Beta decay studies of the most exotic nuclei

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Outline of the lessons:

PARTI: General concepts

How to measure β decay in exotic nuclei

PARTII: β decay Gross properties $T_{1/2}$ and P_n

PARTIII: High resolution vs TAS

Istituto Nazionale di Fisica Nucleare

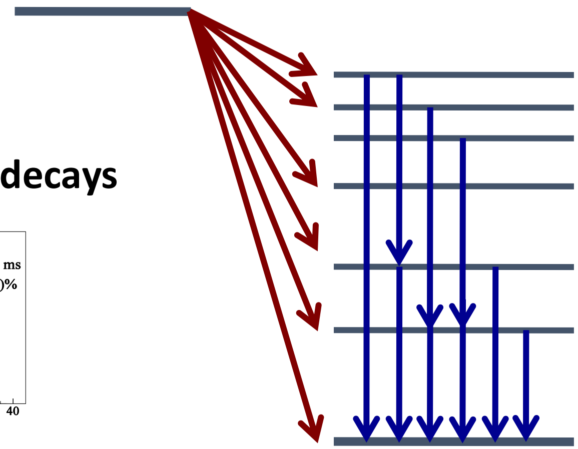
General Properties of β decay

Quantities that can be extracted in a β decay experiment

$T_{1/2}$
P_n
%β, %α …

β- decays

$_{Z}A_{N}$



$_{Z+1}A_{N-1}$

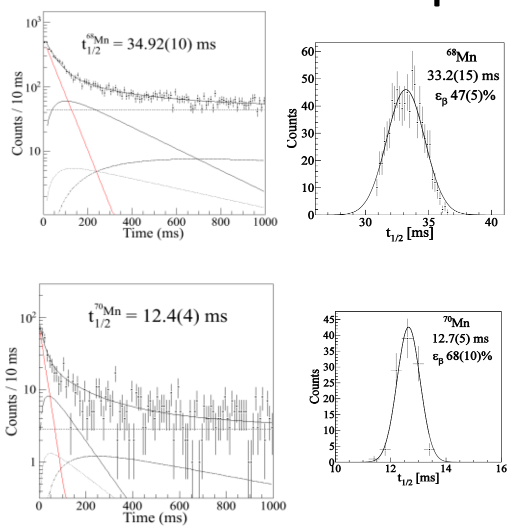
γ transitions

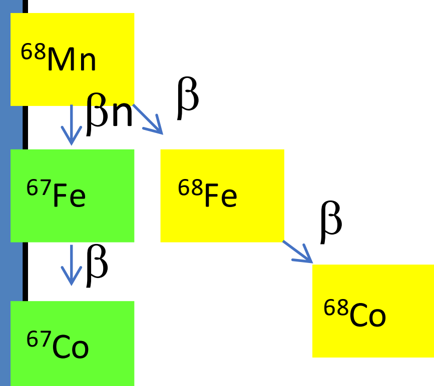
Possible existence of many decaying states

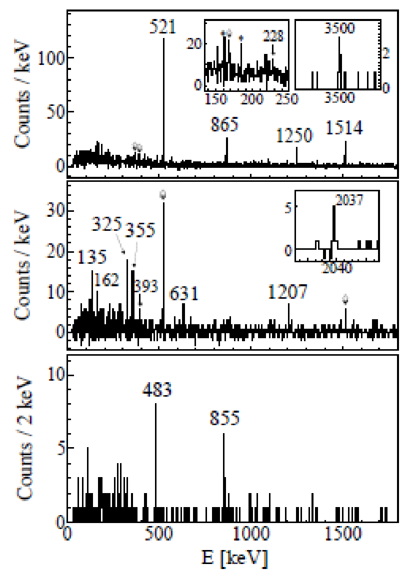
γ–γ coincidences ➔ level schemes

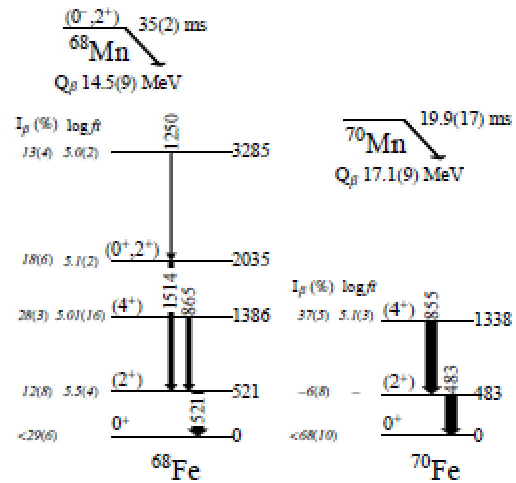
Relative intensities I_β

logft









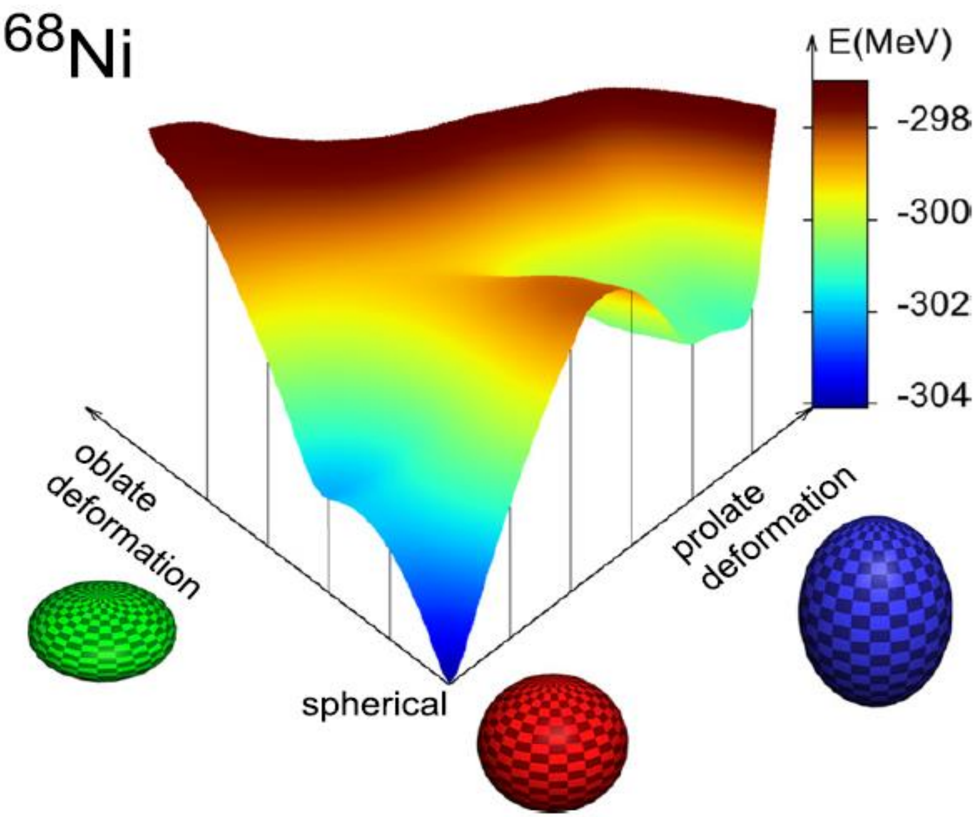
Selection rules allow to suggest/define I^π in both mother and daughter

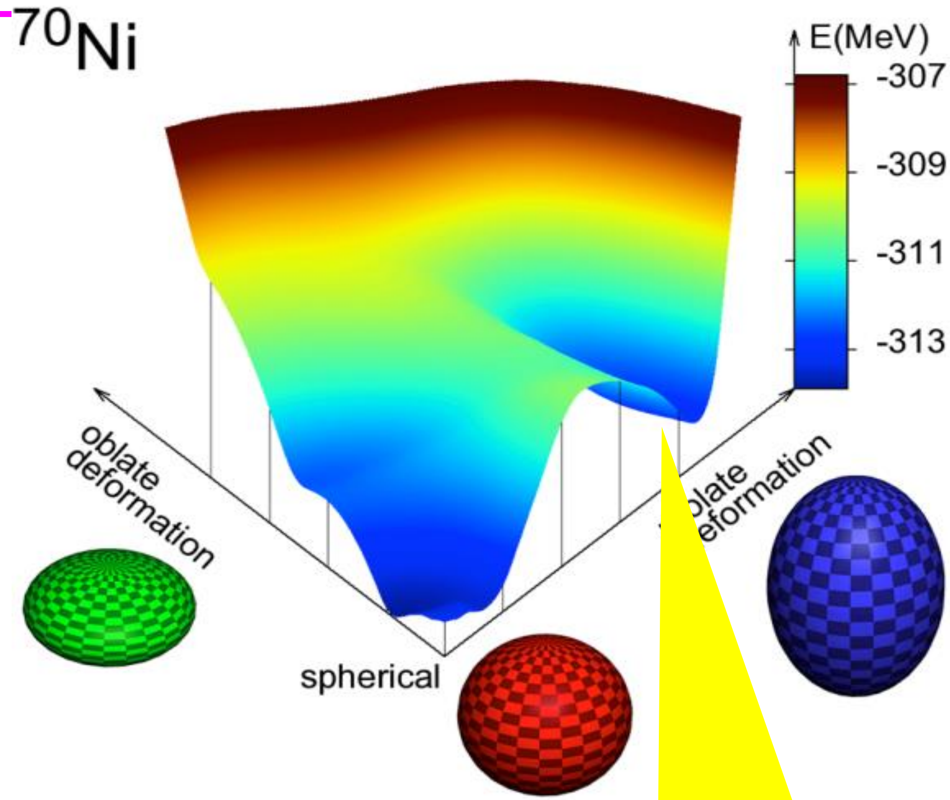
"pandemonium effect" – neutron rich nuclei – log *ft* is a just upper limit

Triple shape coexistence in $^{68-70}Ni$

Shape transition and shell evolution also take place within the same nucleus

Three 0^+ states below 3 MeV in ^{68}Ni, corresponding to local minima at spherical, oblate, and prolate shapes



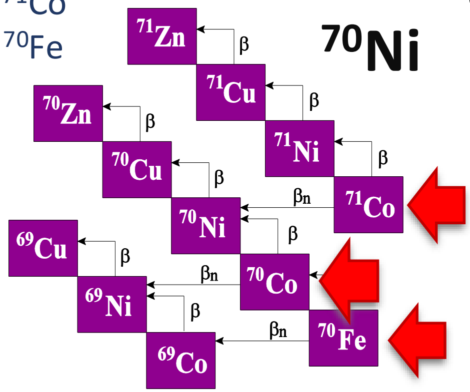


Shape coexistence

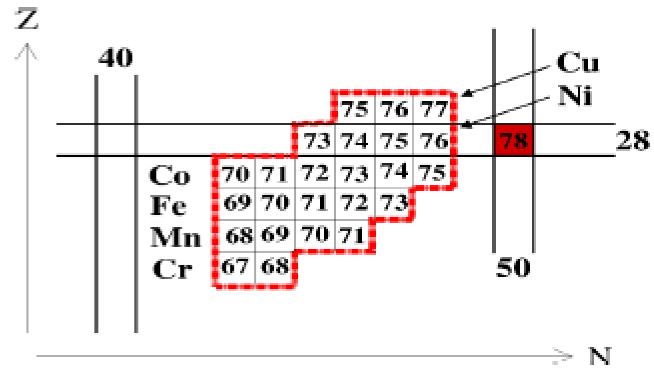
Deeper local minimum at prolate deformation

