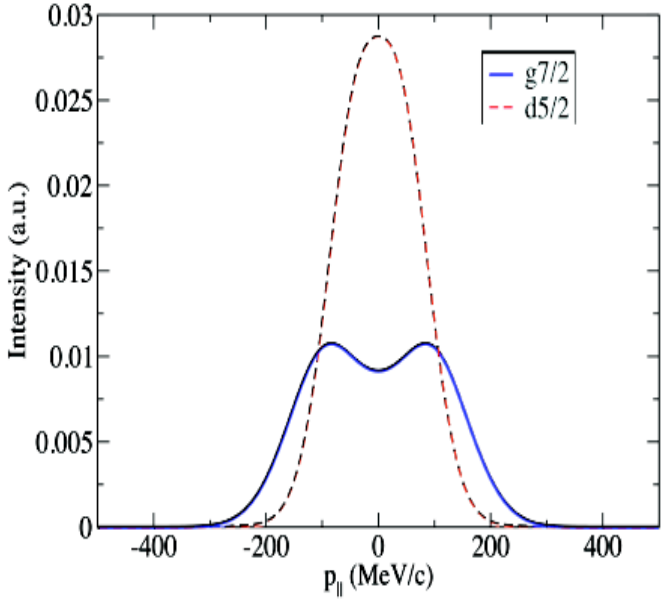
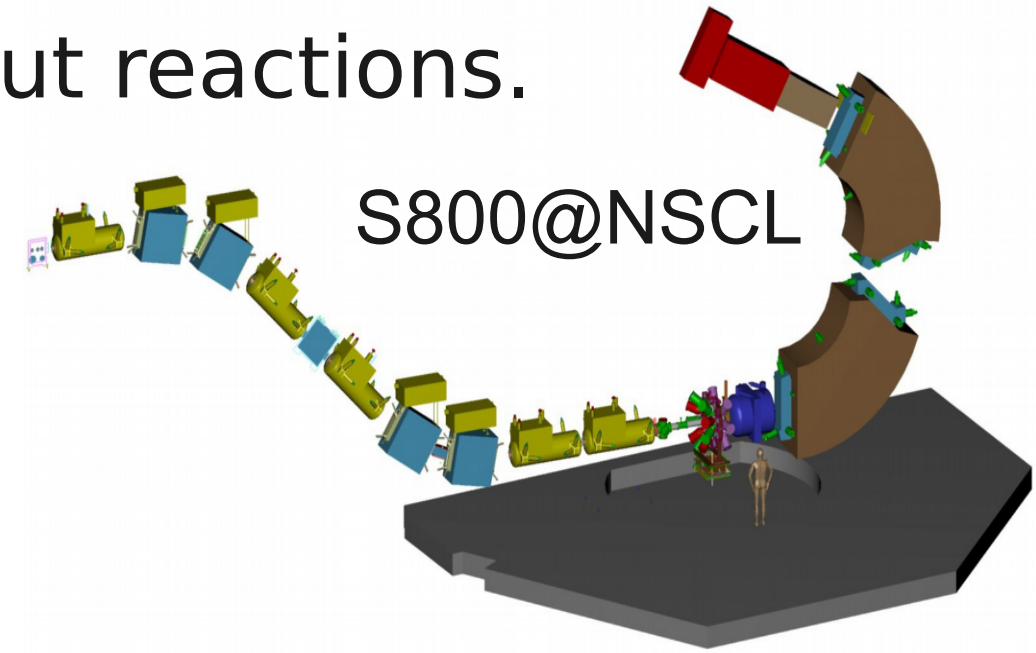


Figure 5: Calculated momentum distributions for ^{105}Sn following the one-neutron knockout of ^{106}Sn assuming a $g_{7/2}$ neutron (blue solid line) or $d_{5/2}$ neutron (red dashed line).



CEASAR

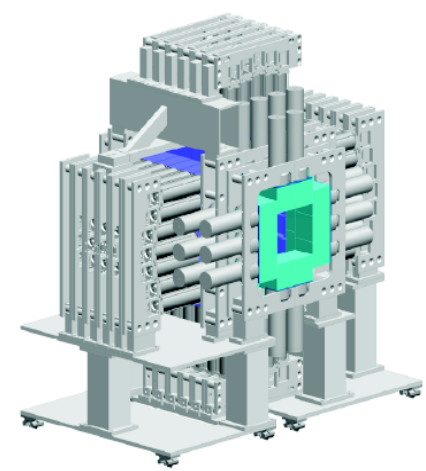


Figure 6: The new high-efficiency γ-ray detector, CAESAR. The setup with CAESAR in the proposed configuration surrounding the target position of the spectrometer is scheduled for commissioning from May 5-8, 2009.

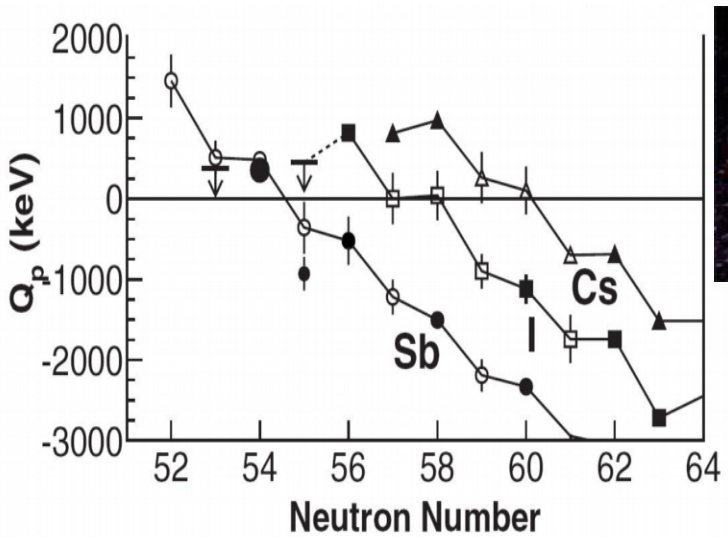
^{108}Sn preliminary data analysis shows that the spins of ^{107}Sn are $5/2^+$ (g.s.) and $7/2^+$ (exc)

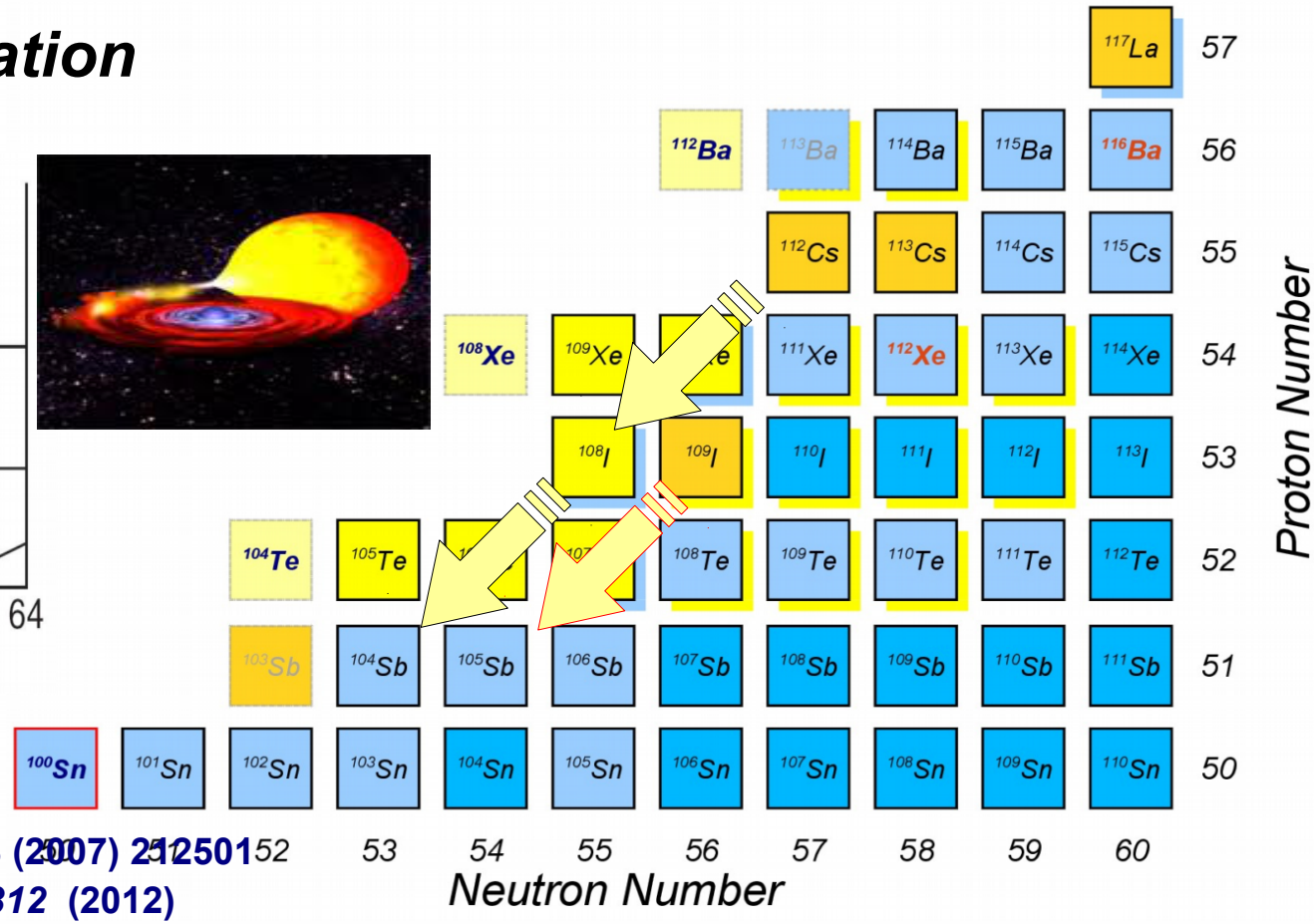
RIKEN studies ? (^{104}Sn, ^{102}Sn, ^{106}Te)

Alpha decay island near ^{100}Sn

Odd-even effect for S_p

pn interactions
rp-process termination

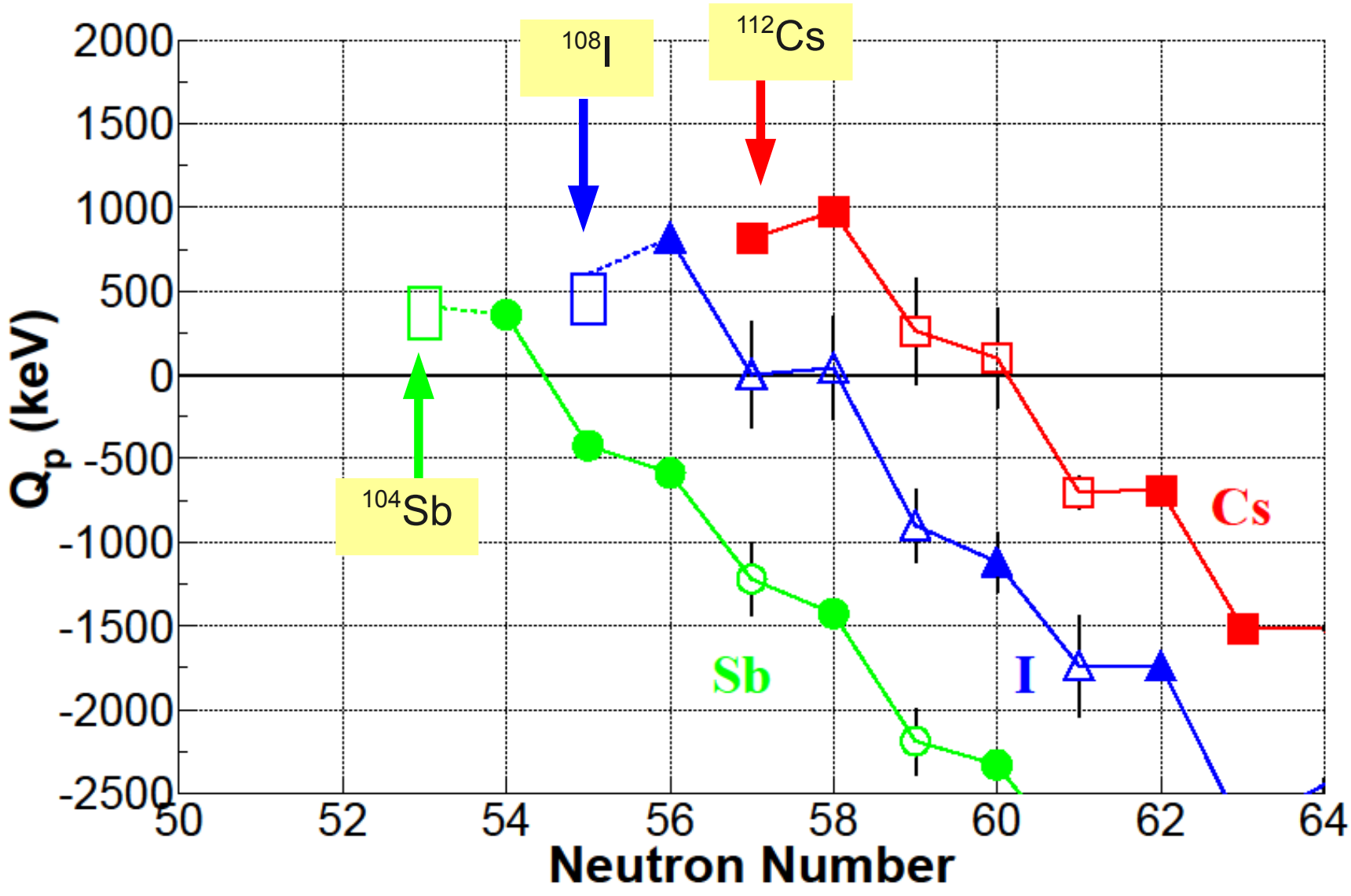




C. Mazzocchi et al., Phys. Rev. Lett. 98 (2007) 212501
L. Cartegni et al. Phys, Rev. C *85, 014312* (2012)

^{101}Sn, Seweryniak *et al.*, PRL**99** 022504 (2007) | ^{101}Sn, Kavatsyuk *et al.*, EPJA**31** 319 (2007) | ^{109}Xe→^{105}Te→^{101}Sn, Liddick *et al.*, PRL**97** 082501 (2006)
^{107}Te→^{103}Sn, Seweryniak *et al.*, PRC**66** 051307(R) (2002) | ^{105}Te→^{101}Sn, Seweryniak *et al.*, PRC**73** 061301(R) (2006) | ^{109}Sn, Eberz *et al.*, ZPA**326** 121 (1987)