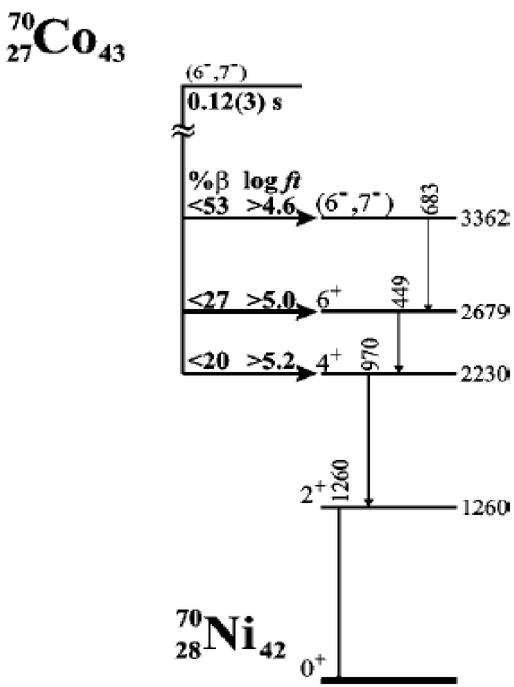
Development of shape coexistence in ^{70}Ni: experiment

- 1.4×10^{5} ^{70}Co
- 1.6×10^{6} ^{71}Co
- 1.8×10^{5} ^{70}Fe



- ^{70}Ni: shape coexistence
  - ^{70}Co -> ^{70}Ni decay
  - ^{71}Co -> ^{70}Ni
  - ^{70}Fe -> ^{70}Co -> ^{70}Ni





- Selection rules? Can we populate $2^+/0^+$ states?

Development of shape coexistence in ^{70}Ni: experiment

- ^{70}Ni: shape coexistence
  - ^{70}Co -> ^{70}Ni decay ➢ 1.4×10^5 ^{70}Co
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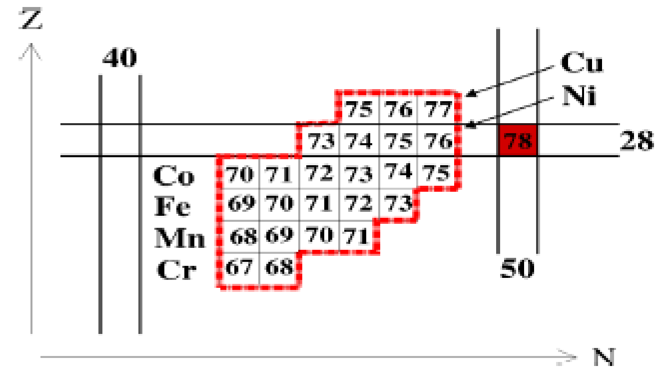
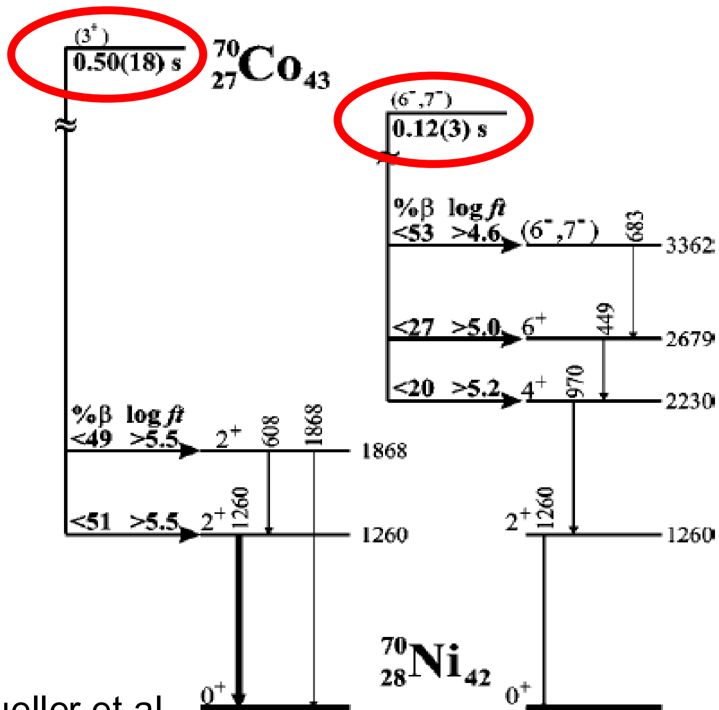
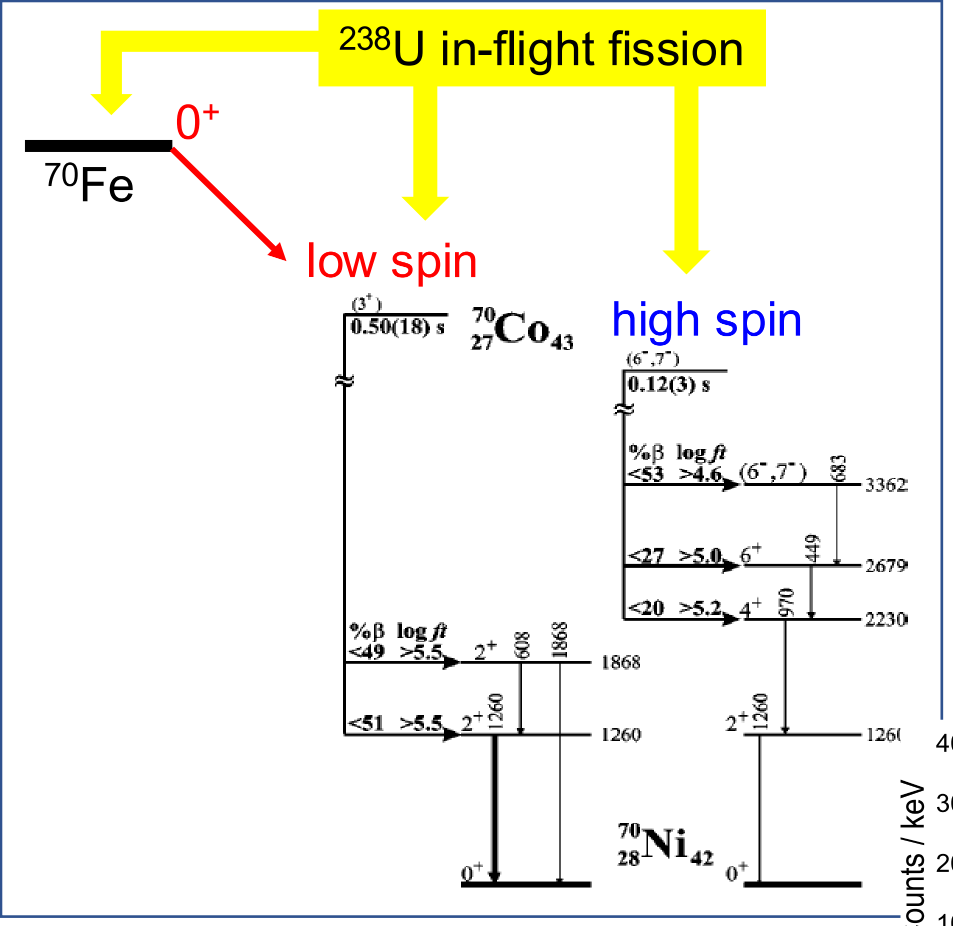




W.F. Mueller et al., PRC 61, 054308 (2000)

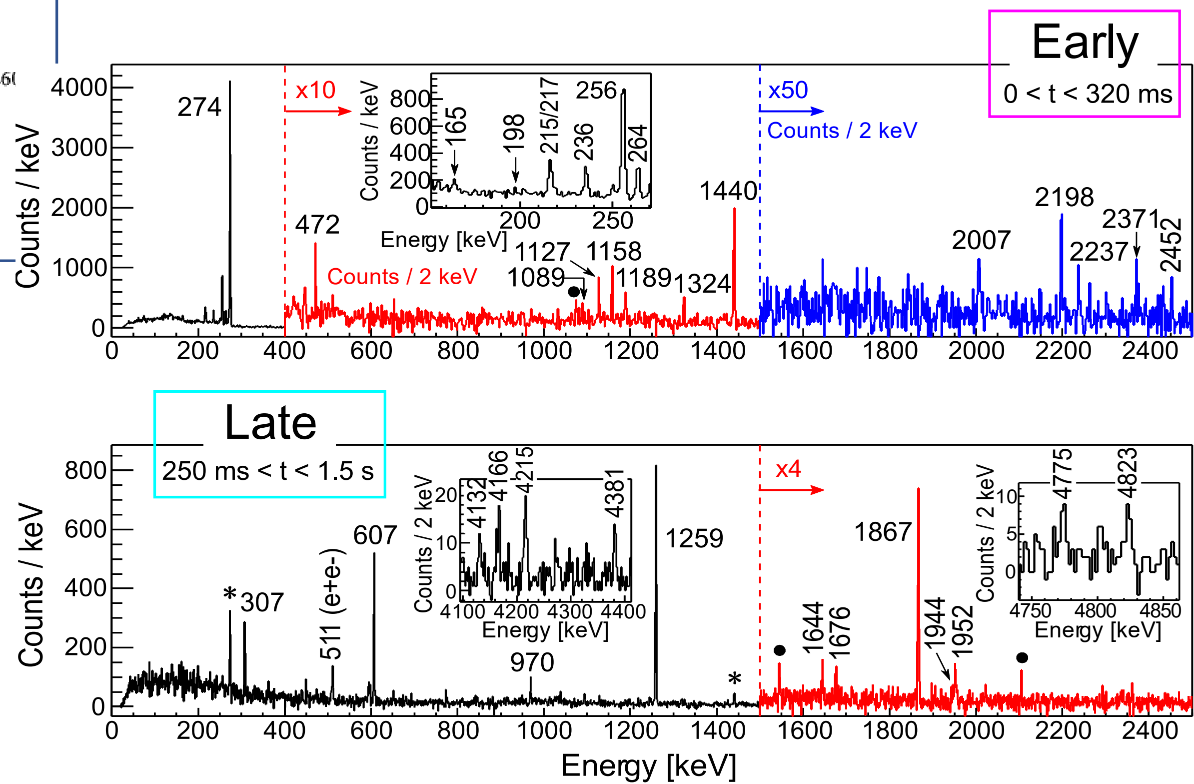
- Selection rules? Can we populate $2^+/0^+$ states?
- ∃ of Isomeric state Jp = 3+ allows population
- Isomeric ratio: probability of populating this state in fragmentation/fission reaction is limited (dependence on spin) (45% in this case)
- T1/2 are similar ➔ difficult to disentangle the two decays
- Help by g-g coincidences BUT high statistics mandatory

➔ use a different decay chain ^{70}Fe -> ^{70}Co -> ^{70}N



β decay in the A = 70 isobaric chain

- Two long-lived β-decaying states at high and low spins in ^{70}Co
- Low-spin β-decaying state in ^{70}Co isolated via the β decay of ^{70}Fe
- Selectively populate low-spin states in ^{70}Ni