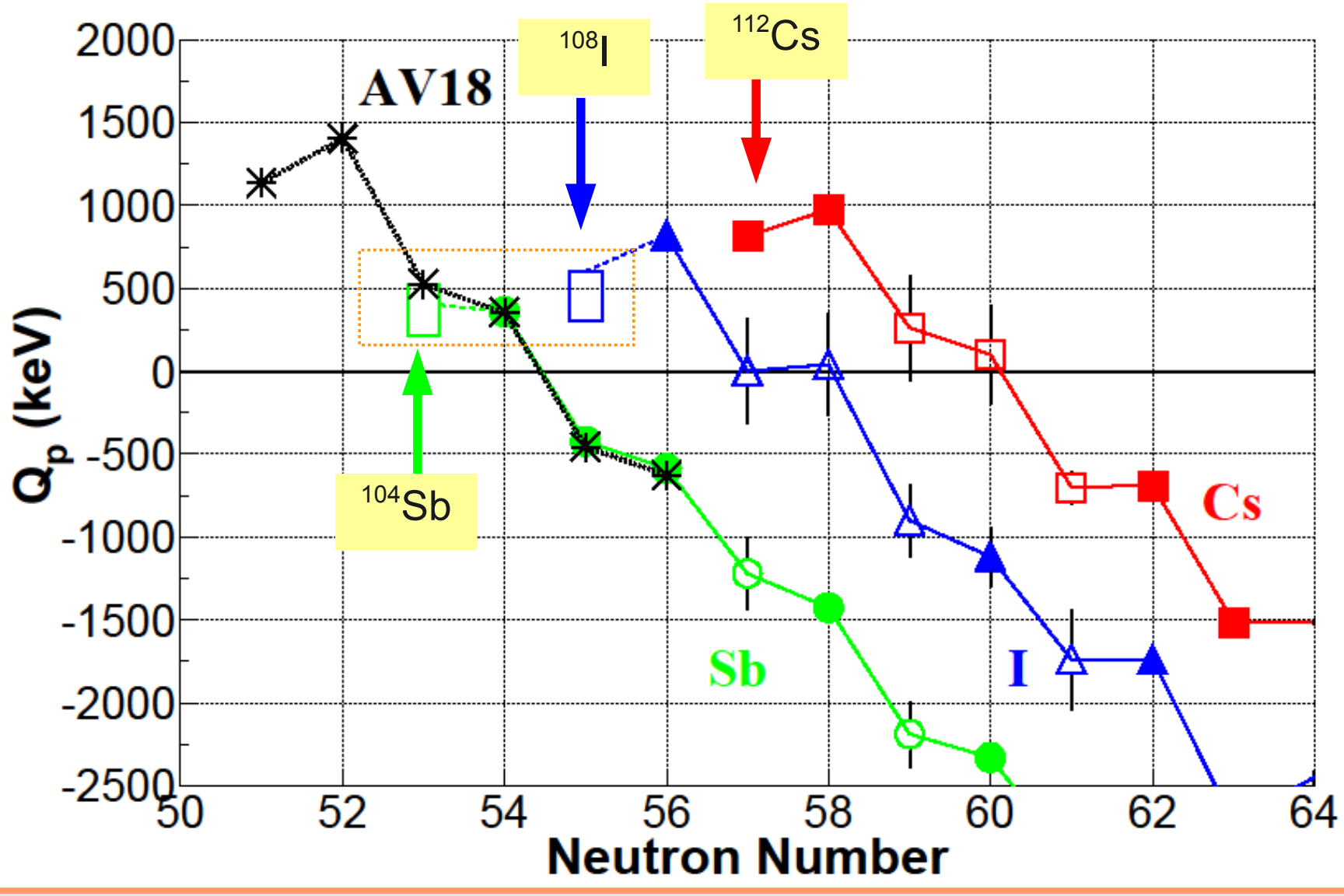
Odd-Even Effect



S_p from AV18 shell model

M. Hjorth-Jensen et al, Phys. Reports **261**, 1995
I.G. Darby et al, Phys. Rev. Lett. **105**, 2010

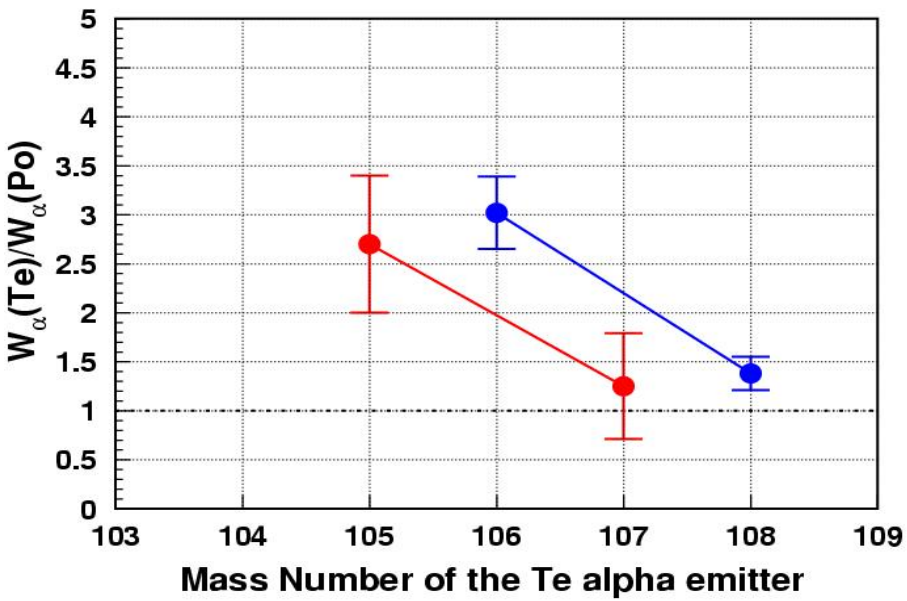
C. Mazzocchi et al., Phys. Rev. Lett. 98 (2007)
L. Cartegni et al. Phys, Rev. C *85, 014312*

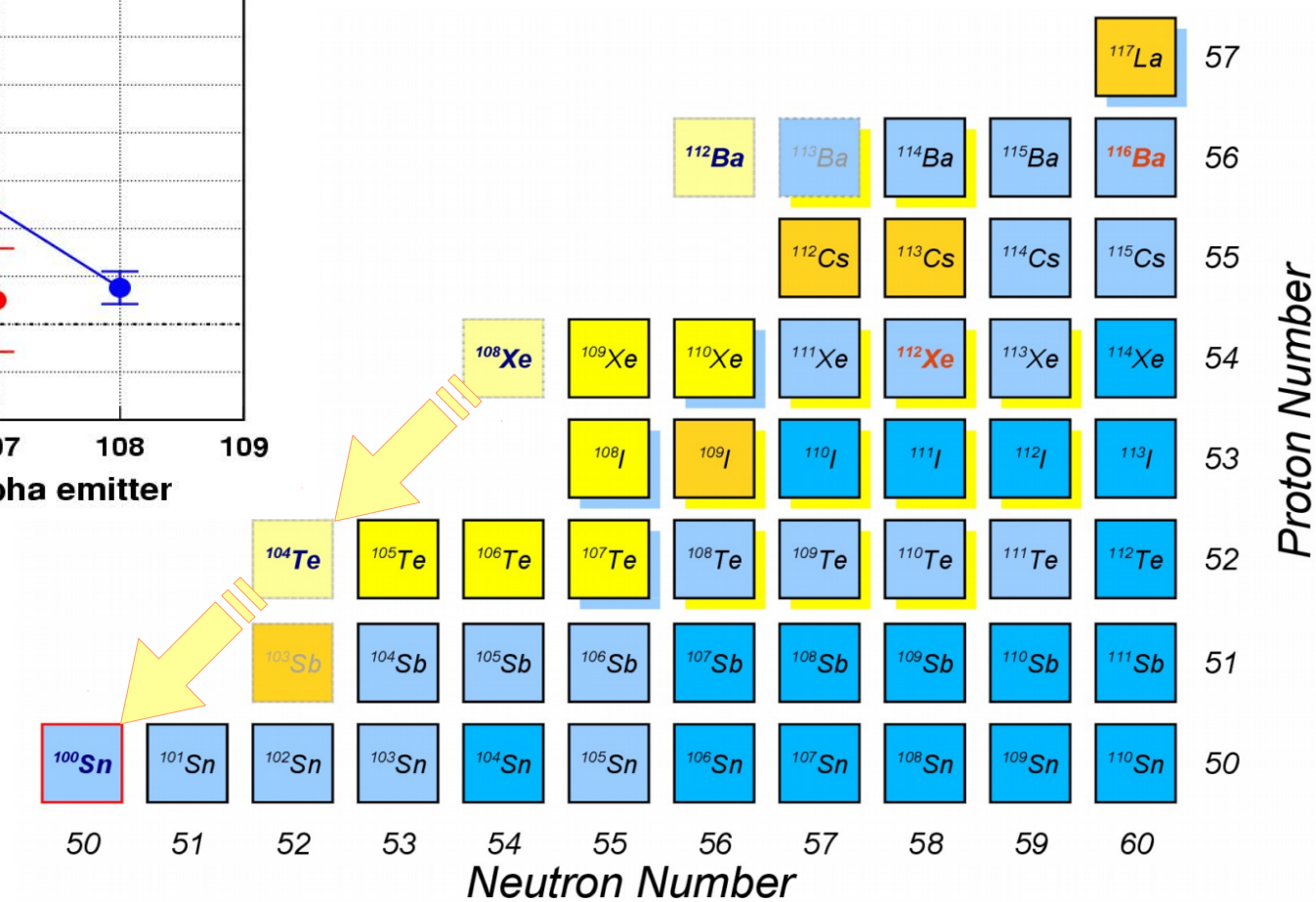


Do we understand alpha preformation?

Search for:

$$^{108}Xe \xrightarrow{100\mu s\text{-}1ms} {}^{104}Te \xrightarrow{10\text{-}100\ ns} {}^{100}Sn$$





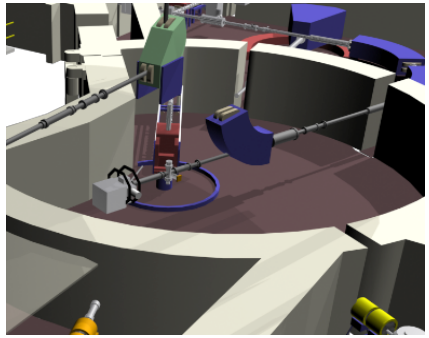
Reduced alpha emission witdh

$$\lambda = \frac{\delta^2 P}{\hbar} \text{ and } W_\alpha = \frac{\delta^2}{\delta^2(¿212\,Po)}$$

decay of $^{212}Po = {}^{208}Pb + \alpha$

Beta Delayed Neutron Spectroscopy on the r-process Path

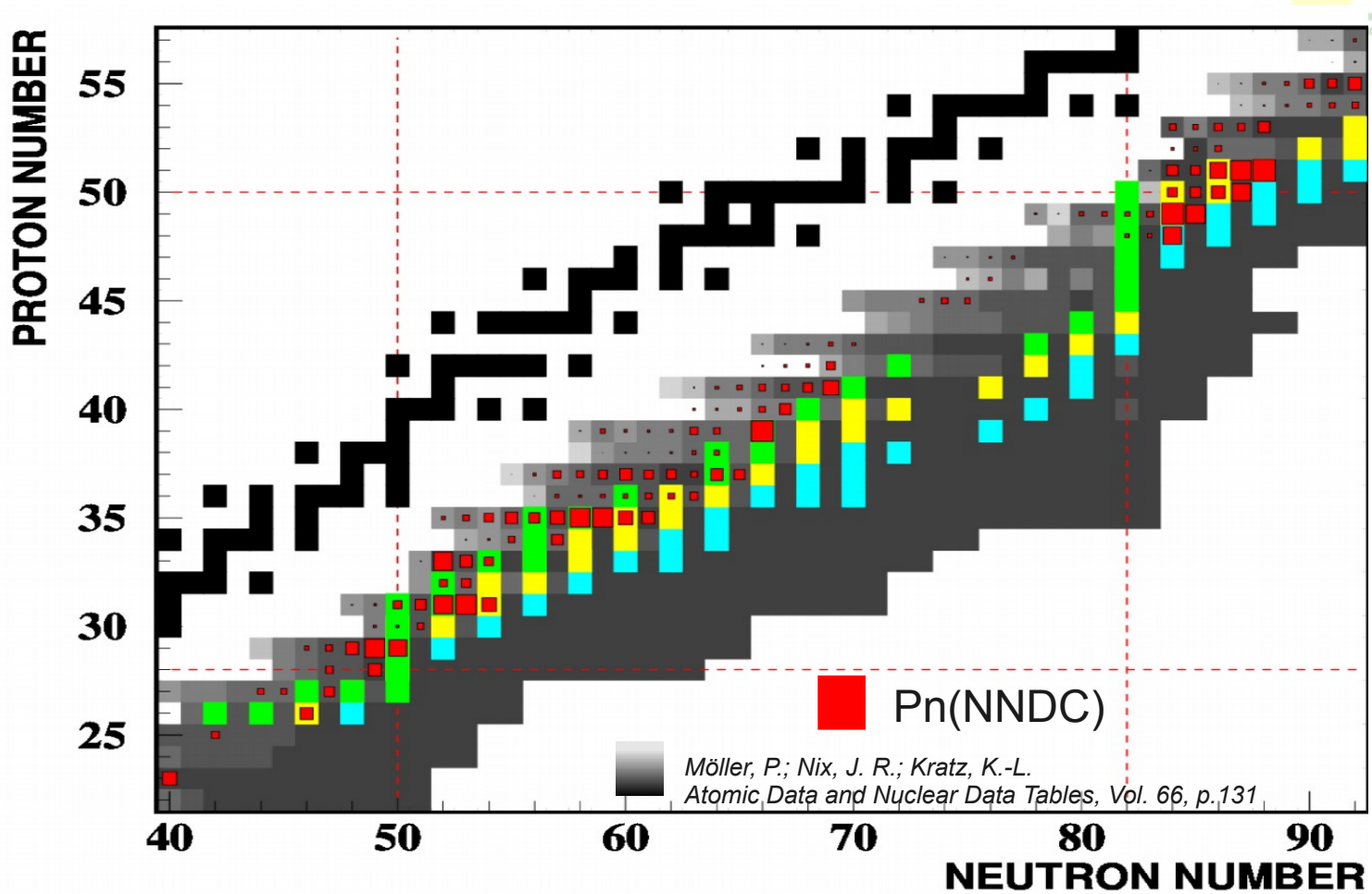
Intense beam (~10 μA) of (50MeV) protons on UCx targets
Isobar separation essential for success of the experiments !
IRIS-1/IRIS-2 platforms, negative and positive ions.



Low-energy Radioactive Ion Beam Spectroscopy Station (LeRIBSS)

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

Increase of decay energies far from stability enables complex decay channels

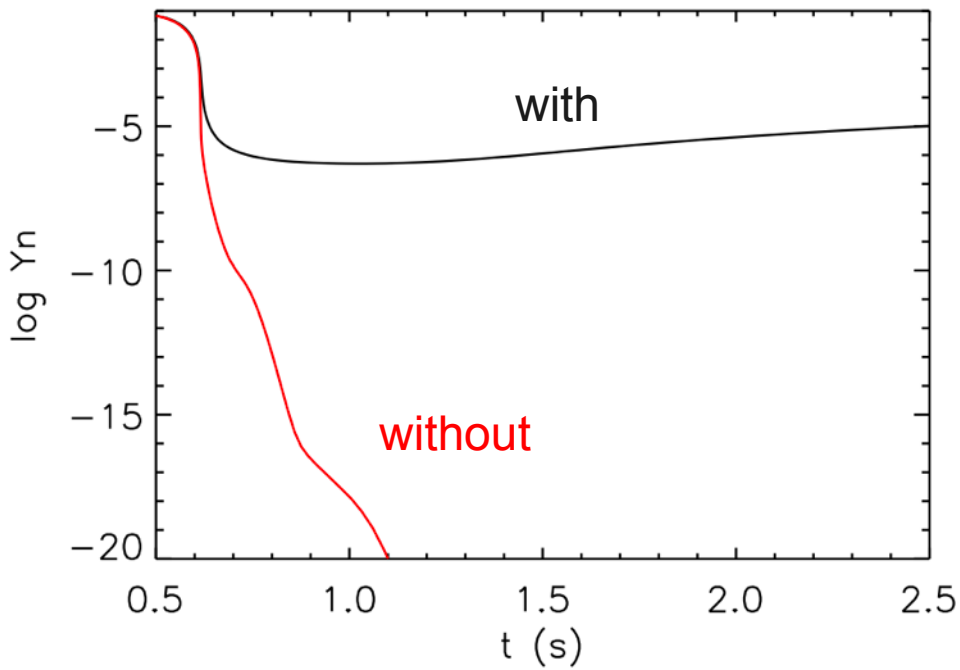


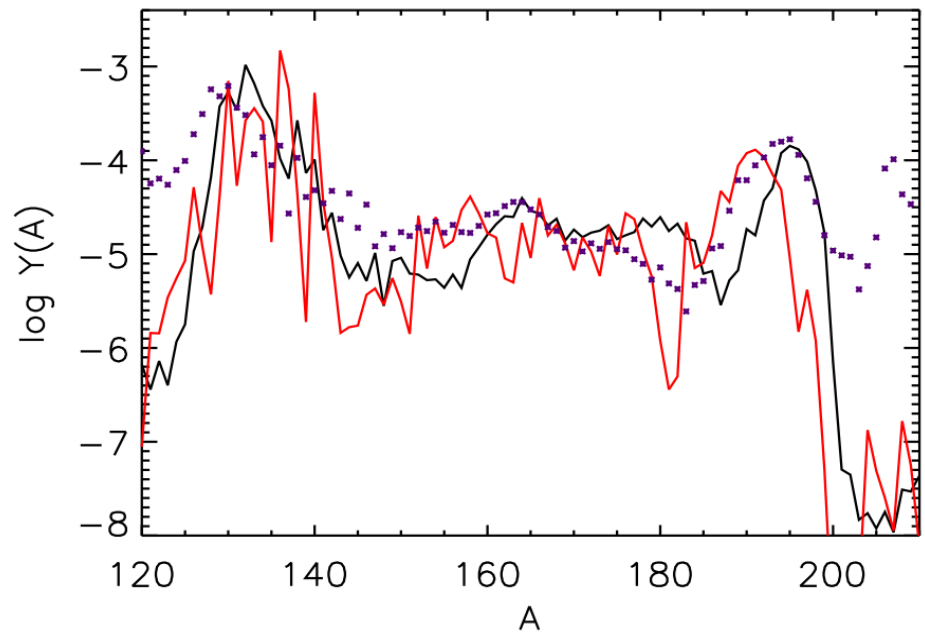
$n_n=10^{20}$
$n_n=10^{23}$
$n_n=10^{26}$
K. L. Kratz

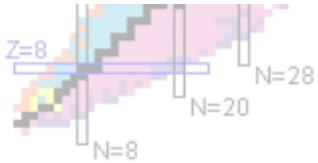
β-delayed neutron emission in a cold r-process

R. Surman

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

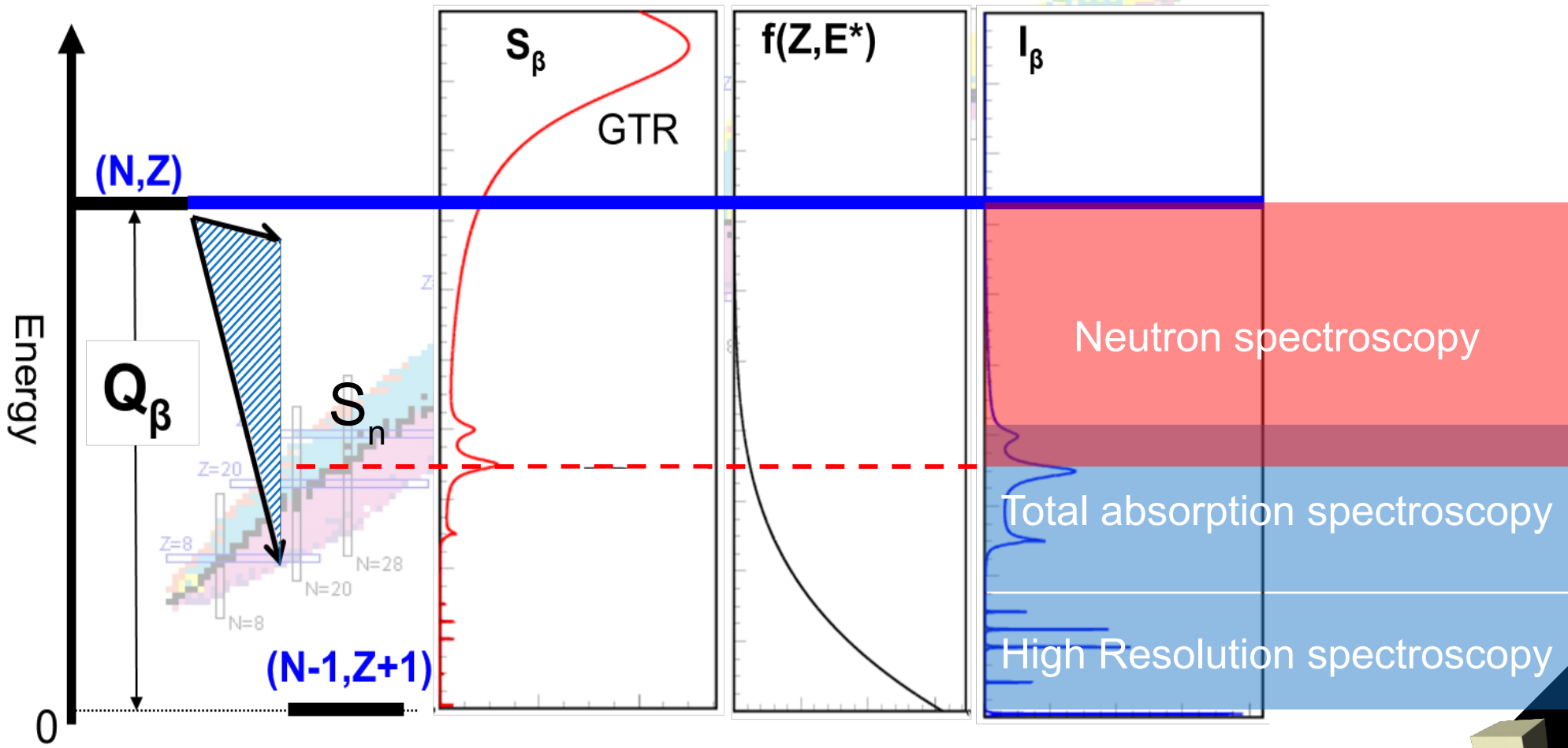




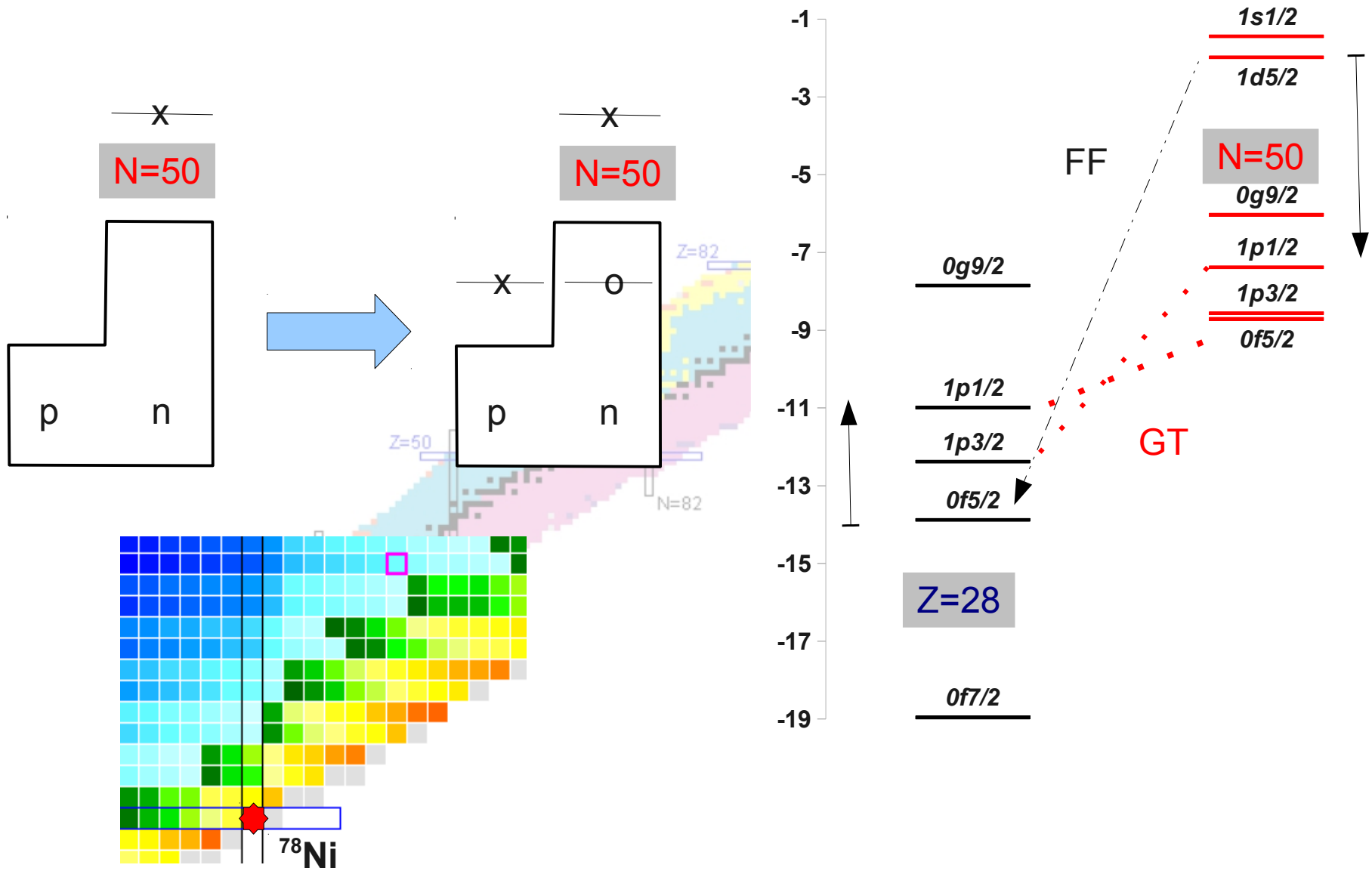


Beta decay of neutron rich nuclei

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

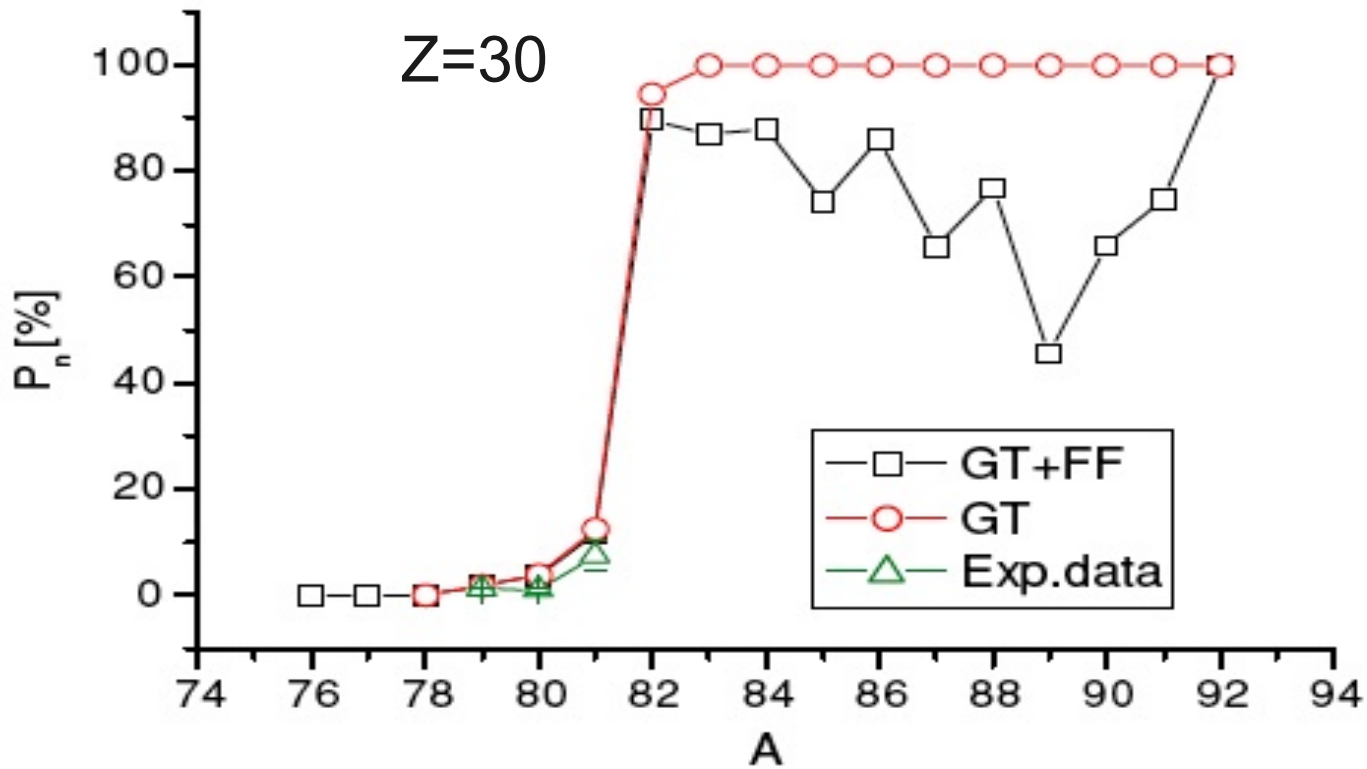


Beta decay of neutron rich nuclei: allowed (GT) and forbidden transitions



Neutron branching ratios: allowed (GT) and forbidden (FF) transitions

GT – "saturate" the Pn past N=50
FF - "erode" the Pn
Balancing between position and strength of FF and GT transitions.



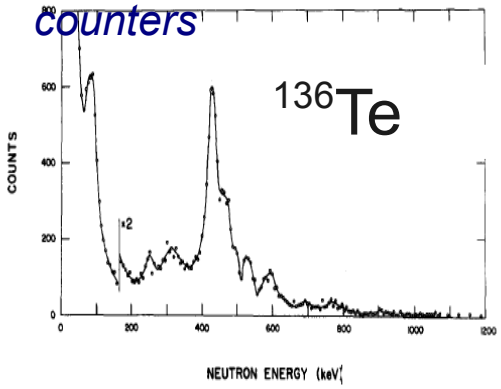
DF3a+QRPA
I. Borzov

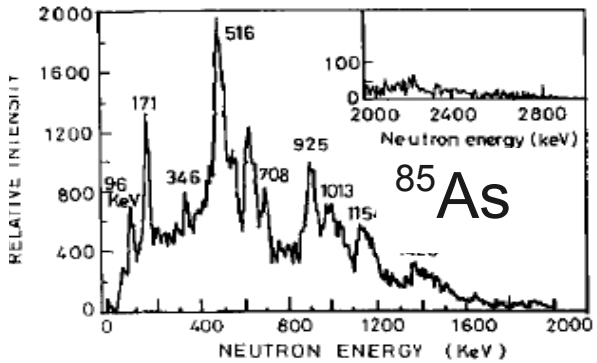
Measuring P_n only is not enough !

Beta-delayed neutrons from 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

^{3}He ionization chambers
H_2 and CH_4 proton-recoil proportional counters





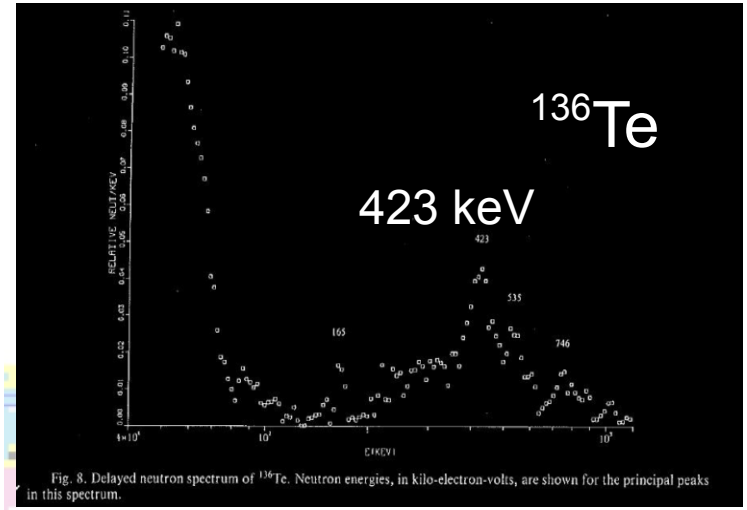
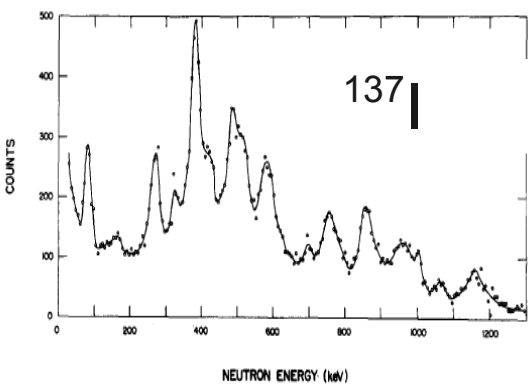


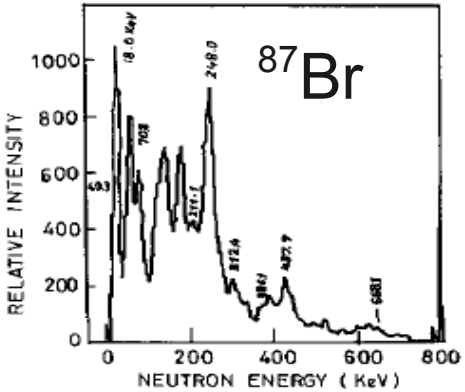
Fig. 8. Delayed neutron spectrum of ^{136}Te. Neutron energies, in kilo-electron-volts, are shown for the principal peaks in this spectrum.