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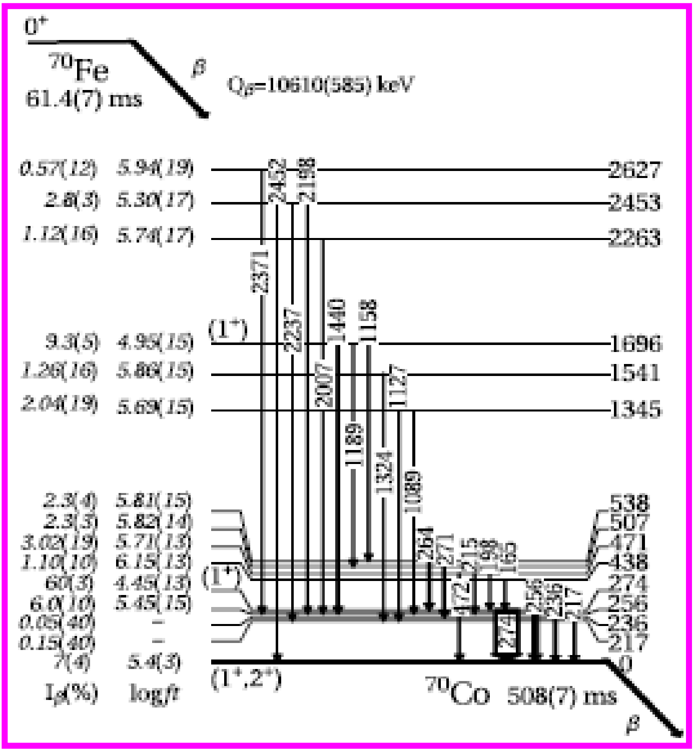

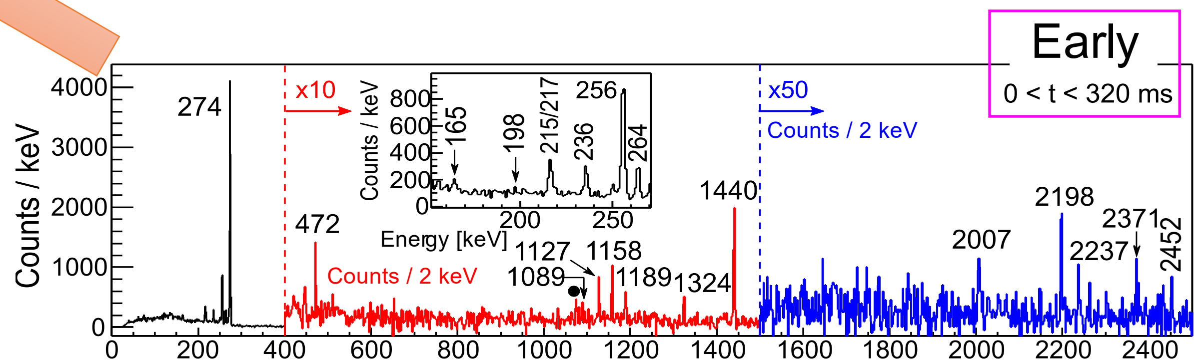

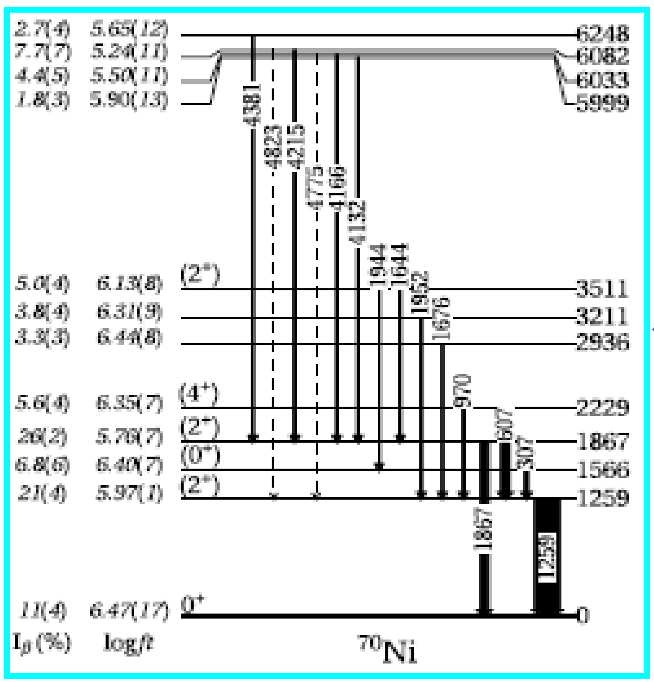

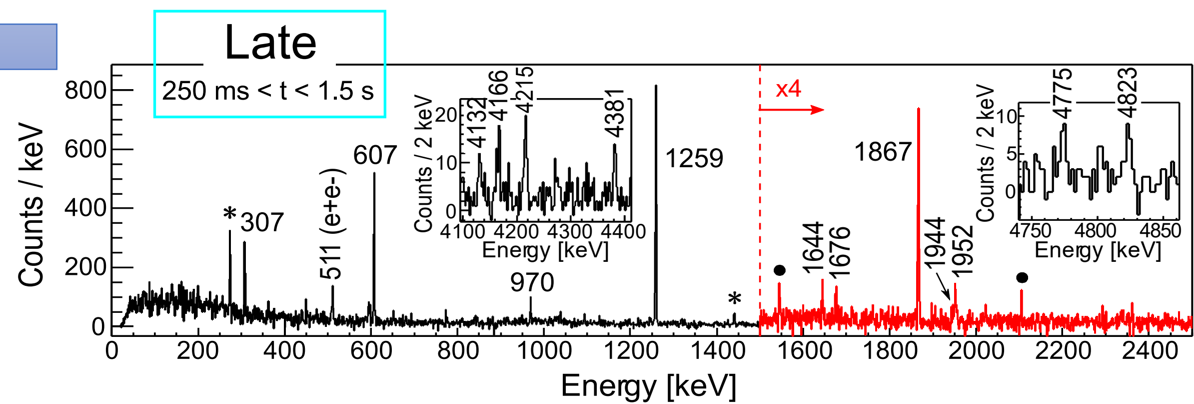

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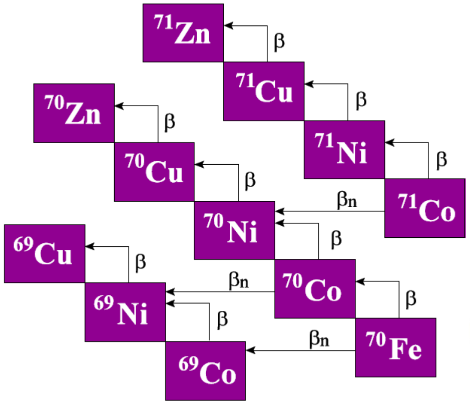

- ^{70}Ni: shape coexistence
  - ^{70}Co -> ^{70}Ni decay
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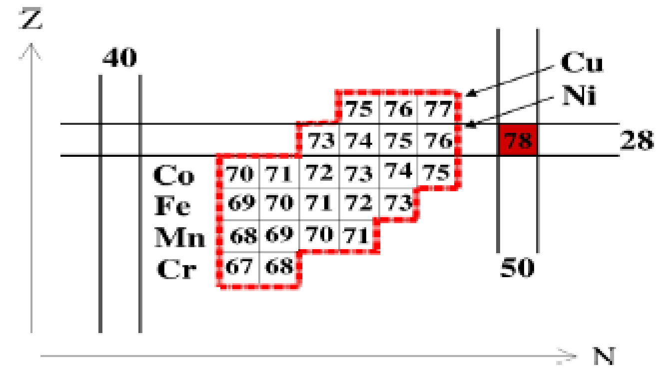
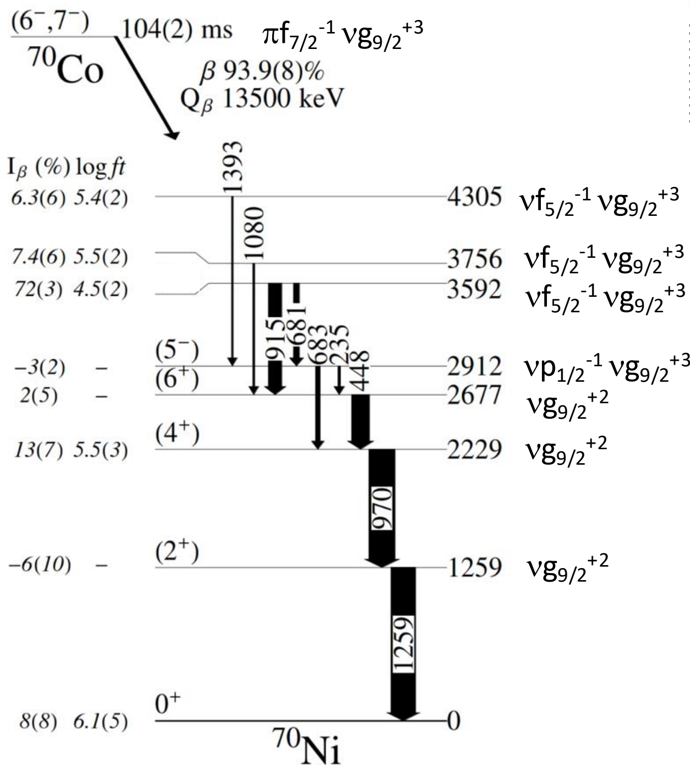
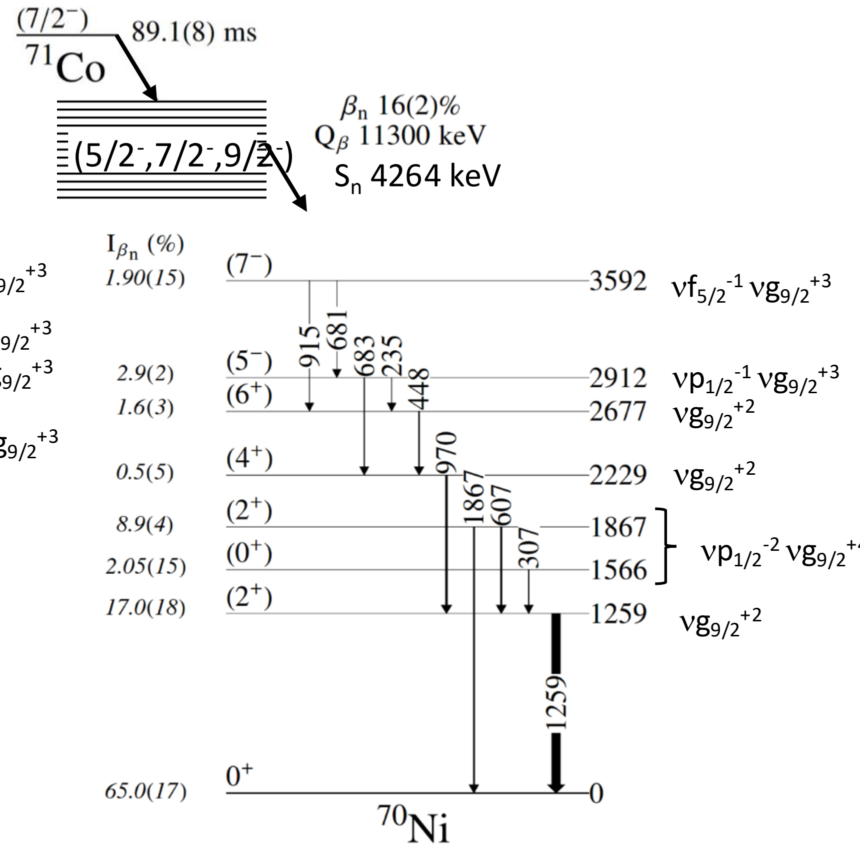