R.C. Greenwood
(Brookhaven, TRISTAN)

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



G. Rudstam et al.
(Studsvik)



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

Good energy resolution
Low threshold
Very low intrinsic efficiency
(NOT very useful for exotic nuclei)
Limited isotope separation tools
Focus mainly on reactor physics
No gamma-ray detection

Beta delayed neutron spectroscopy very far from stability
Future of the spectroscopy of n-rich nuclei

Qβn ~ 2-3 MeV

Pn ~ 1-10 %

Neutron spectroscopy

< 1 MeV probed experimentally

Total absorption spectroscopy

High Resolution spectroscopy

Qβn ~ 6-8 MeV

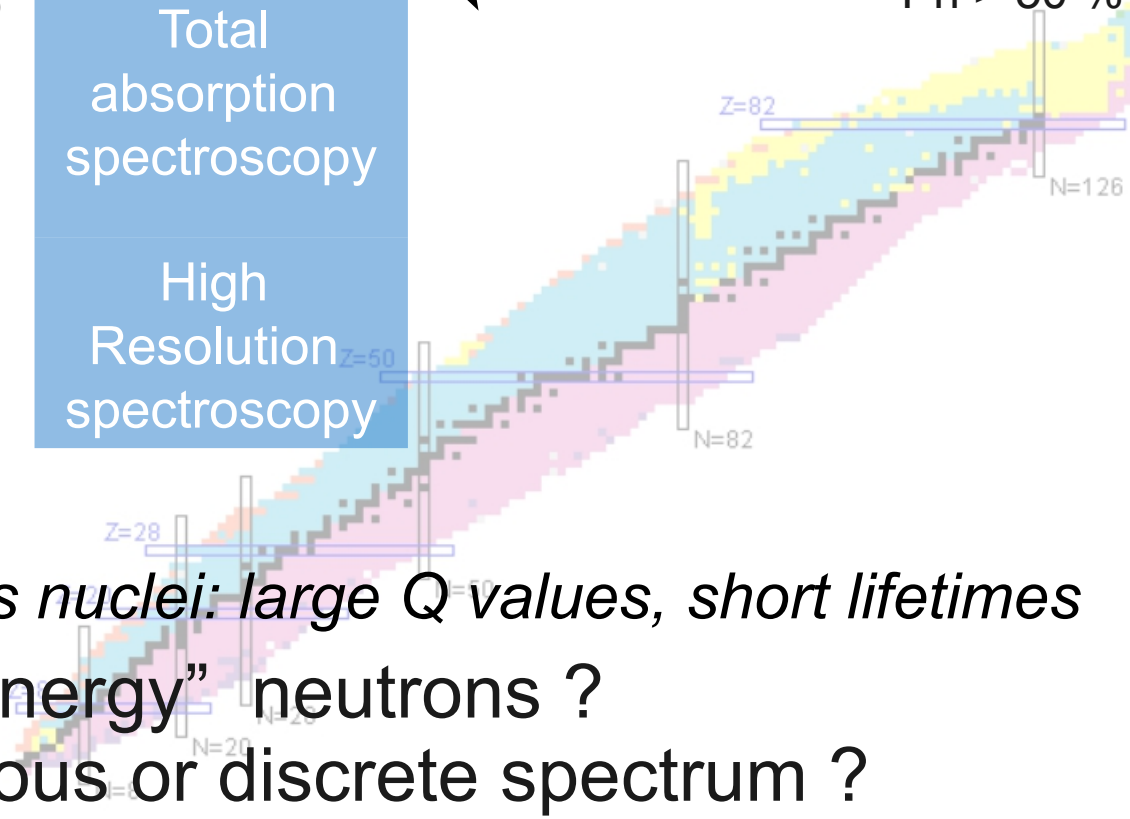
Pn > 50 %

2n

Neutron spectroscopy

Total absorption spectroscopy

High Resolution spectroscopy



r-process nuclei: large Q values, short lifetimes

"Low energy" neutrons ?

Continous or discrete spectrum ?

True challenge –measure energy of the neutrons !

VANDLE - neutron time of flight detector

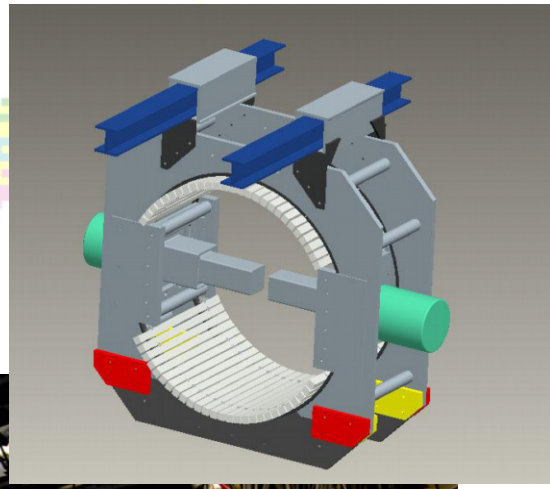
The Versatile Array of Neutron Detectors at Low Energy

Center of Excellence for Radioactive Ion Beam Studies for Stewardship Science

Maximize the detection efficiency in the broad energy range (100 keV – 6 MeV)

Neutrons (scattering of the scintillator material)

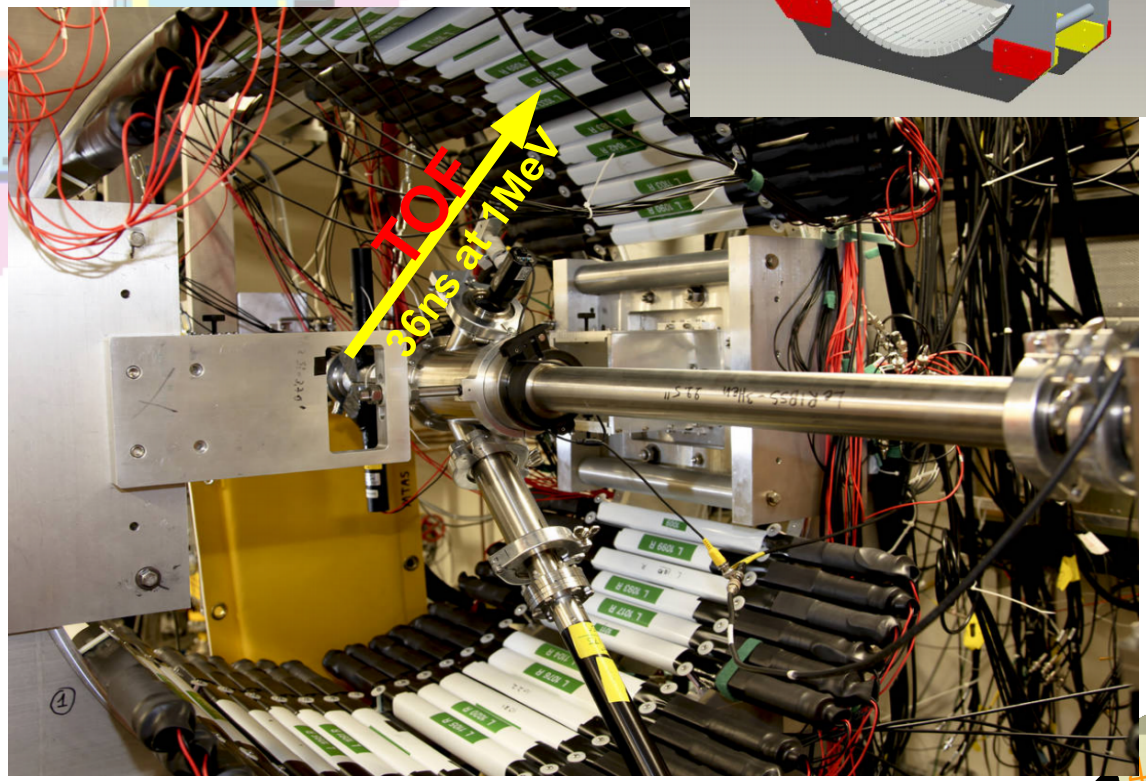
- **48 bars 3x3 x 60 cm^3**
- **Ω = 10% (23%) of 4π**
- **~3% (6%) total efficiency @ 1MeV**
- **50 cm TOF radius**
- **40-60% efficiency beta "START" detector**



Gamma rays:

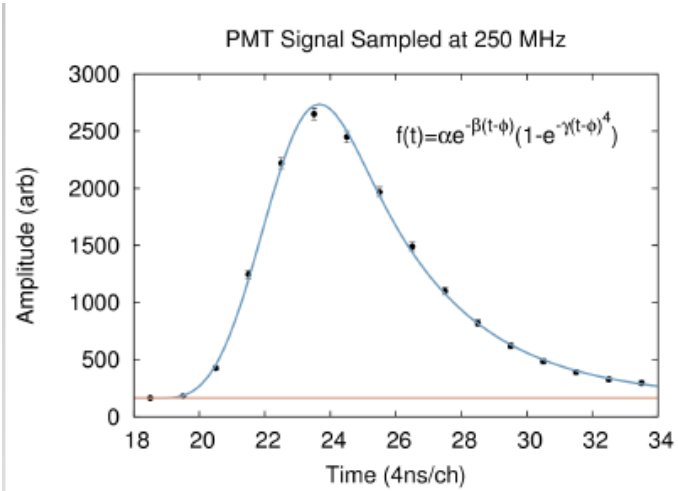
- **2 clovers, 3% efficient @ 1MeV**

Tape transport and beam-kicker
Digital signal processing

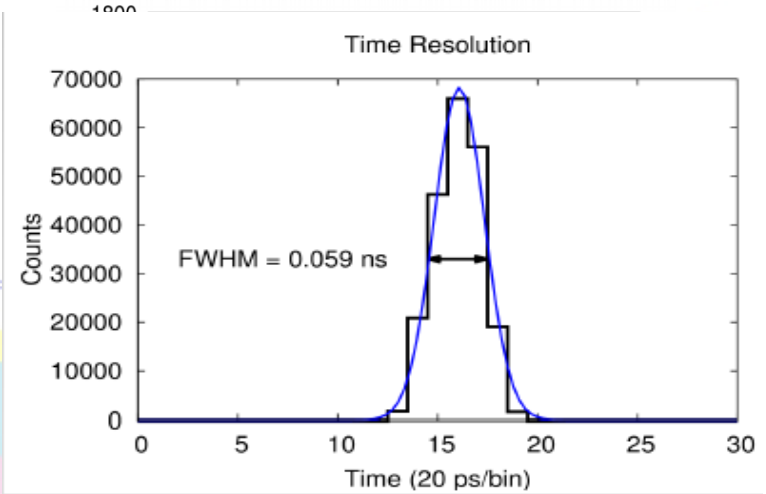


Low threshold/high efficiency digital electronics for VANDLE

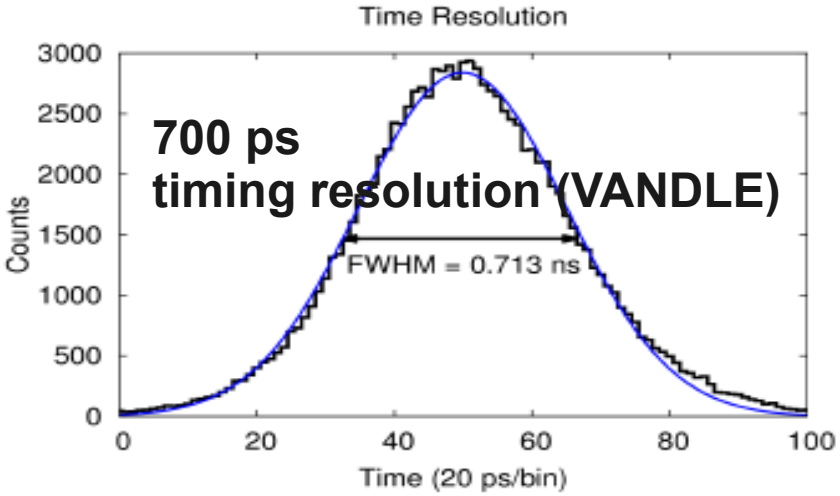
250 MSPS (4ns) 12bit FADC
Pulse shape analysis

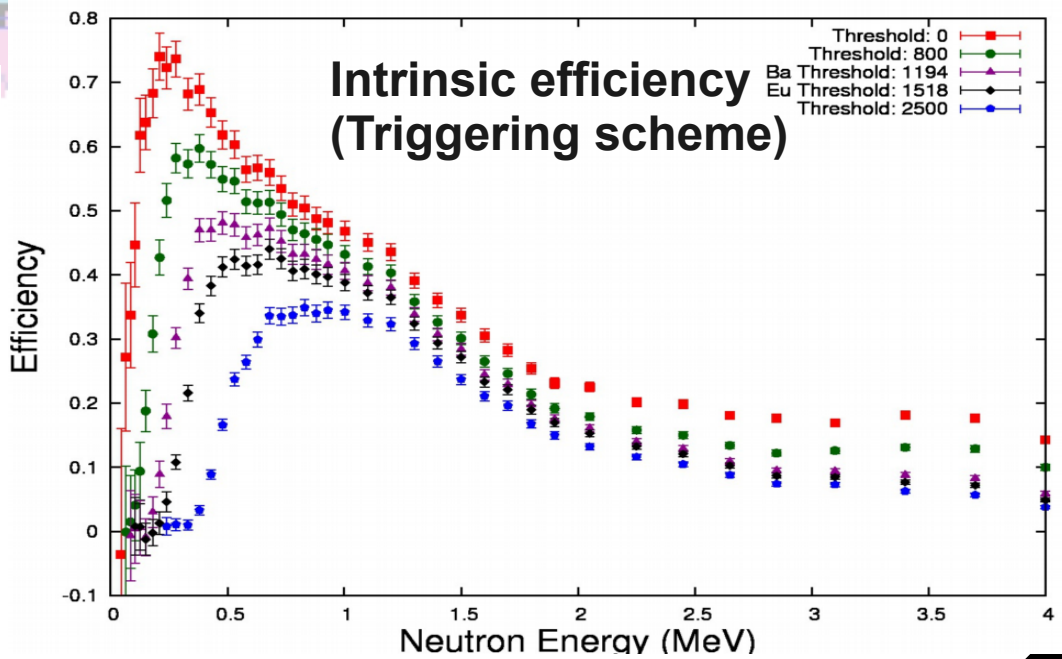


Better than 100 ps timing resolution (digitizer)

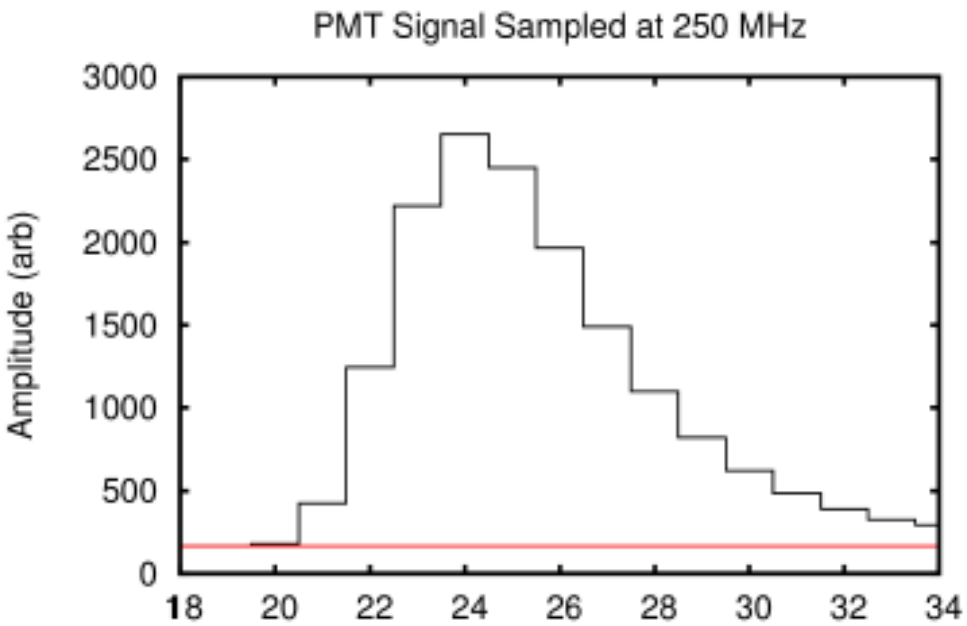


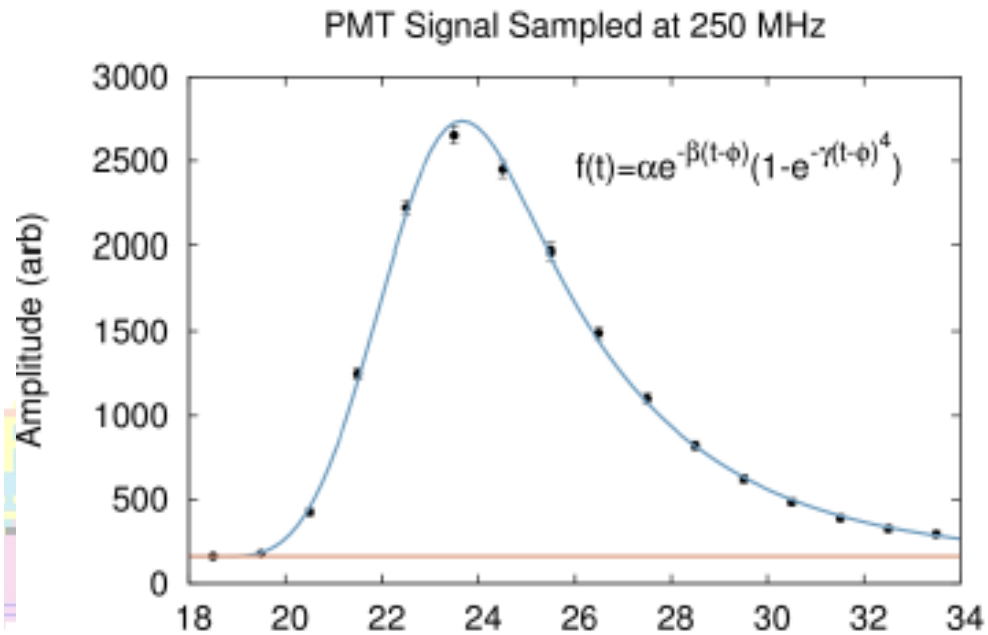
S. Paulauskas, M. Madurga

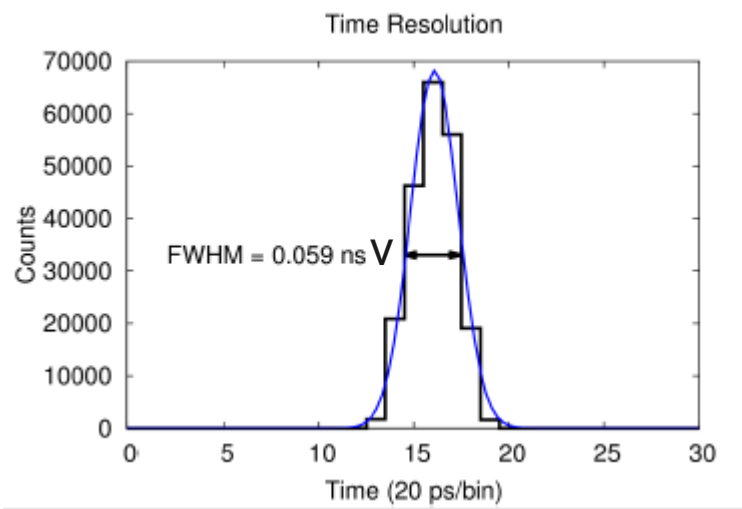


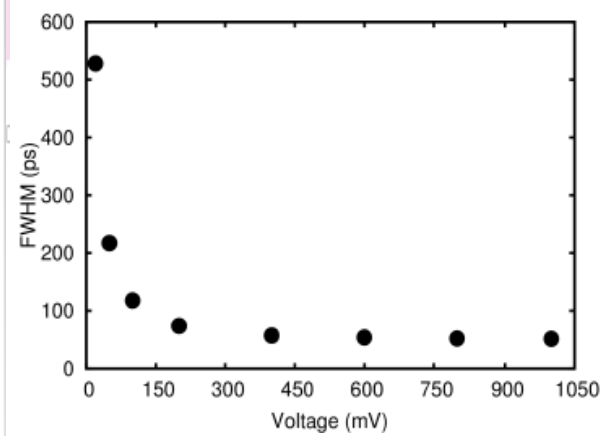


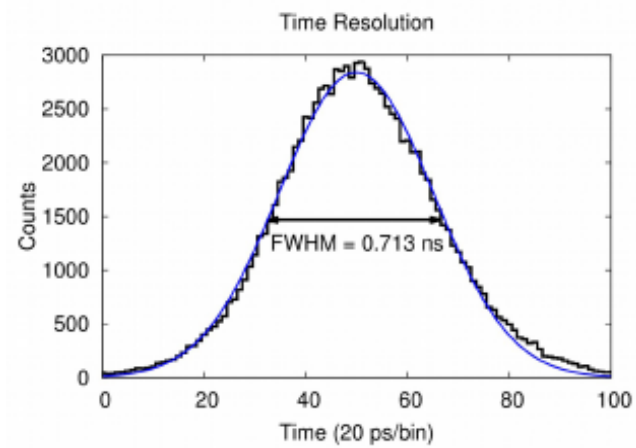
Timing analysis (S. Paulauskas)
How to get sub-ns resolution with 250MHz digitizer ?



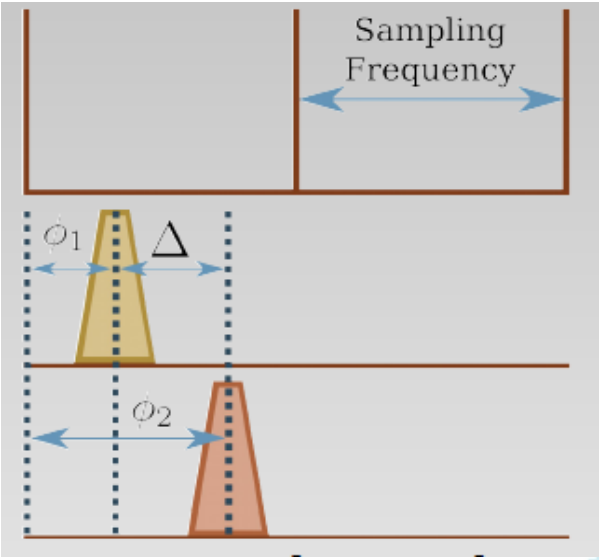


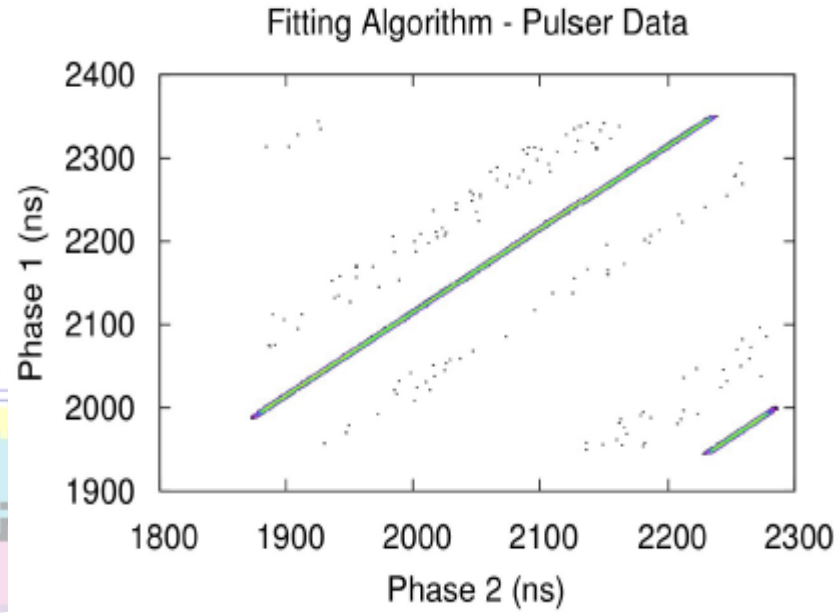


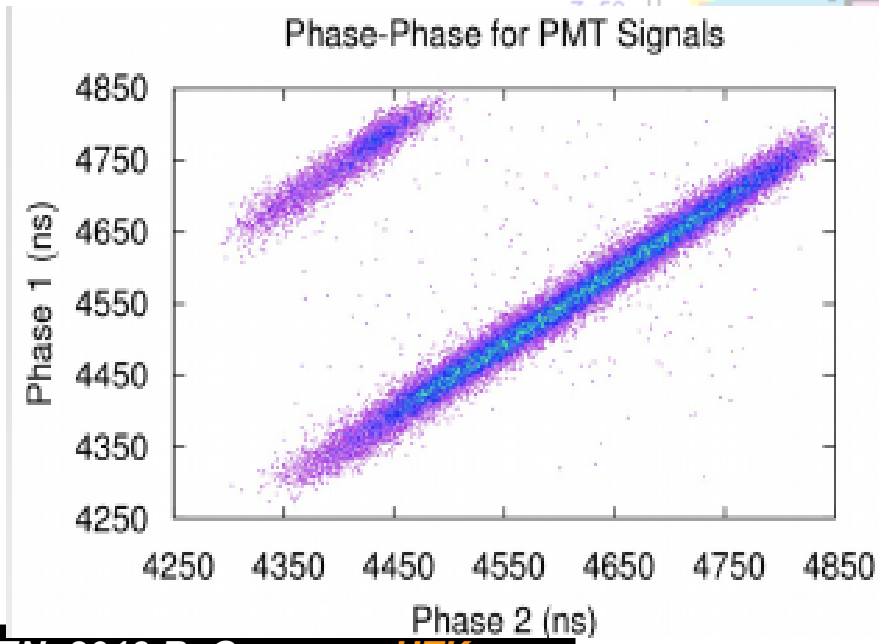


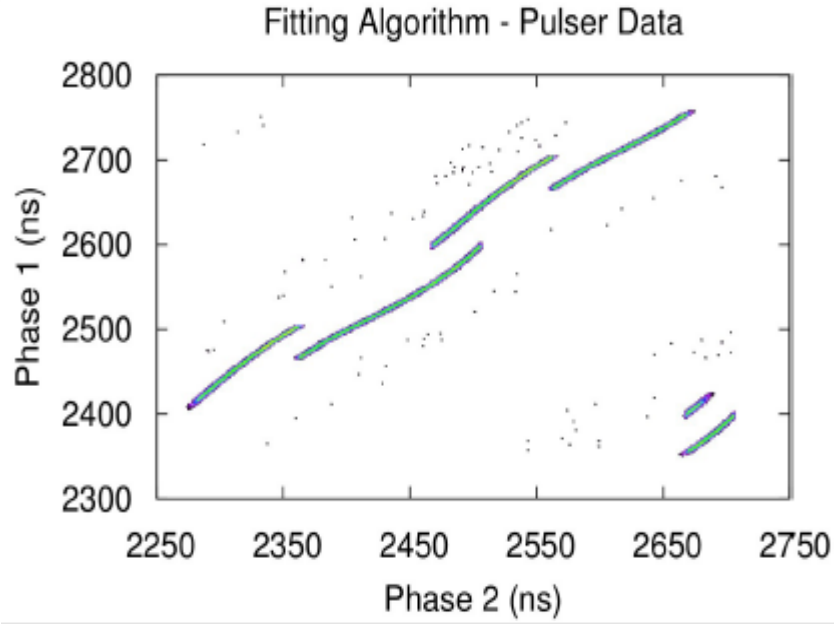


Timing analysis:
"Phase – phase plot" (M. Madurga, S. Paulauskas)