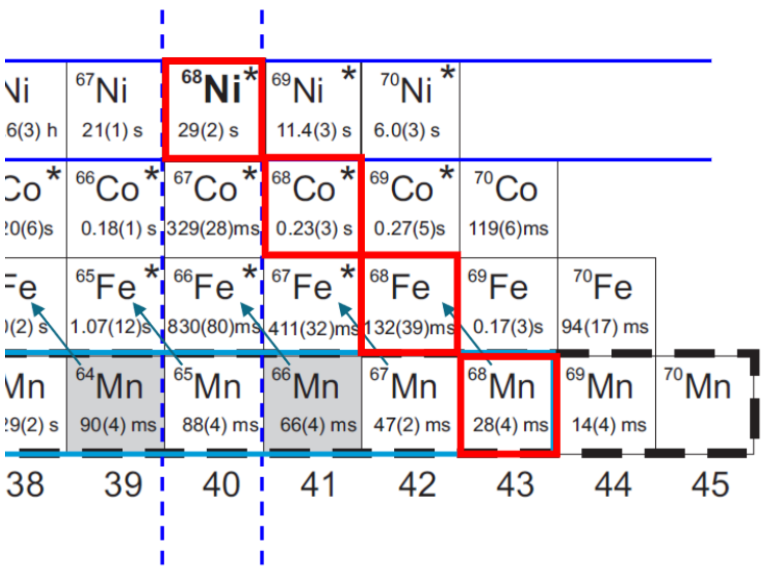


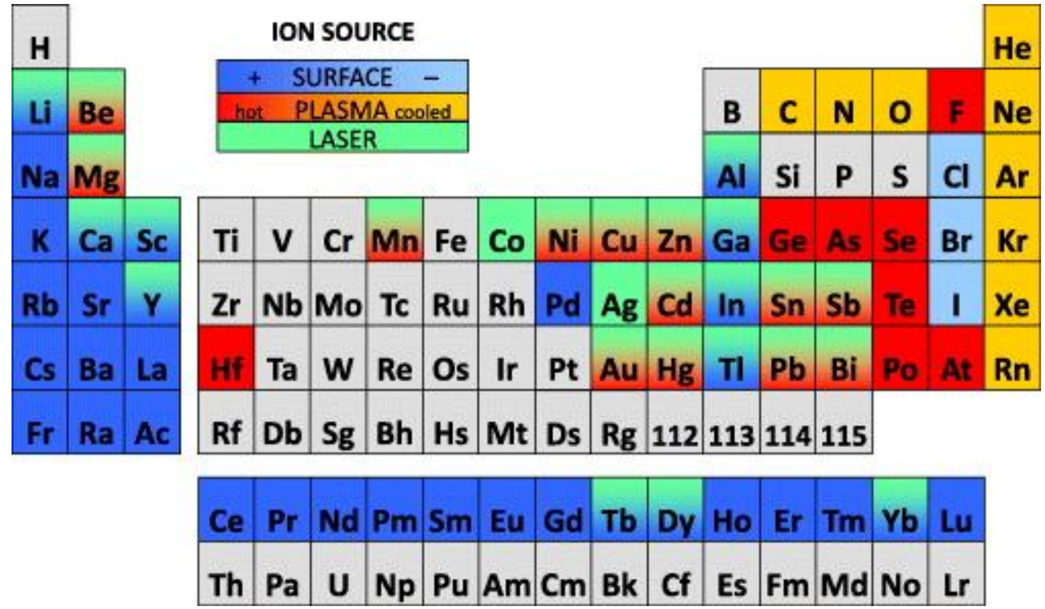
Morales et al. PRC93 (2016)
Morales et al. PLB765 (2017)

Use different decay paths to effectively populate wanted nuclei

➔ Access to refractory elements at ISOL facility via decay chains

- **A=68**
  - Previous exp. : 2 isomers in ^{68}Co
    - (7^-) $T_{1/2}$= 0,23(3) s
    - **$(1^+,3^+)$ $T_{1/2}$ = 1,6(3) s**
  - ISOLDE: **Selectivity of $^{68}Fe_{gs}$ (0^+) decay**






PHYSICAL REVIEW C 91, 034310 (2015)

Characterization of the low-lying 0^+ and 2^+ states in ^{68}Ni via β decay of the low-spin ^{68}Co isomer

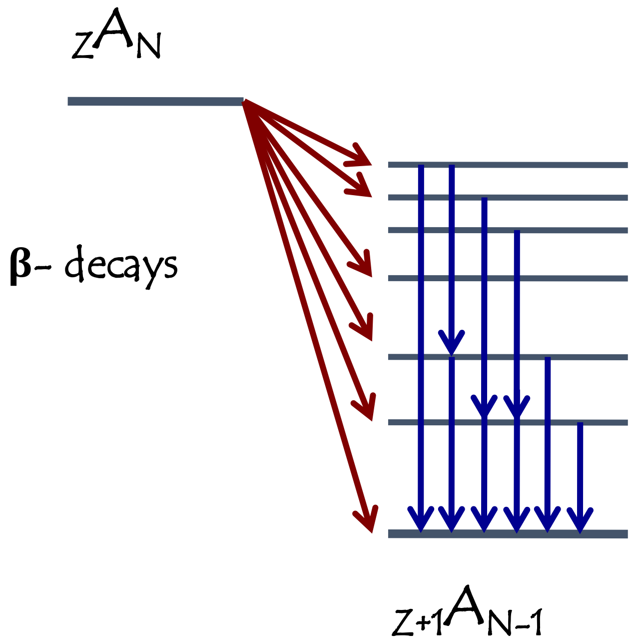
F. Flavigny, D. Pauwels, D. Radulov, I. J. Darby, H. De Witte, J. Diriken, D. V. Fedorov, V. N. Fedosseev, L. M. Fraile, M. Huyse, V. S. Ivanov, U. Köster, B. A. Marsh, T. Otsuka, L. Popescu, R. Raabe, M. D. Seliverstov, N. Shimizu, A. M. Sjödin, Y. Tsunoda, P. Van den Bergh, P. Van Duppen, J. Van de Walle, M. Venhart, W. B. Walters, and K. Wimmer

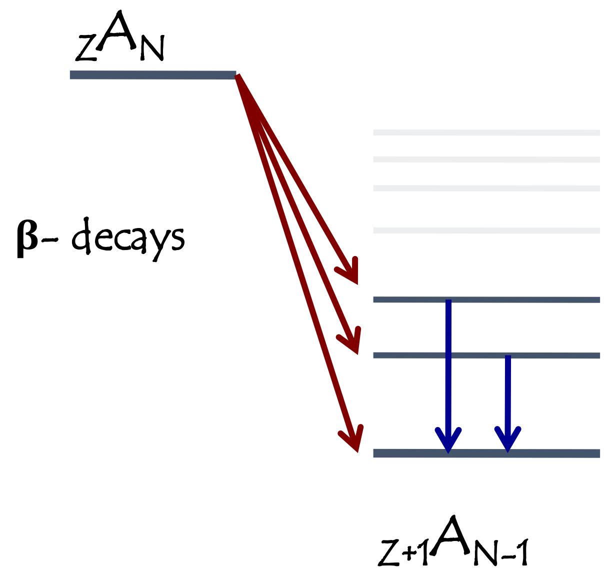
[1] KU Leuven, Instituut voor Kern- en Stralingsfysica, Celestijnenlaan 200D, 3001 Leuven, Belgium

[2] Belgian Nuclear Research Centre SCK•CEN, Boeretang 200, B-2400 Mol, Belgium

➔ Help of high Pn to reach wanted species with low contaminants

General Properties of β decay





- HPGe detectors are conventionally used to construct the level scheme populated in the decay

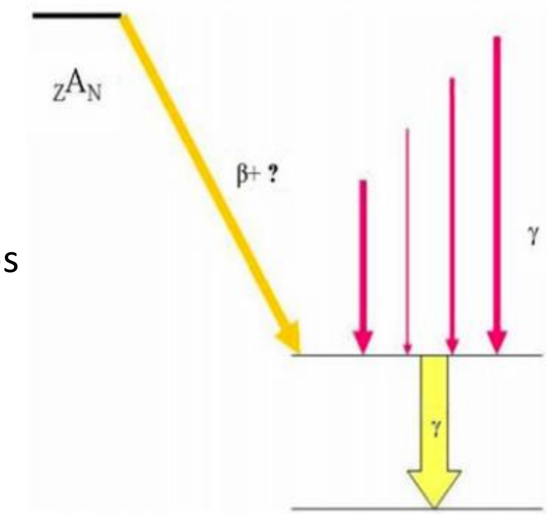
➔ Higher Qvalue higher possibility of missing feeding

- From the γ intensity balance we deduce the β-feeding

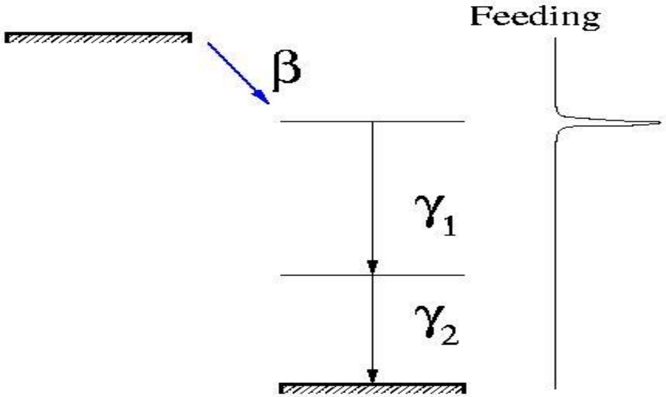
Pandemonium effect implies

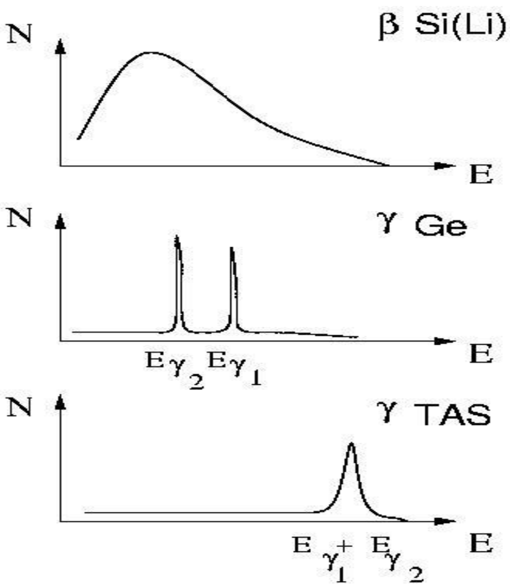
➔ Wrong definition of gamma feeding and branching ratios

I_b and logft



TAGS measurements





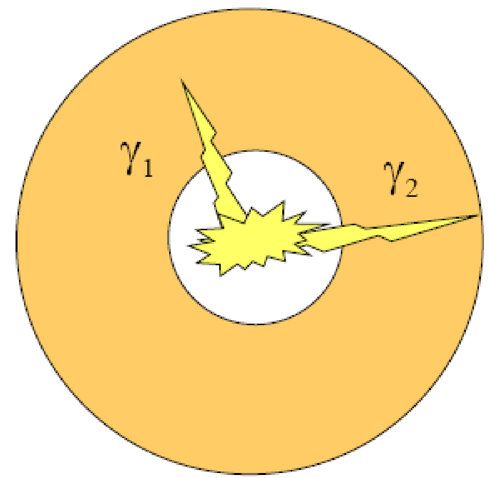
Since the gamma detection is the only reasonable way to solve the problem, we need a highly efficient device:

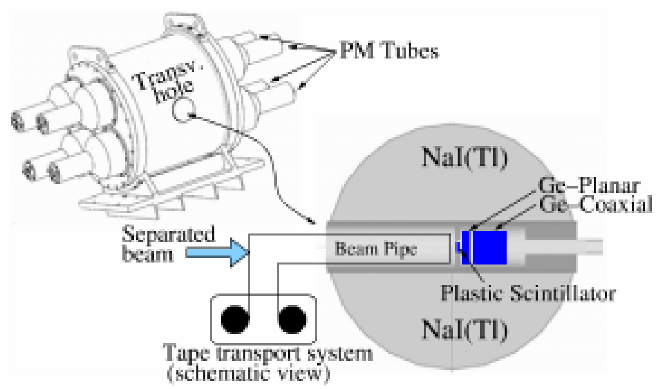
A TOTAL ABSORTION SPECTROMETER

But there is a change in philosophy. Instead of detecting the individual gamma rays we sum the energy deposited by the gamma cascades in the detector.

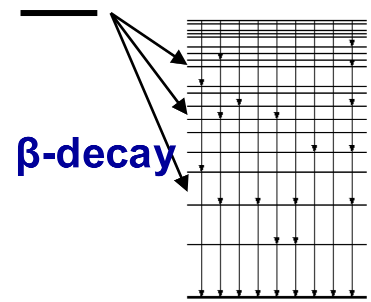
A TAS is like a calorimeter!

Big crystal, 4π (BaF_2/NaI/HPGe)





TAGS analysis



$$d_i = \sum_{j=1}^{j_{max}} R_{ij} I(E_j)$$

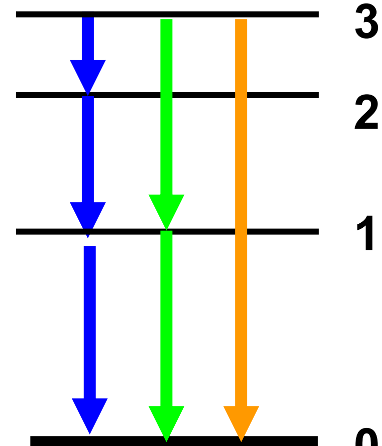
d_j = exp. data in channel I
$I(E_j)$ = beta feeding of j state

R is the response function of the spectrometer, $\boldsymbol{R_{ij}}$ means the probability that feeding at a level ***j*** gives counts in data channel ***i*** *of the spectrum*

The response matrix $\mathbf{R}$ can be constructed by recursive convolution:

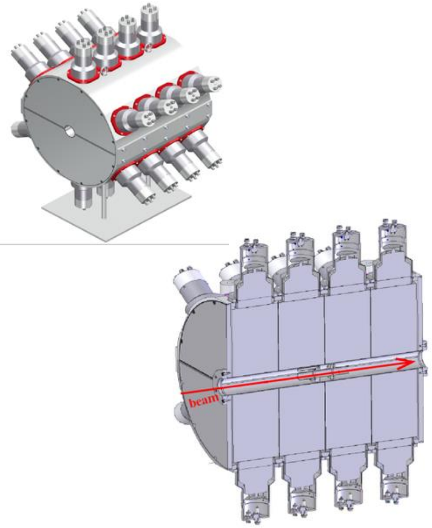
$$\mathbf{R_j} = \sum_{k=0}^{j-1} b_{jk} \mathbf{g_{jk}} \otimes \mathbf{R_k}$$

$\mathbf{g_{jk}}$: γ-response for *j* (*k* transition
$\mathbf{R_k}$: response for level *k*
b_{jk}: branching ratio for *j* (*k* transition



Mathematical formalization by Tain, Cano, et al.

TAS measurement $^{70}Co \rightarrow {}^{70}Ni$



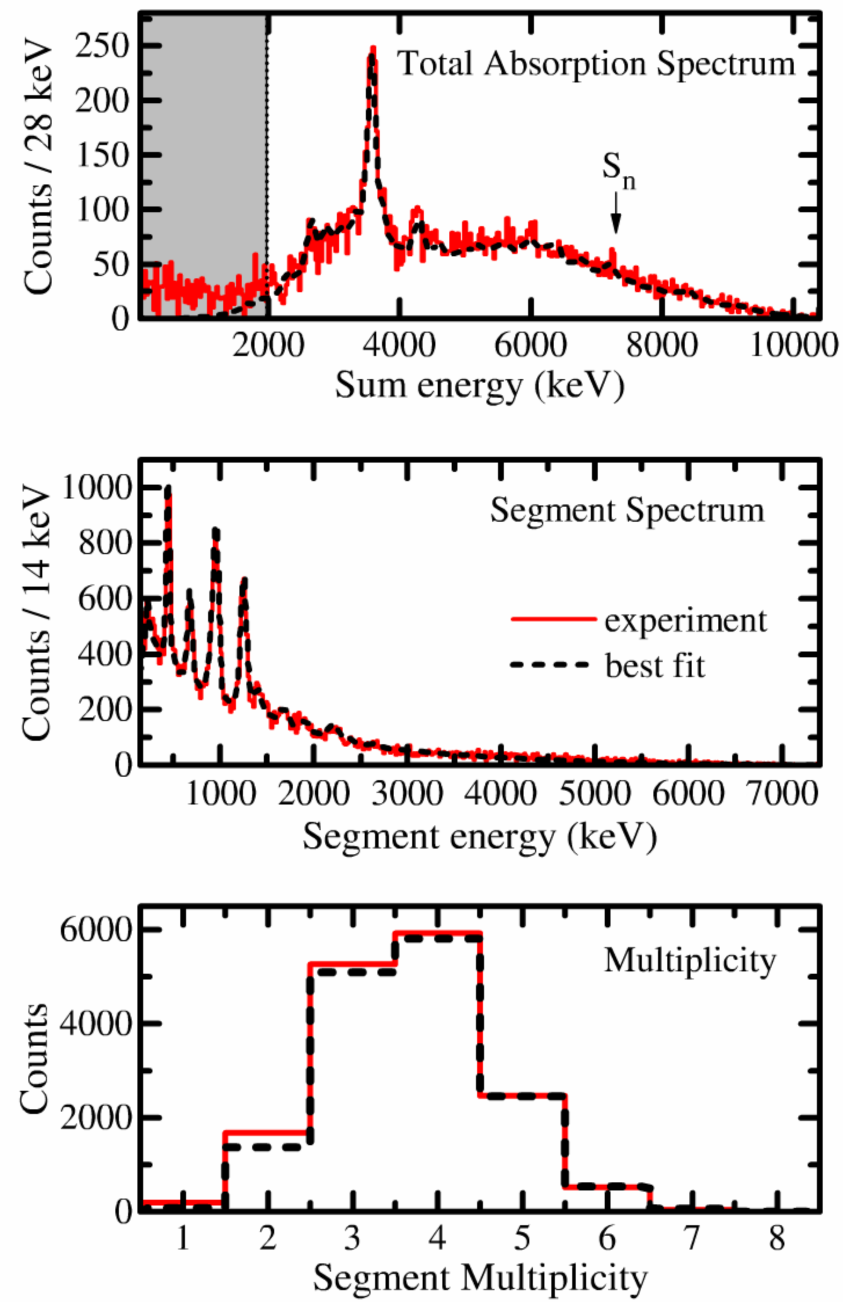
NSCL ^{86}Kr @140MeV/u on ^{9}Be
Summing NaI (SuN)
$^{70}Co \rightarrow {}^{70}Ni$
Only visible decay from g.s. ($6^-/7^-$)

To extract S_β one uses 3 information:

- Energy sum of each segment
- Energy spectrum of individual segments → individual γs
- Multiplicity

Compared to GEANT4 simulation of response:

- Known level scheme up to 4 MeV
- Statistical decay above (up to Q_β = 13.5 MeV)

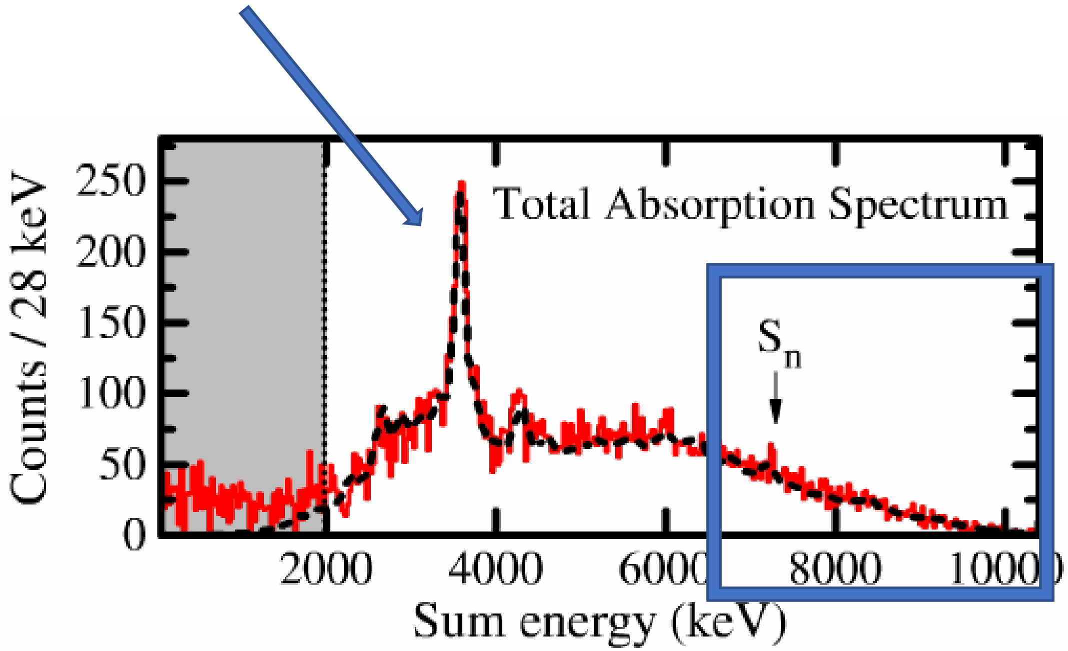


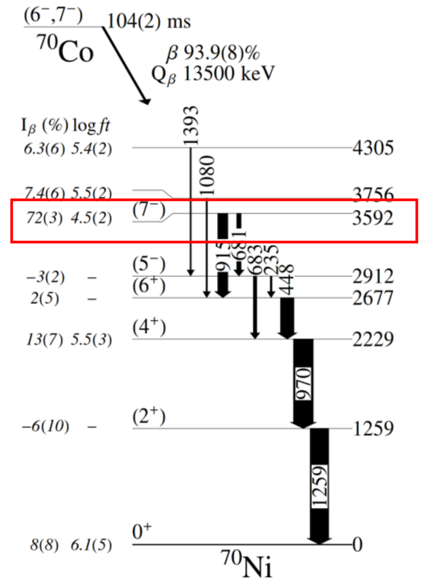
PRL 117, 142701 (2016) PHYSICAL REVIEW LETTERS week ending 30 SEPTEMBER 2016