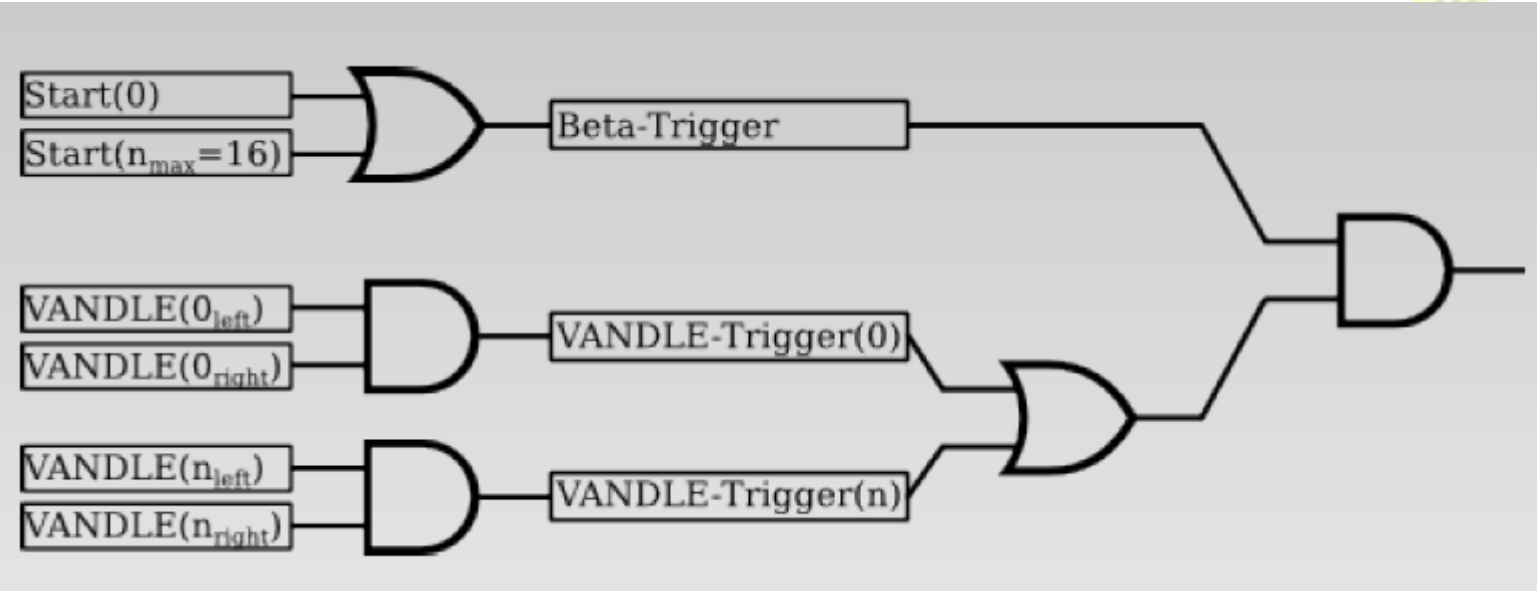








VANDLE trigger scheme

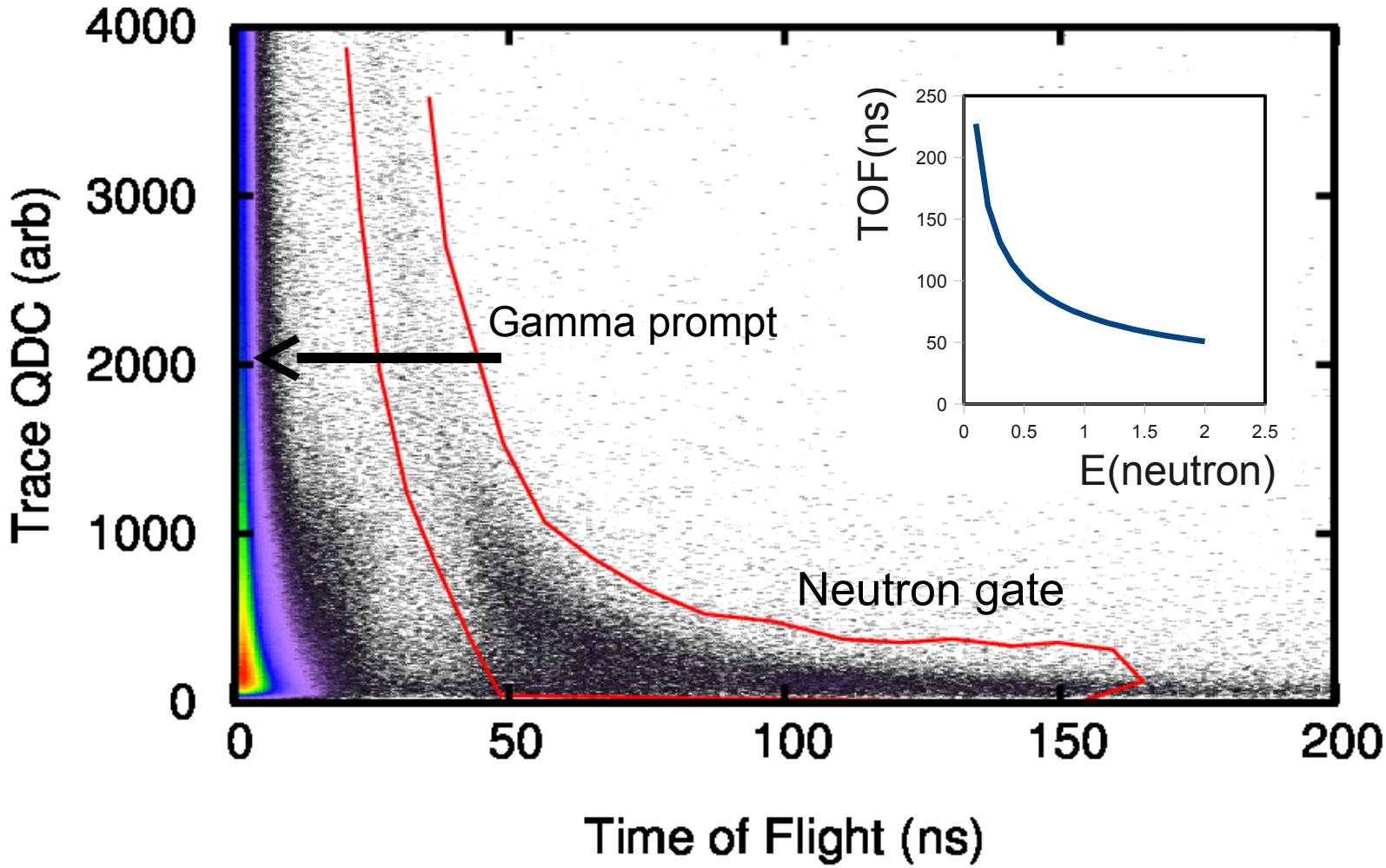


Distributed logic
No auxiliary electronic

Light output vs time of flight

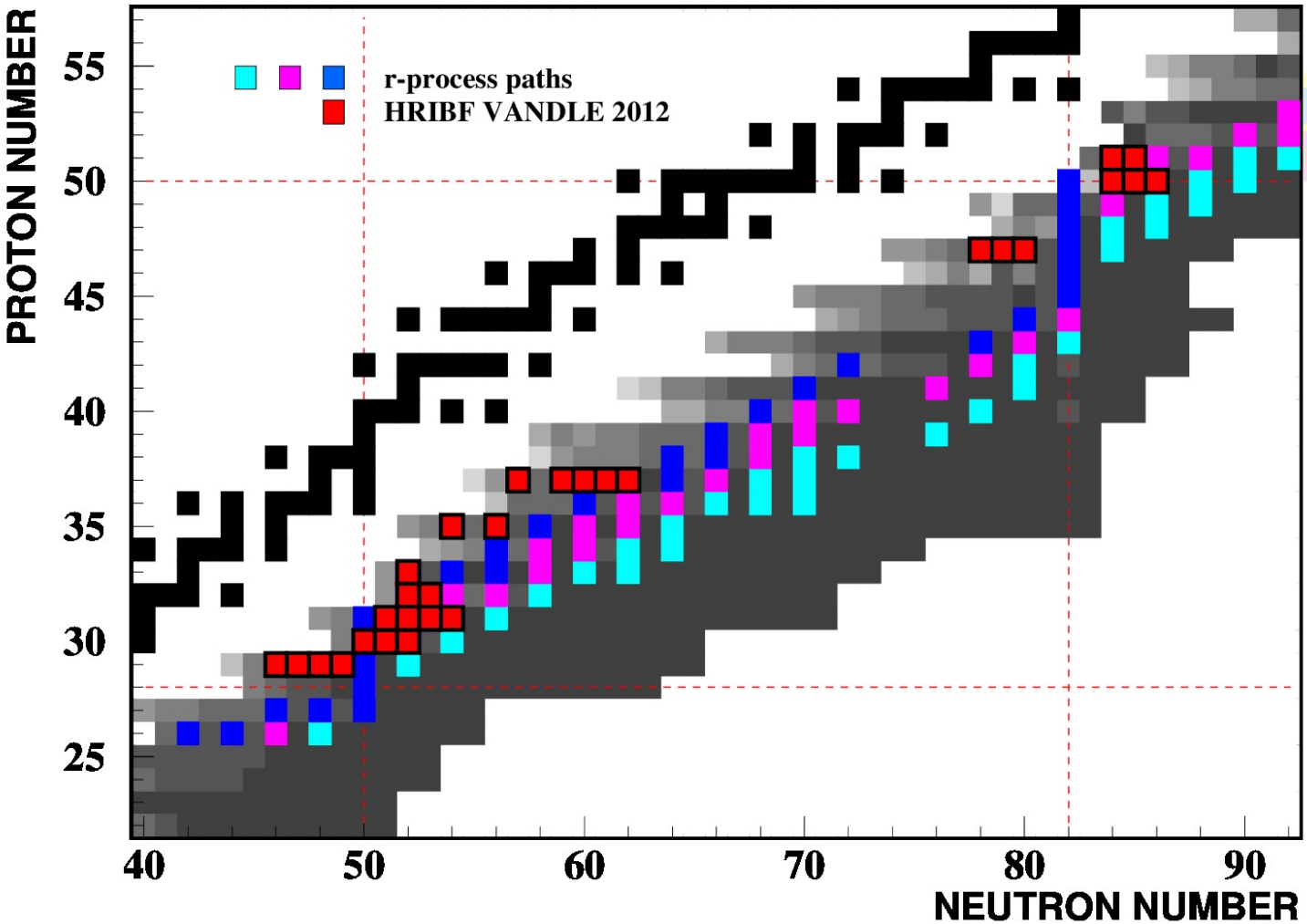
”Start” provided by beta, “Stop” by VANDLE

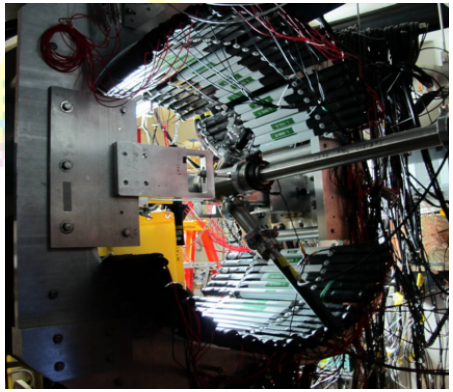
Energy of the neutron can be measured independently of the energy deposit
Kinematical compression !



The Versatile Array of Neutron Detectors at Low Energy

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

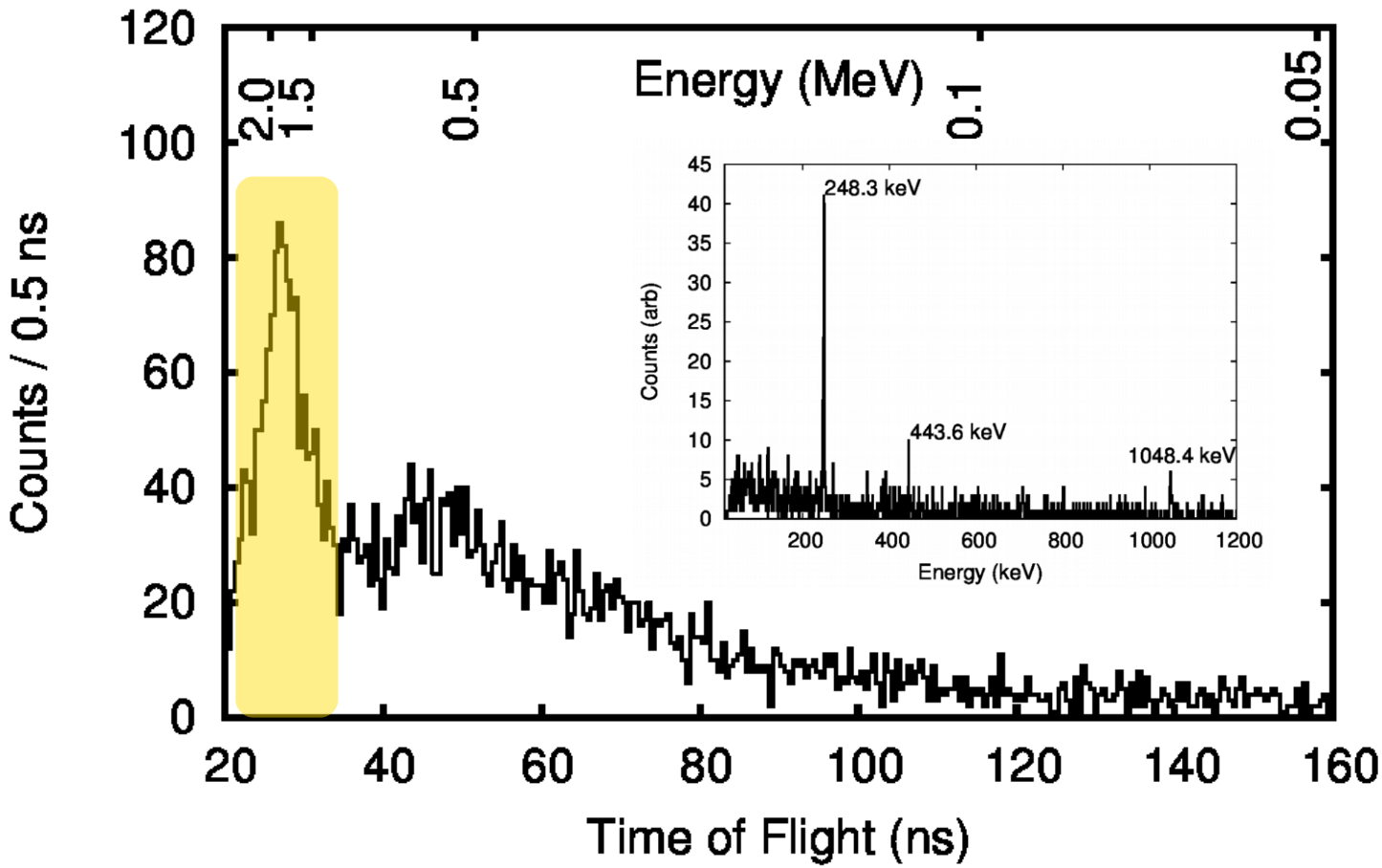




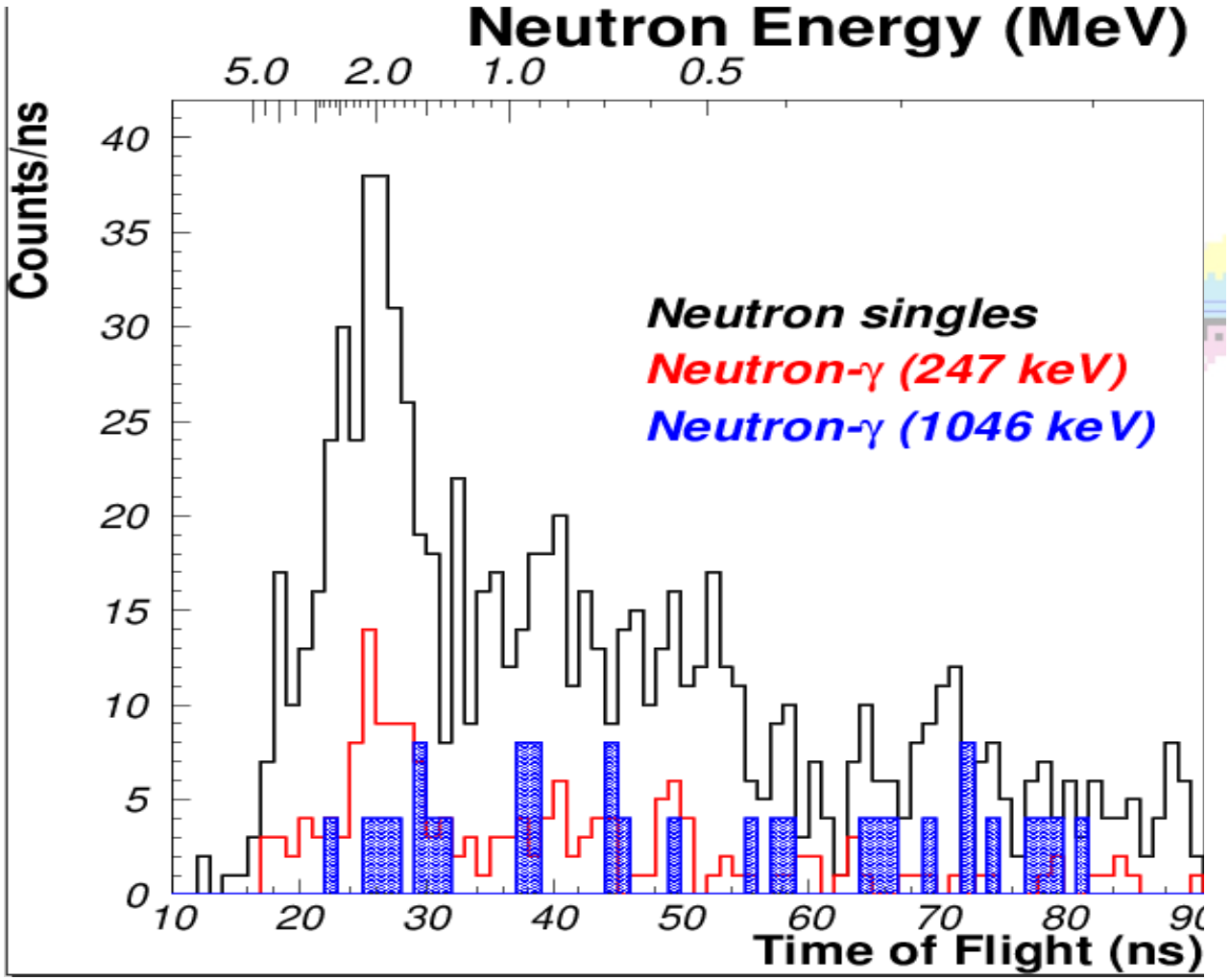
$T_{1/2}$ > 50ms
rates > 10pps
$I_{\beta n}$ > 1%
3MeV<$Q_{\beta n}$-S_n < 8 MeV

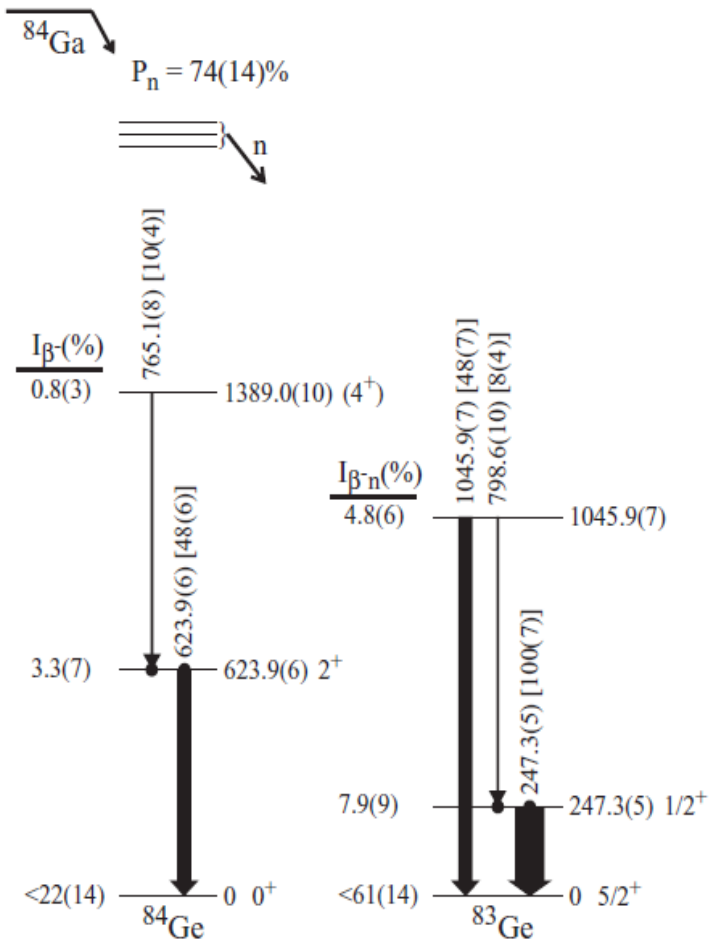
“Resonant” decay of ^{84}Ga (~30 h measurement)

$Q_\beta - S_n = 8.6$ MeV, $P_n = 74(14)\%$



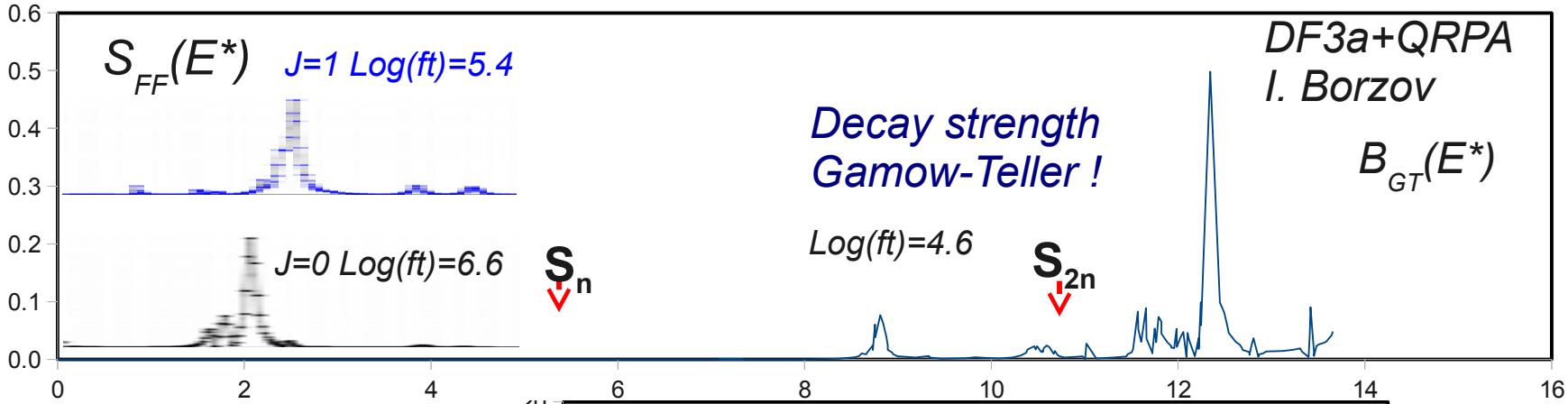
Neutron energy and gamma coincidences





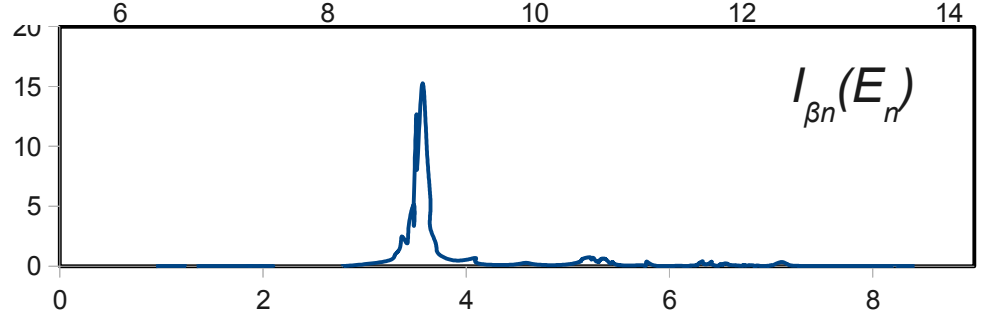
J.A. Winger Phys. Rev. C 81

^{84}Ga decay strength distribution (PRELIMINARY)