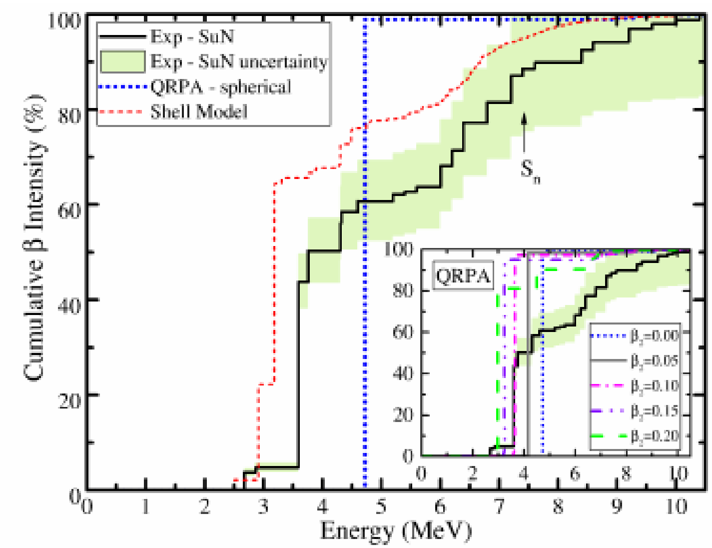
Strong Neutron-γ Competition above the Neutron Threshold in the Decay of ^{70}Co

A. Spyrou,[1,2,3,*] S. N. Liddick,[1,4,3] F. Naqvi,[1,3] B. P. Crider,[1] A. C. Dombos,[1,2,3] D. L. Bleuel,[5] B. A. Brown,[1,2,3] A. Couture,[6] L. Crespo Campo,[7] M. Guttormsen,[7] A. C. Larsen,[7] R. Lewis,[1,4] P. Möller,[6] S. Mosby,[6] M. R. Mumpower,[6] G. Perdikakis,[8,1,3] C. J. Prokop,[1,4] T. Renstrøm,[7] S. Siem,[7] S. J. Quinn,[1,2,3] and S. Valenta[9]

Strong population of 3.592 MeV state







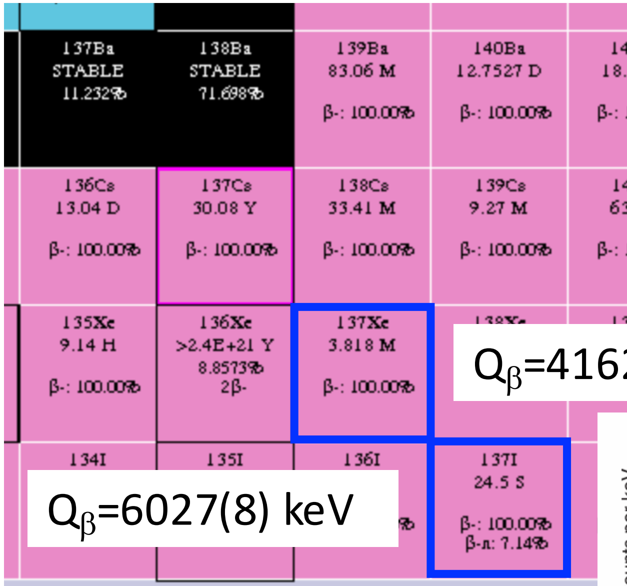
continuous distribution and strong γ-ray emission above the neutron-separation energy at 7.3 MeV

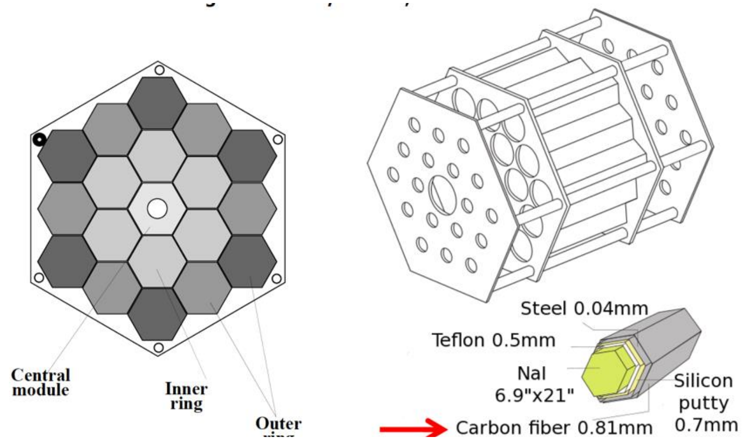
WARNING: no β-delayed n emission seen

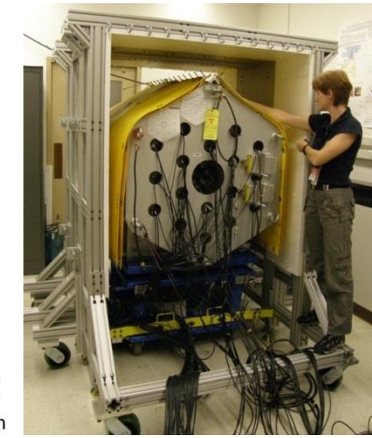
➔ 10% error owing to this missing information

$S_n < Q_\beta$ is not sufficient to guarantee sizable contribution of β-n channel

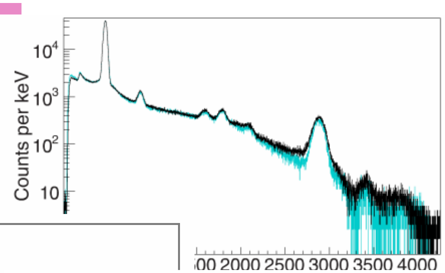
TAS measurement for decay heat evaluation

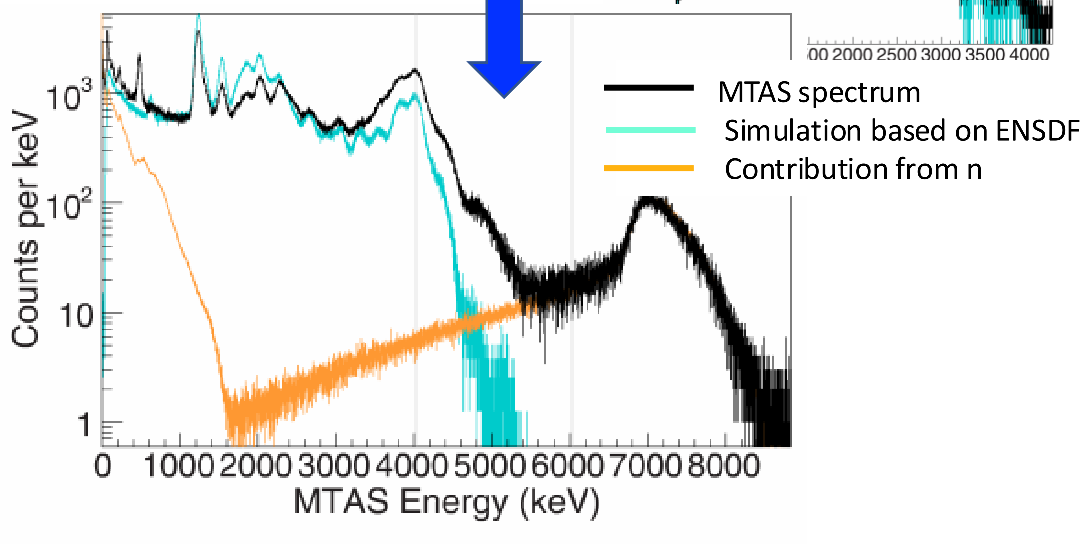






2200 pounds of NaI(Tl) - Modular Total Absorption Spectrometer (MTAS) and its 12,000 pound shielding





Compared to the ENSDF β-feeding data there are many more γ rays measured by MTAS in the continuously binned region above Sn energy than previously reported

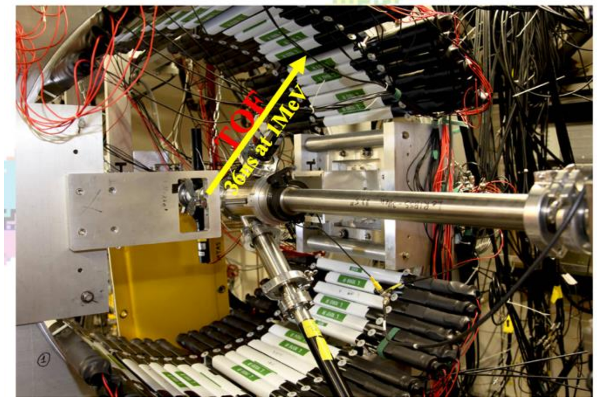
The average γ energy for ^{137}I decay measured with MTAS increases by 19% compared to the ENSDF data

G.s. feeding increases from 45.2±0.7% to 49±1%.

Rasco et al. PRC95 (2017) 054328

Measuring GT with neutrons

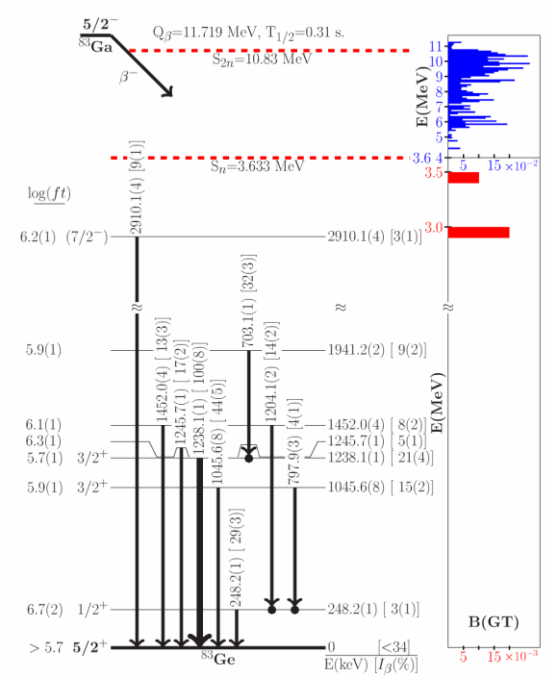
Madurga et al. PRL 117 (2016) 092502
Alshudifat et al. PRC93 (2016) 044325

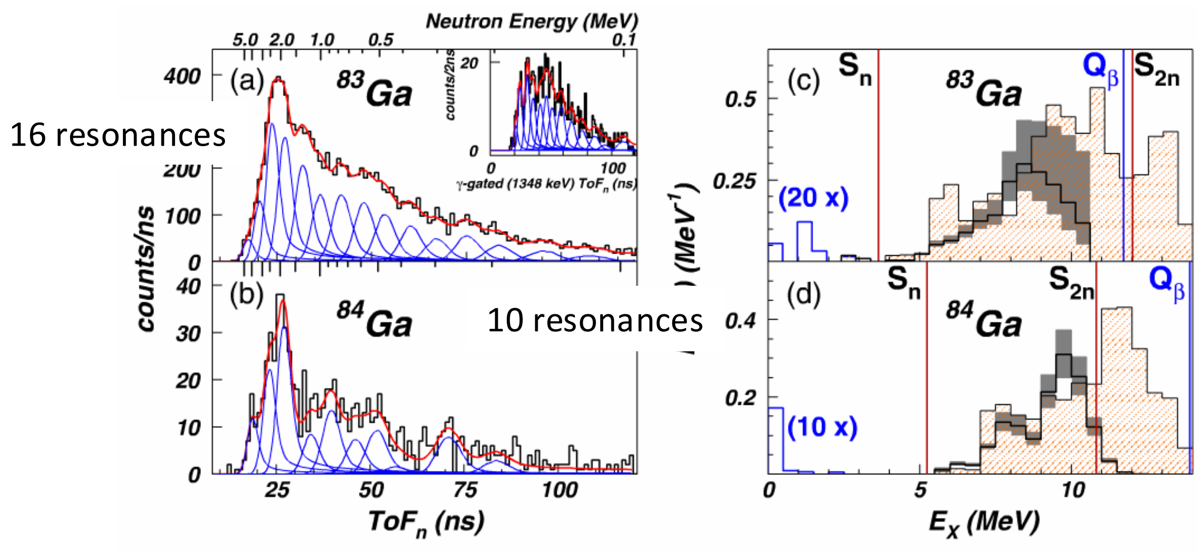


VANDLE array at HRIBF (USA): measuring n via TOF

- ➔ 48 bars 3x3 x 60 cm3
- ➔ Ω = 10% (23%) of 4π
- ➔ ~3% (6%) total efficiency @ 1MeV
- ➔ 50 cm TOF radius
- ➔ 40-60% efficiency beta "START" detector

+ 2 HPGe detectors (3% eff at 1.3 MeV)

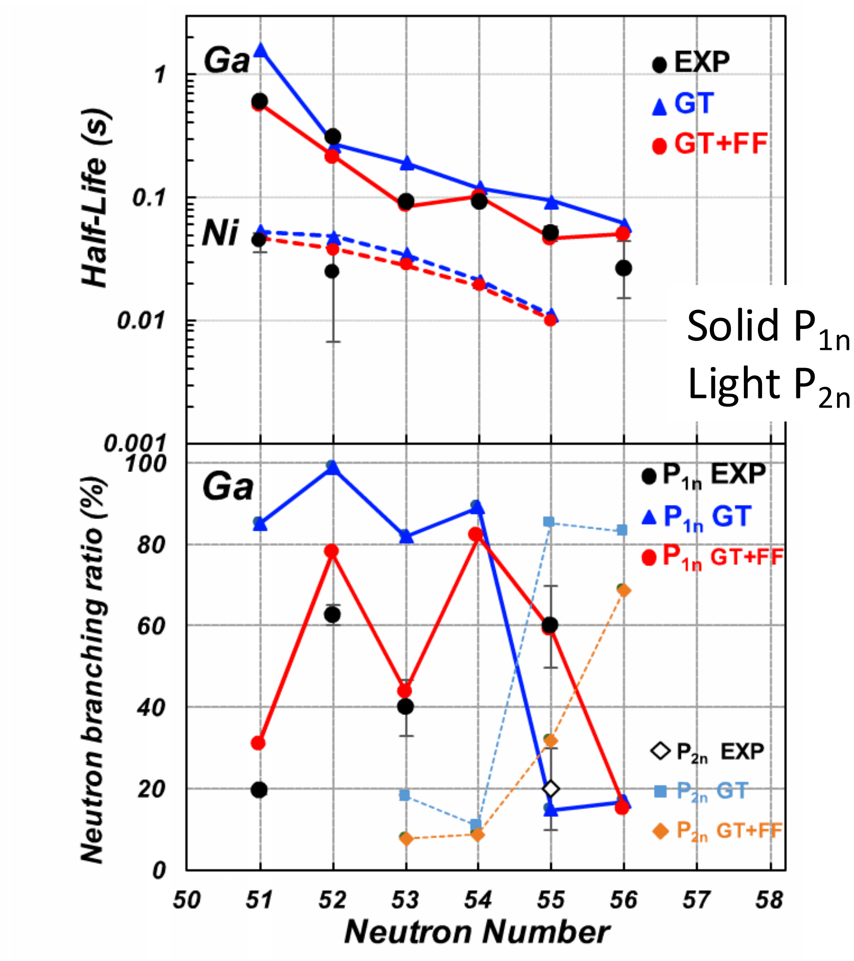


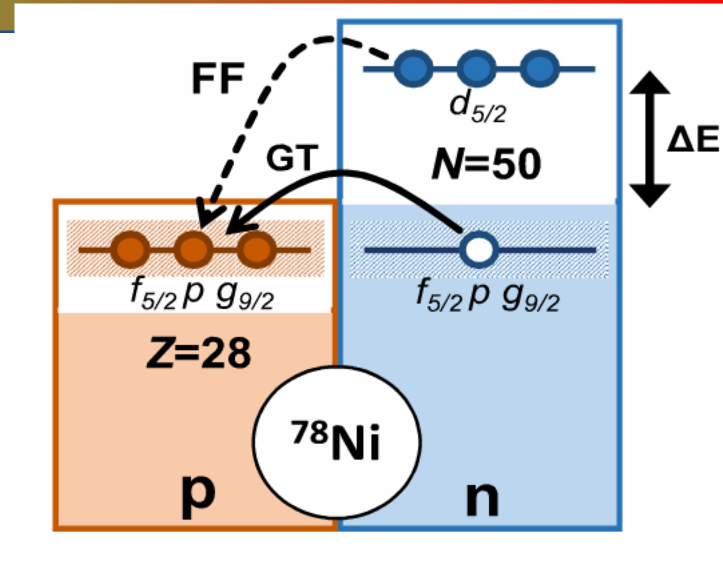


the decay above the neutron separation energy is dominated by allowed Gamow-Teller transitions.

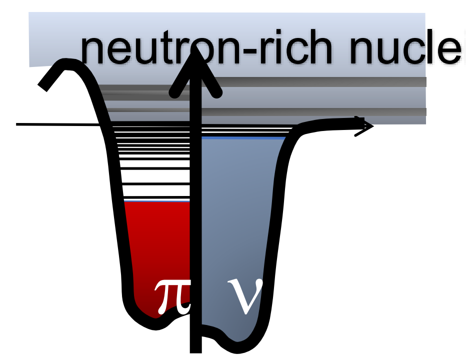
Measuring GT with neutrons

Madurga et al. PRL 117 (2016) 092502
Alshudifat et al. PRC93 (2016) 044325

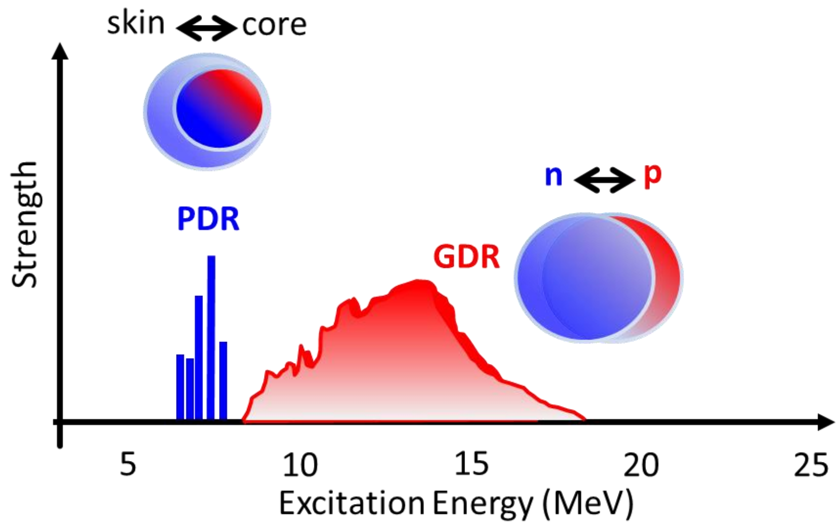




The GT decay transforms ns in the 78Ni core orbitals (f5/2, p3/2, p1/2, and g9/2) into p occupying their spin-orbit partners outside the Z=28 core. These transitions are coupled with very strong matrix elements. The alternative decay mode, through the first forbidden (FF) d5/2 → f5/2 transformation, populates neutron bound states in 84Ge.

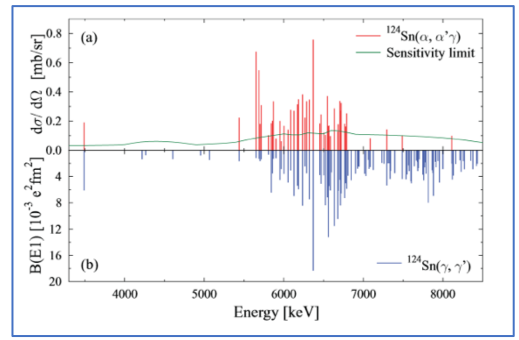


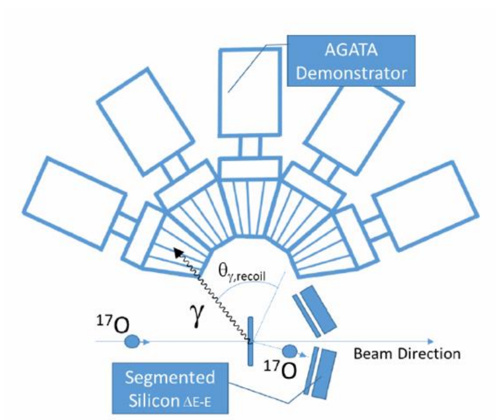
Nuclear Structure information from the E1 response in Nuclei

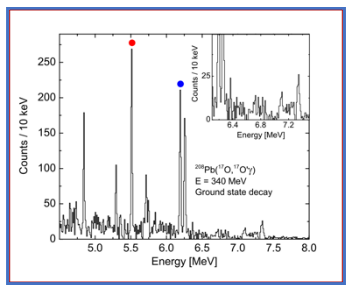


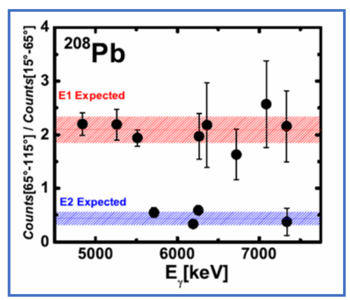
Commonly studied via:
(γ,γ□), (α,α'), Inelastic scattering of ^{17}O, virtual phonon scattering