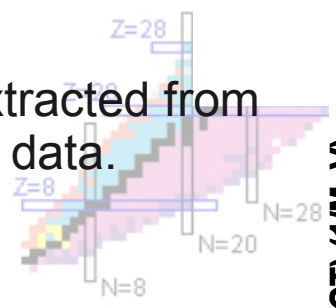


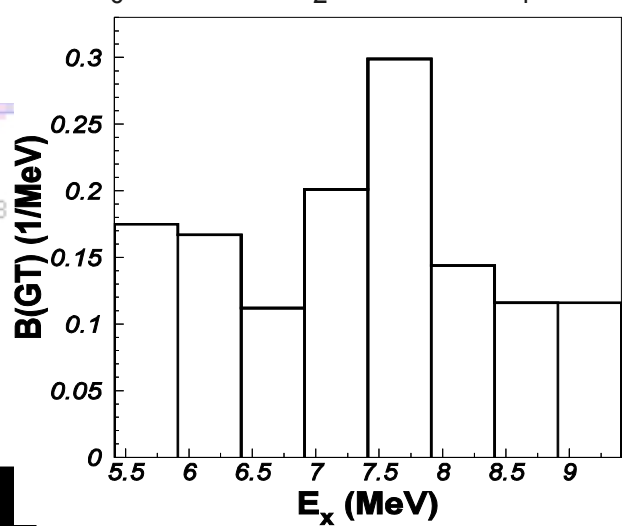
$P_n = 74(14)\%$

$P_{n,the} = 60\%$



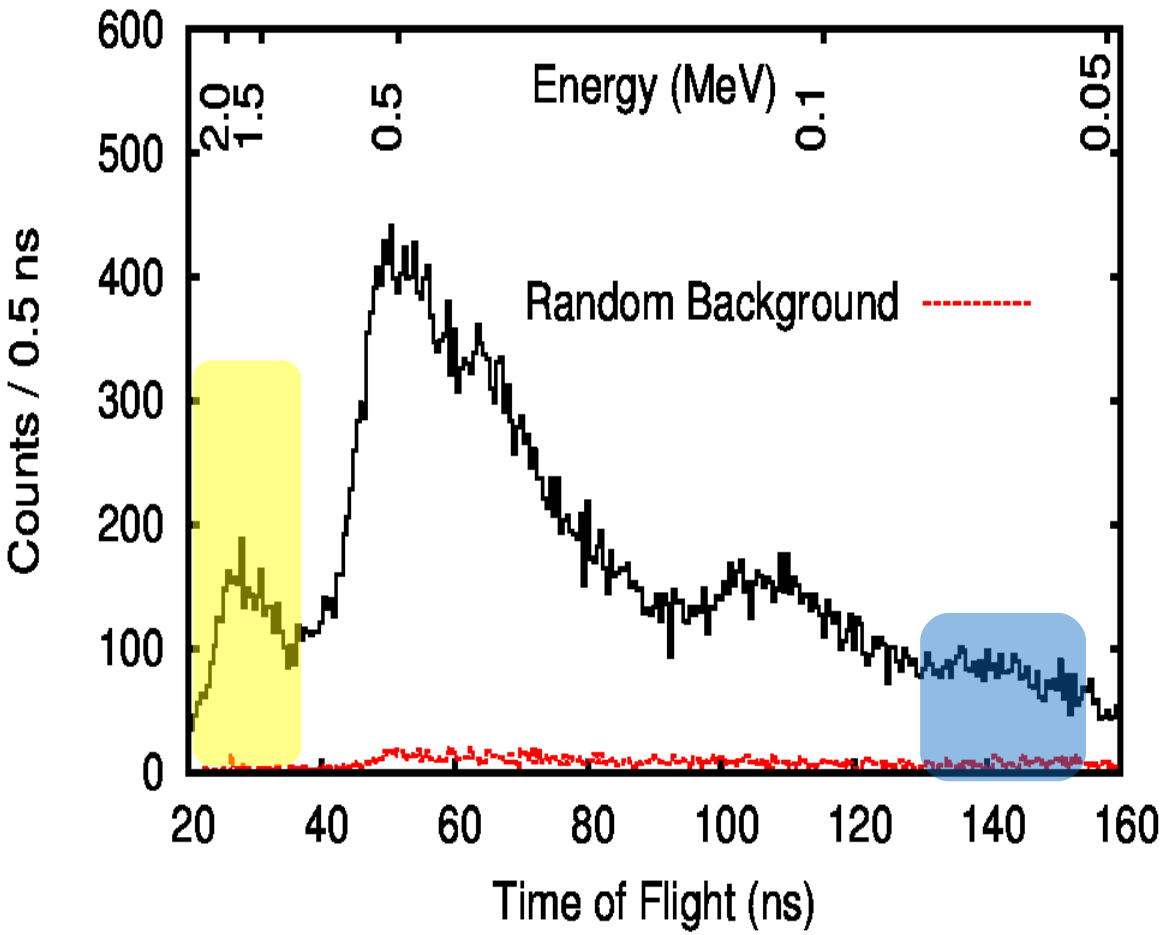
B(GT) extracted from VANDLE data.





VANDLE results (preliminary)
Low/high energy neutrons from ^{77}Cu

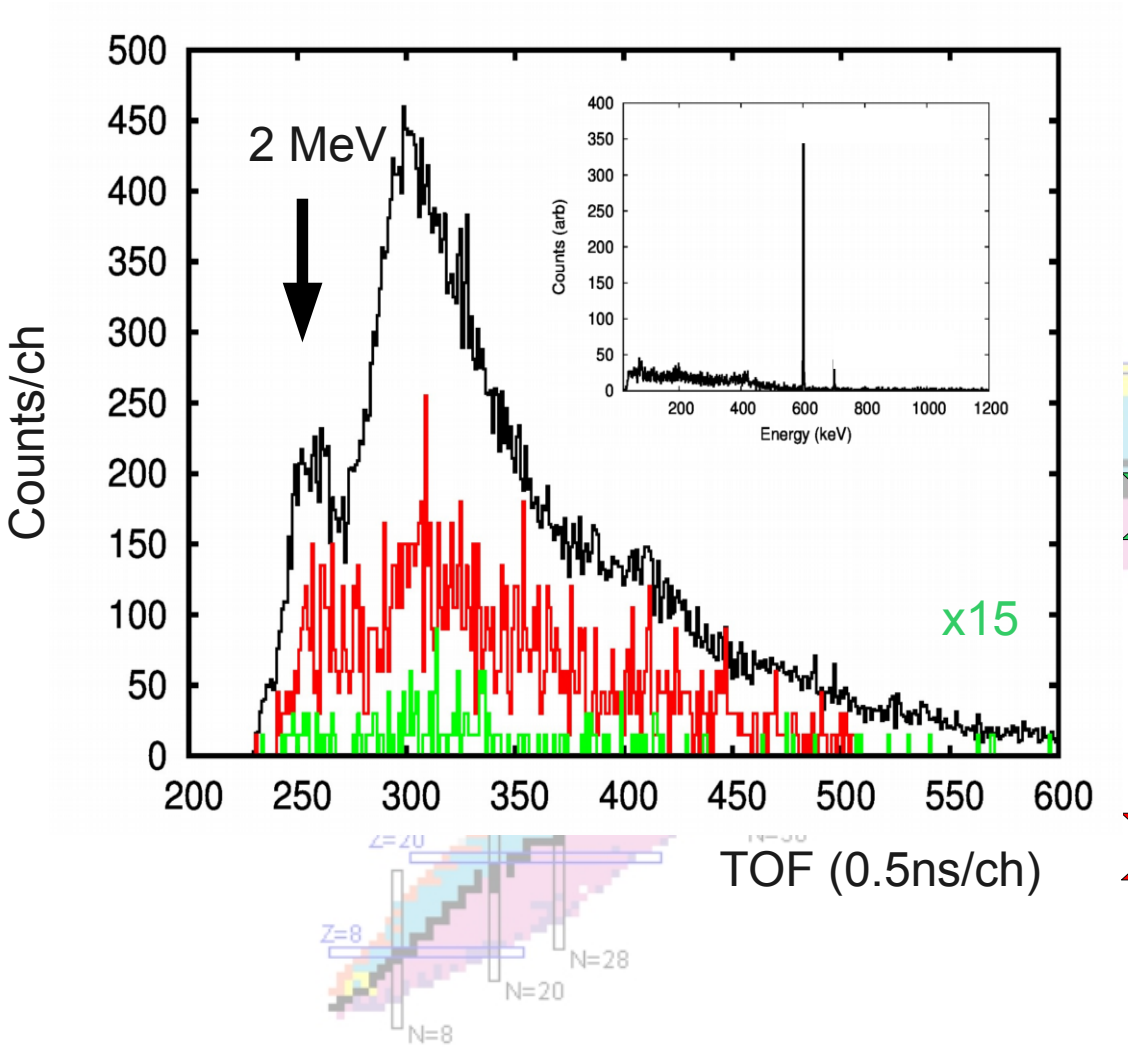
$Q_\beta - S_n = 5.5$ MeV, $P_n = 30.3(20)\%$

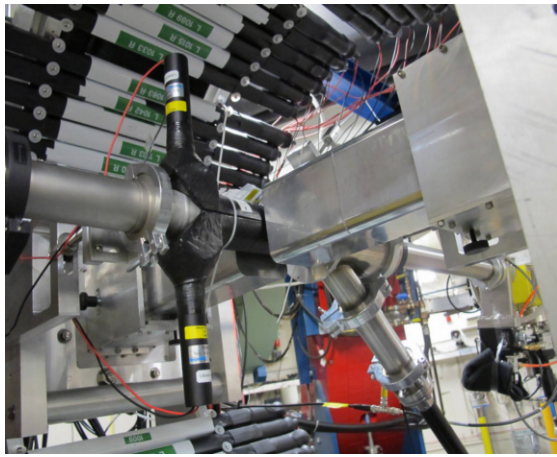


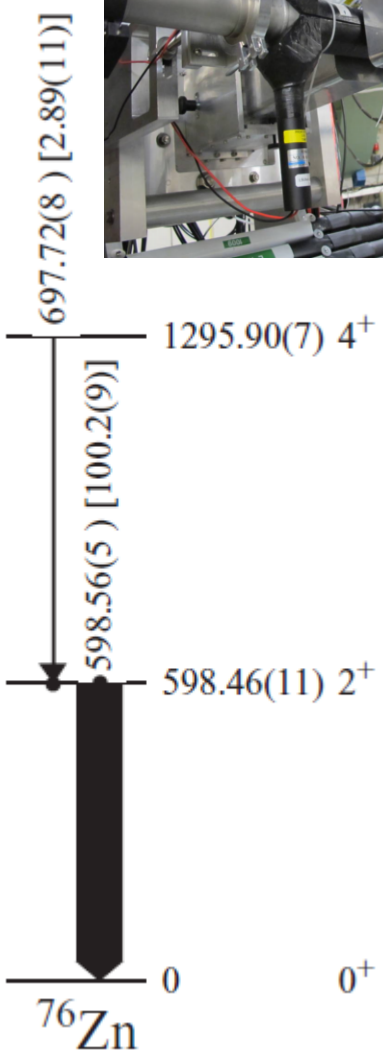
- Gamow-Teller decays at 0.5 and 2 MeV above Sn
- 100 keV neutrons detected!
- ~70 keV neutrons?
- Level 50 keV above Sn previously observed @ LeRIBSS

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

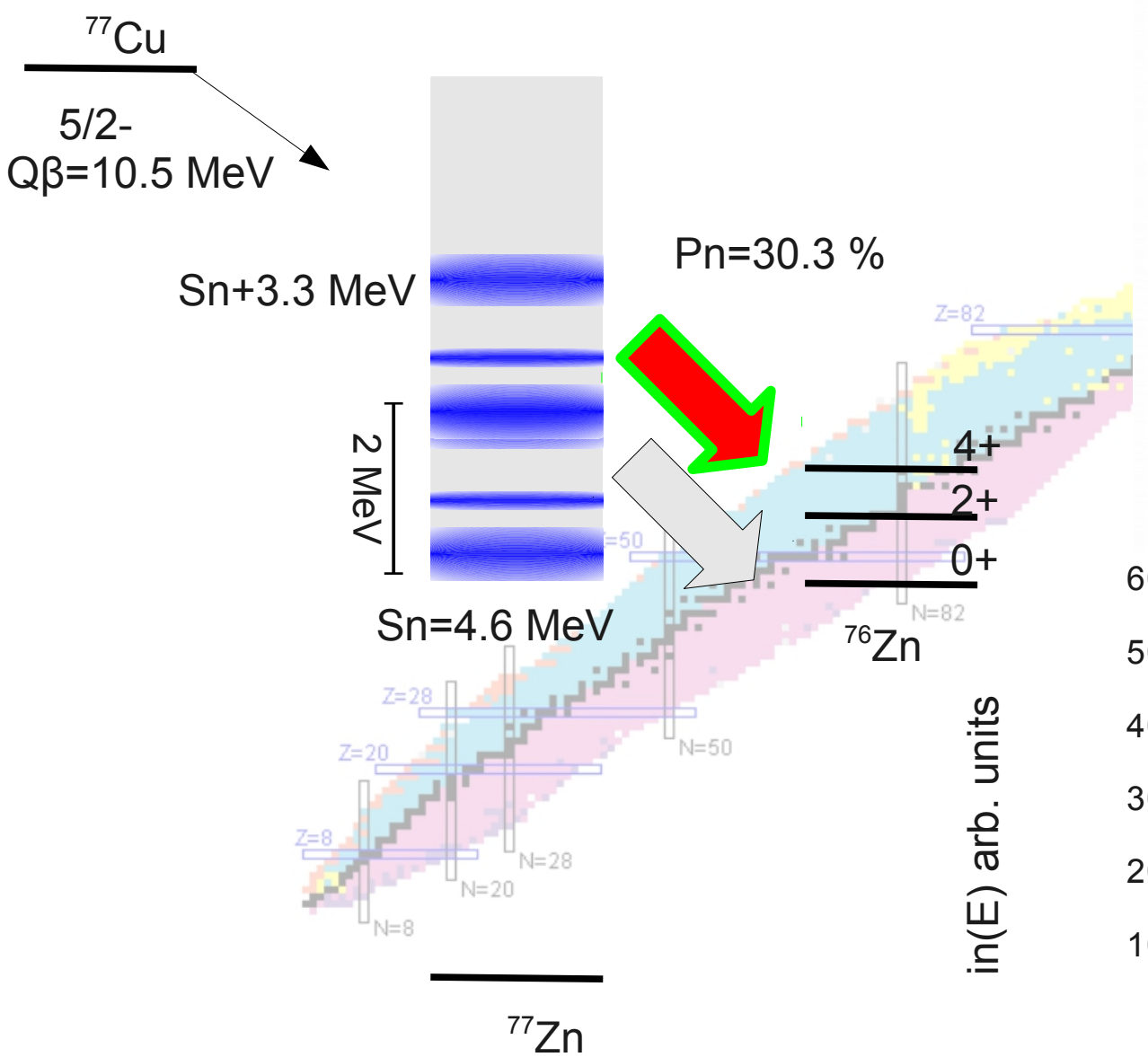
Gamma-gated neutron spectra from ^{77}Cu