(*) figure from J. Endres et al., Phys. Rev. Lett. 105, 212503 (2010)





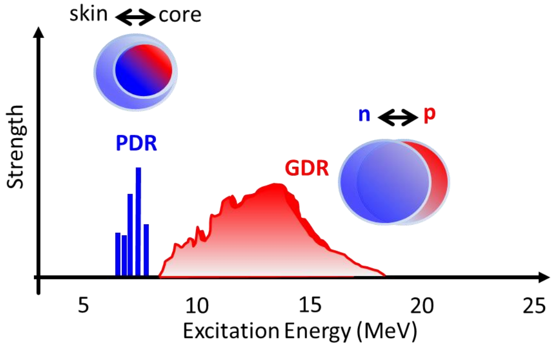




- ❑ low energy part → isoscalar character (*neutron-skin oscillations*)
- ❑ high-energy states → isovector nature (*transition towards the GDR*)

A. Bracco, F.C.L. Crespi and E.G. Lanza, EPJA (2015) 51: 99
F.C.L. Crespi, et al., PRL113 (2014) 012501

Resonances populated via β decay in n-rich nuclei



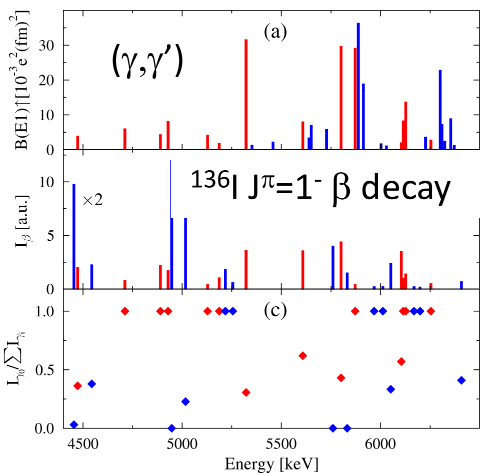
- The large Q_β-value window (> 12 MeV) allows populating at least the PDR

Proof of principle in a recently published paper

PRL **116,** 132501 (2016) PHYSICAL REVIEW LETTERS week ending 1 APRIL 2016

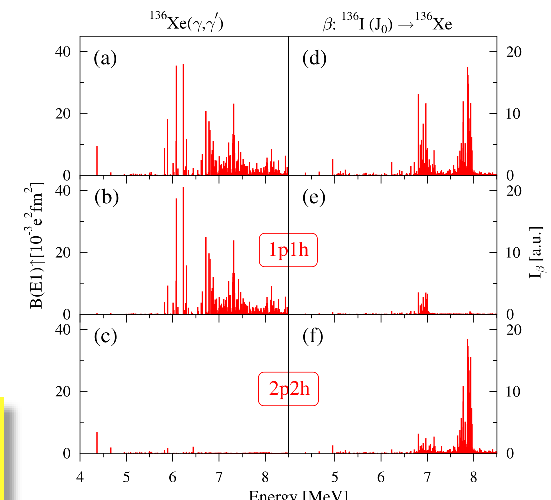
Investigating the Pygmy Dipole Resonance Using *β* Decay

M. Scheck,[1,2,*] S. Mishev,[3,4] V. Yu. Ponomarev,[5] R. Chapman,[1,2] L. P. Gaffney,[1,2] E. T. Gregor,[1,2] N. Pietralla,[5]
P. Spagnoletti,[1,2] D. Savran,[6] and G. S. Simpson[1,2]



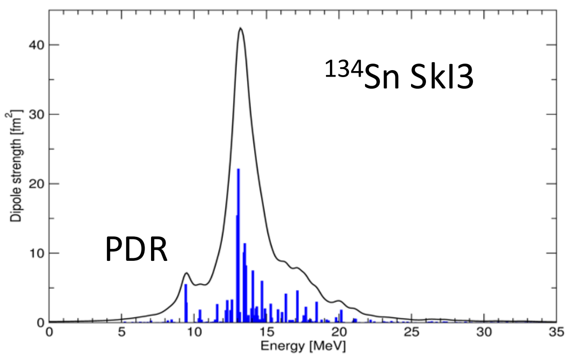
States seen in NRF are seen in β decay
β decays shows greater number of states ➔ access to 2p2h excitations

Useful tool to complement the studies BUT relies heavily on theory for the interpretation of nature of states



QPM

Resonances populated via β decay:

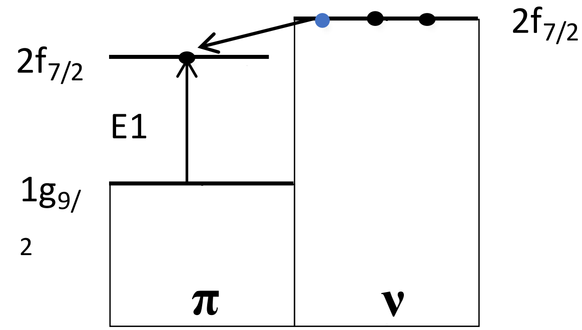


Example: ^{134}In -> ^{134}Sn (Q_β= 14.7 MeV)

$\nu f_{7/2}$ -> $\pi g_{9/2}$

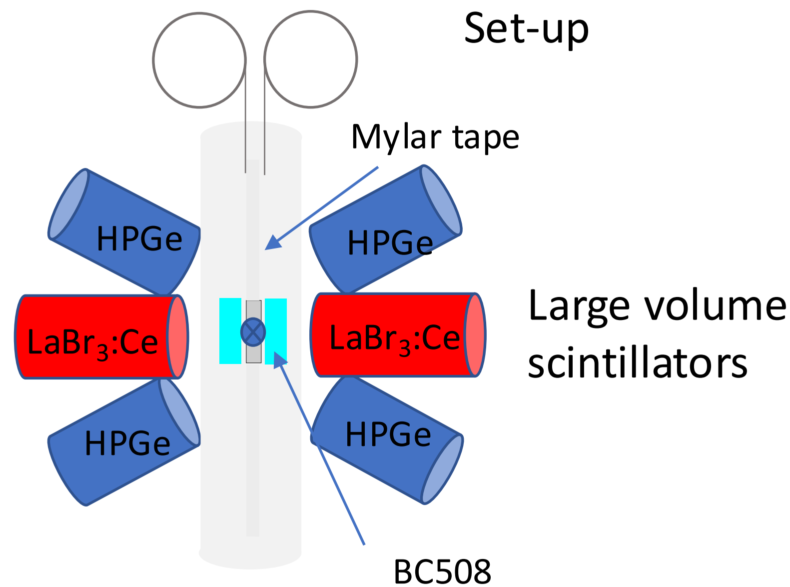
β decay: $\nu 2f_{7/2}$ -> $\pi 2f_{7/2}$, $\pi 2f_{5/2}$;

QRPA calculations with the SkI3 interaction: PDR at 10 MeV

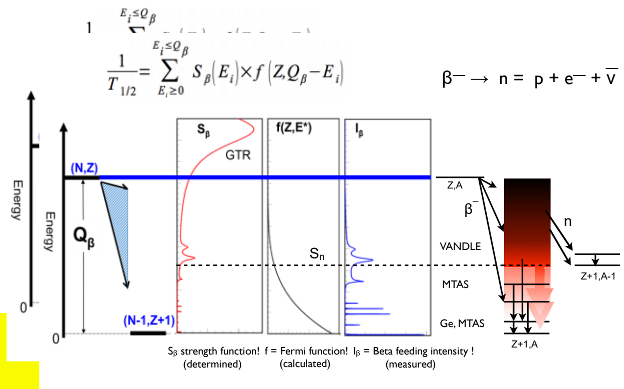


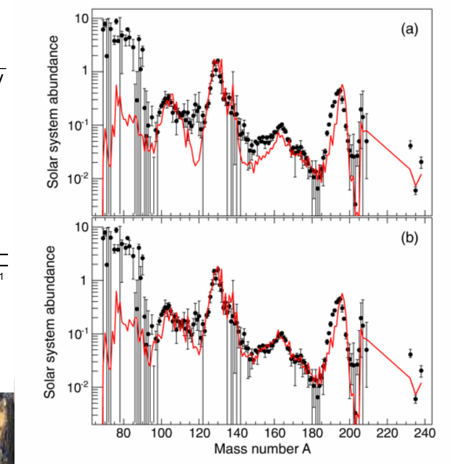
Mother	J^π	Daughter	S_n[keV]	Q_β [keV]	I [pps] @5μA	I [pps] @200μA
^{84}Ga	(0^-)	^{84}Ge	5243	12900	1.01×10^3	4.02×10^4
^{86}Br	(1^-)	^{86}Kr	9857	7626	1.93×10^7	7.73×10^8
^{96}Y	0^-	^{96}Zr	7856	7096	1.12×10^7	4.47×10^8
^{98}Y	(0^-)	^{98}Zr	6415	8824	5.30×10^5	2.12×10^7
^{130}In	$1^{(-)}$	^{136}Sn	7596	10249	1.93×10^4	7.72×10^5
^{136}I	(1^-)	^{136}Xe	8084	6930	2.6×10^8	1.04×10^10
^{140}Cs	1^-	^{140}Ba	6428	6220	8.53×10^8	3.4×10^{10}
^{142}Cs	0^-	^{142}Ba	6181	7325	3.35×10^7	1.34×10^9
^{144}Cs	$1^{(-)}$	^{144}Ba	5901	8500	4.35×10^6	1.74×10^8
^{146}Cs	1^-	^{146}Ba	5495	9370	1.12×10^5	4.46×10^6

Easy to produce
(Surface Ionization)



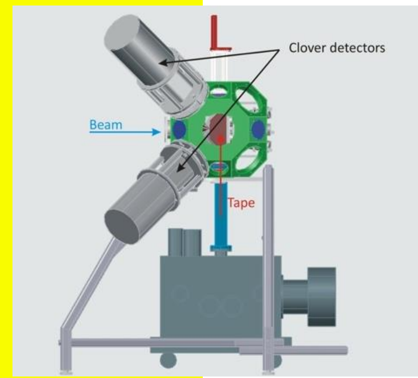
Conclusions

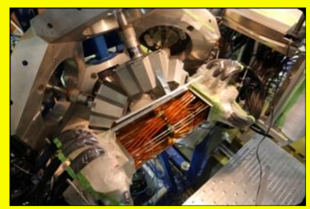




- ➢ Broad field of application:
  - Inputs for stellar nucleosynthesis
  - Nuclear structure studies
  - Inputs for Nuclear Energy

- ➢ Simple equipment
- ➢ Versatile flexible and modular:
  - ➢ Minimal setup to extract $T_{1/2}$, P_n, β–γ coincidences
  - ➢ γ detectors to construct level schemes
  - ➢ Fast-timing setup: lifetimes ~ns range
  - ➢ E0 measurements and long-living activity
  - ➢ Complete spectroscopy using TAS





- ➢ Strong complementarity with in-beam spectroscopy
- ➢ Access to structure information already with few pps beams
- ➢ No need for post-acceleration
- ➢ Need for purified beams, even though known contribution from strong contaminants can be removed by off-line analysis

➔ **HRMS & RILIS & TRAPS**

Thank you for attention