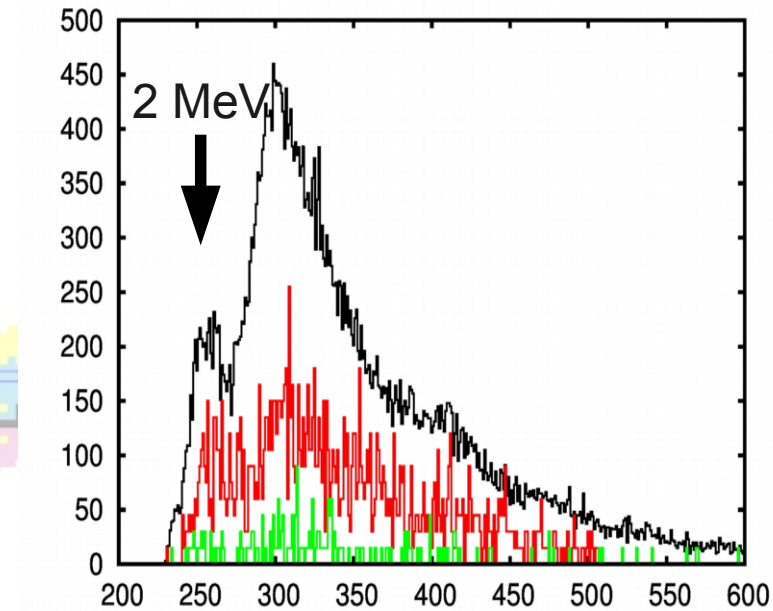


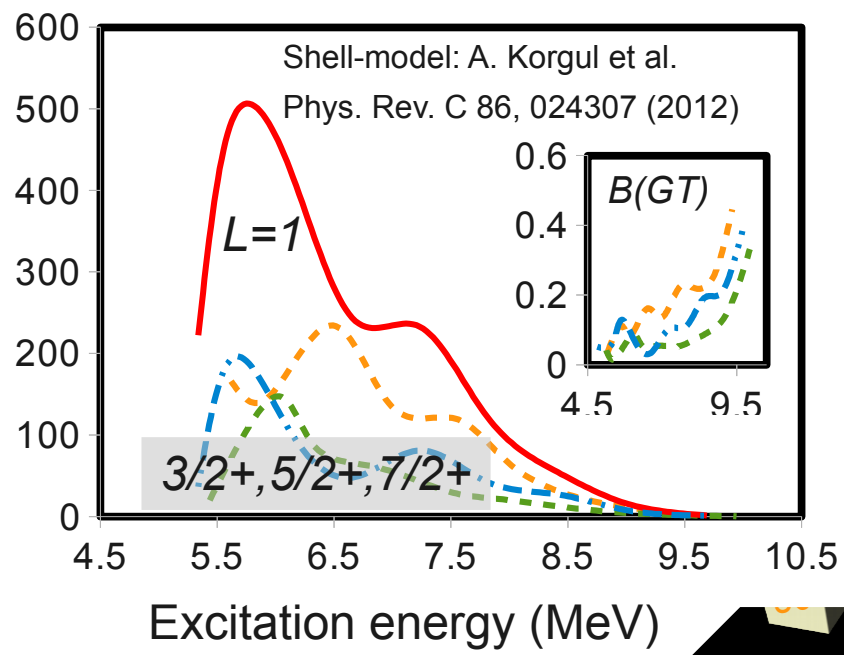




Beta-n decay of ^{77}Cu
Importance of gamma-rays





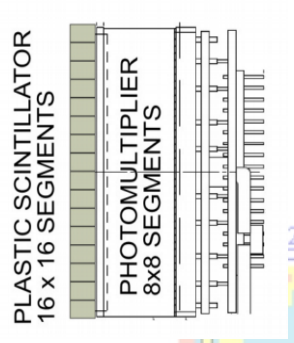


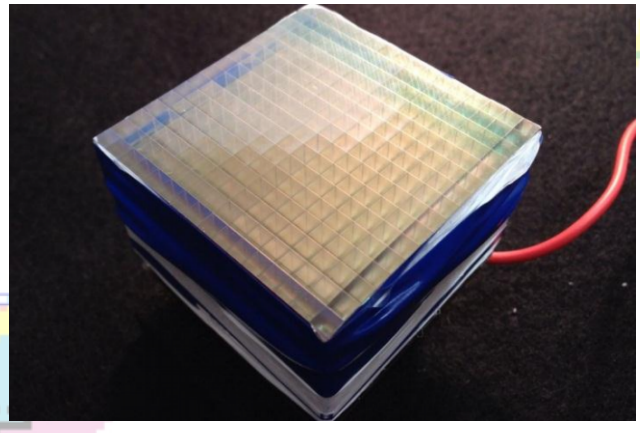
Segmented plastic scintillator + segmented PMT VANDLE Trigger detector for fragmentation-type experiments

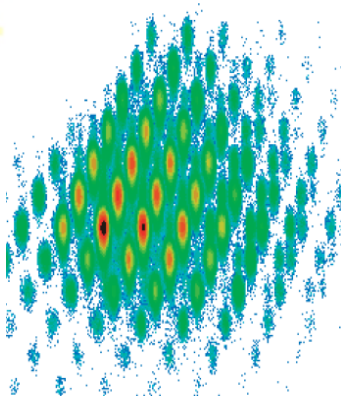
(Cannot use silicon strip detectors)

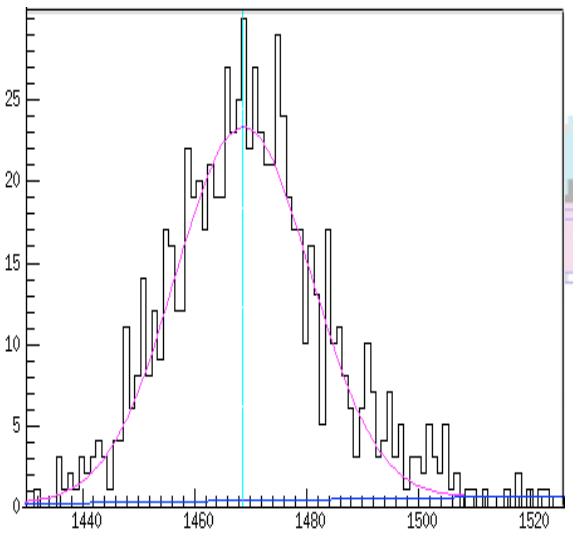
Demonstrated:

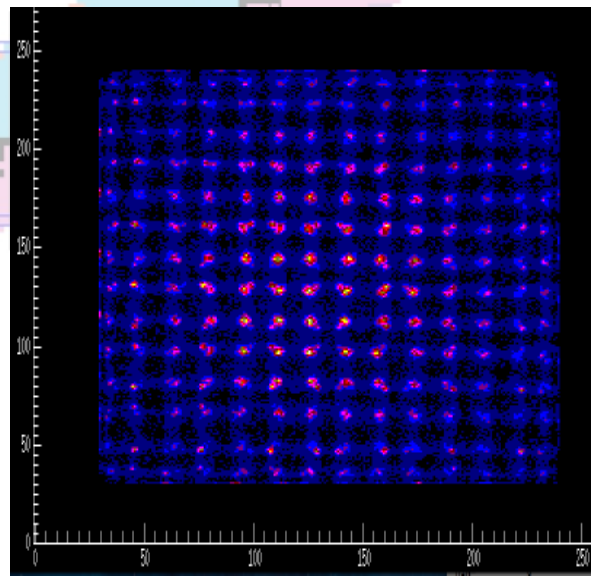
- event localization (3mm)
- timing (~ 500 ps)
- low energy threshold ~100 keV
- Digital DACQ

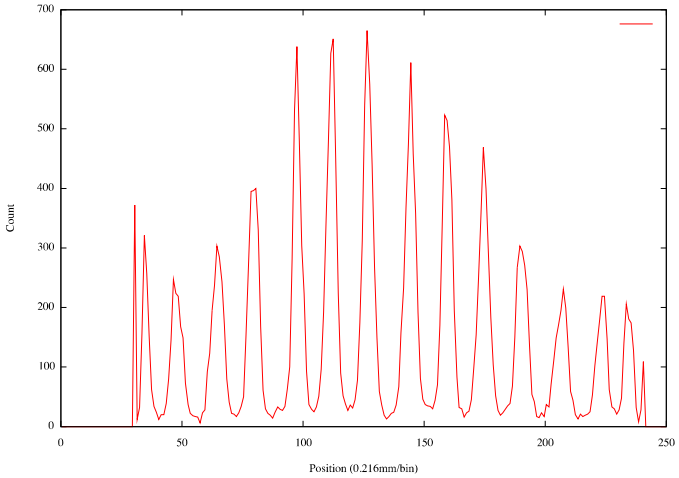








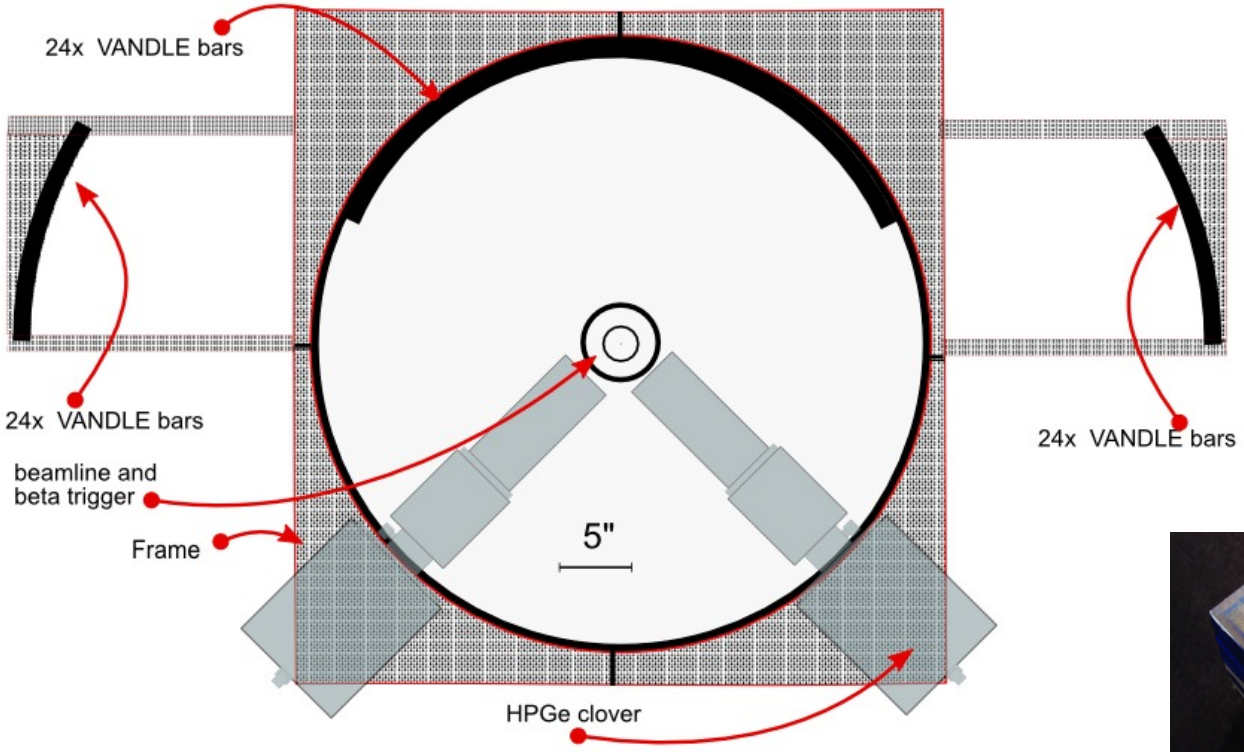


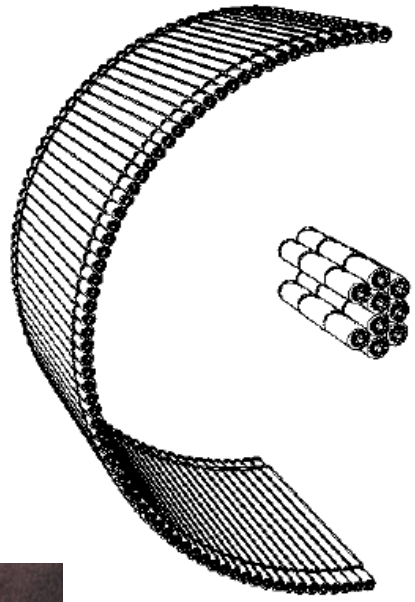


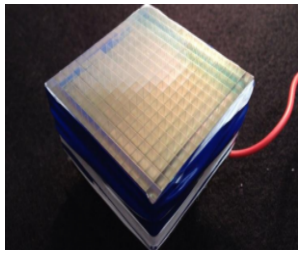
M. AlShudifat UTK

VANDLE as a precision instrument

- Increase nTOF base from 50 cm to 100 cm TOF
- Replace 3x3x60 cm^3 bars with 6x3x120 cm
- Move gamma-ray detectors from 180° to 90° geometry (ε(n)~10 %)
- Increase the gamma-ray detection efficiency with $LaBr_3$ array (ε~20%)
- Replace the beta-trigger (in vacuum, timing resolution)







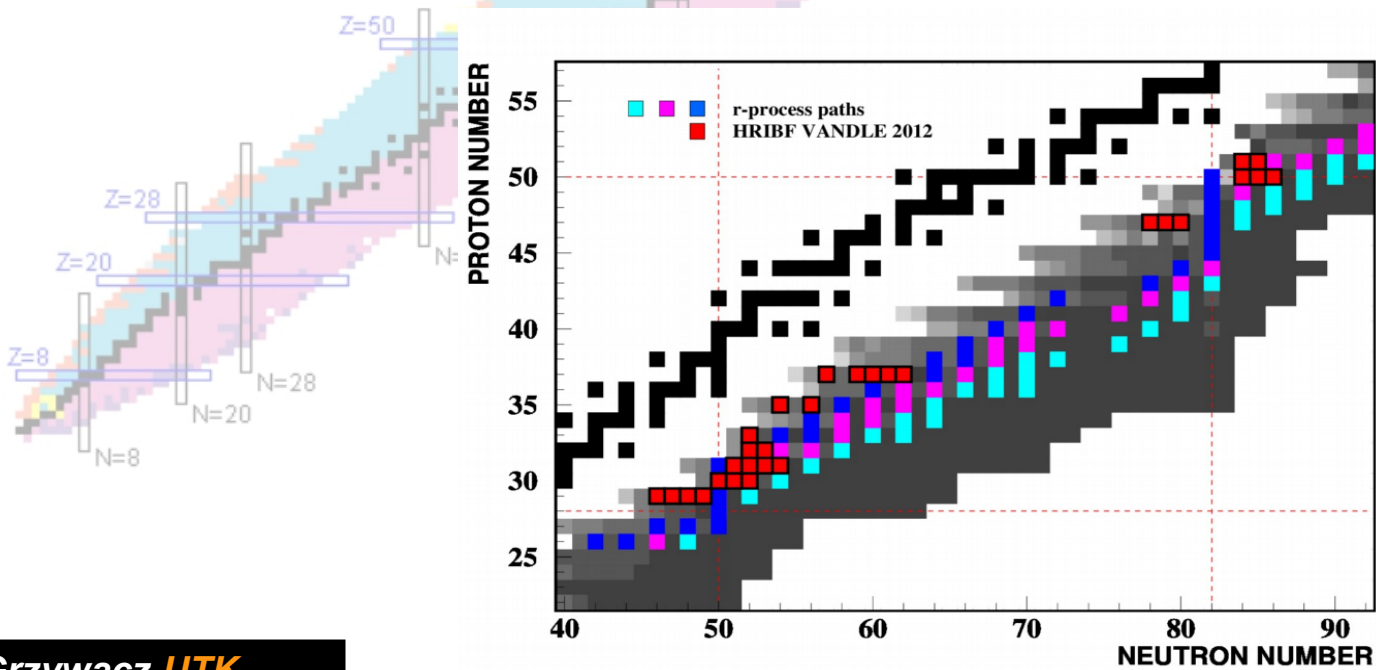
Beta-n studies of fission fragments

Comprehensive studies of decay strength distribution

Decay strength at high excitation energy:

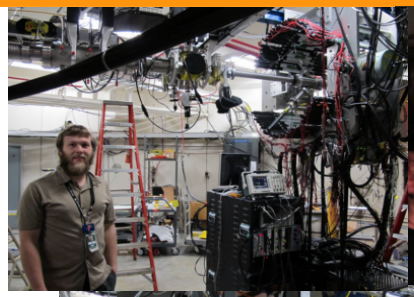
- **Will affects nuclear lifetimes and branching ratios (βn, β2n,β3n)**
- **Affect the energy sharing between e-,n,γ,ν !**
- **Neutron-gamma coincidence essential to reconstruct true feeding.**
- **Neutron-counters measurements will be affected**
- **Missing neutrons < 100 keV**

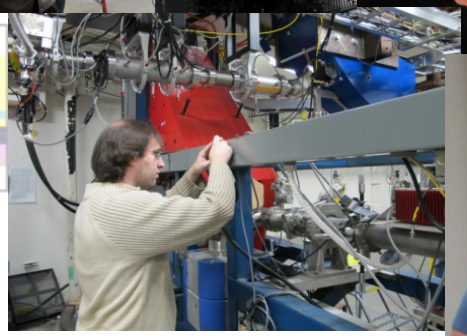
- **Hybrid-3Hen produced first physics results**
- **Beta-2n emission consistent with VANDLE results**



THANK YOU !

VANDLE PART
K. Rykaczewski,C. Gross,A.J. Mendes II, D. Stracener, C. Jost, Y. Liu,
M. Al-Shudifat, L. Cartegni, **M. Madurga**, A. Fijalkowska,
D. Miller, S. Padgett, **S. Paulauskas**, *UTK*
D. W. Bardayan, K. Miernik, M. Wolinska-Cichocka,*ORNL*
J..C. Batchelder, S. Liu, C. Matei, **W. Peters** and I. Spassova, *ORAU*
N. Brewer,J.K. Hwang, *Vanderbilt*
P.D. O'Malley, M. Howard, B. Manning, E. Merino, and J. Cizewski, *RutgersU.*
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*






Alpha decay:
K.P. Rykaczewski ,C. J. Gross, J. Johnson, J. McConnell (ORNL)
I.G. Darby,S.N. Liddick, C. Mazzocchi,D. T. Miller, L. Cartegni, M. Rajabali, S. Padgett, C.R. Bingham (UTK)
J.C. Batchelder, A. Korgul (ORAU)
E. Zganjar, *Louisiana State U.*
R.D. Page, D.T. Joss, (U. Liverpool)
M. Hjorth-Jensen, (U. Oslo)
W. Nazarewicz, T. Papenbrock (UTK)