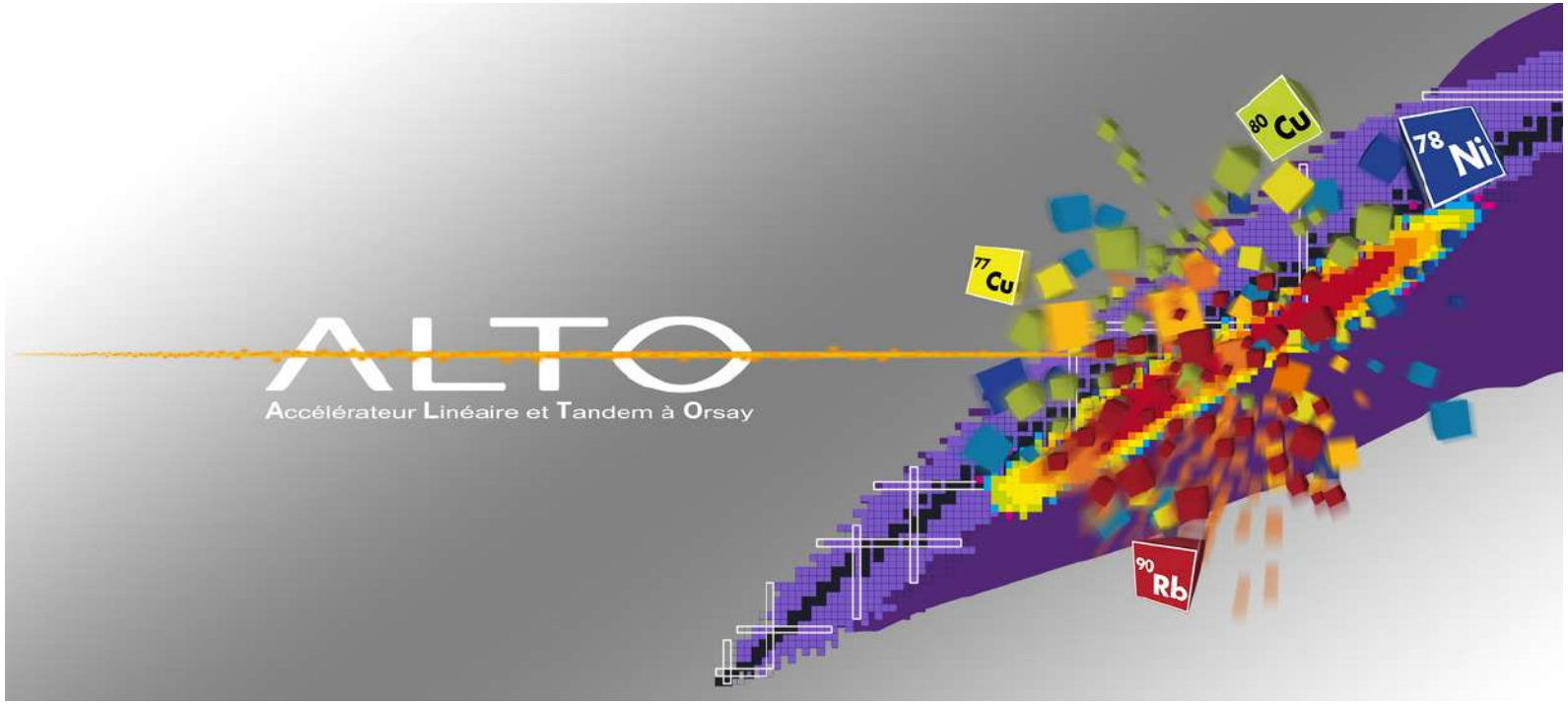
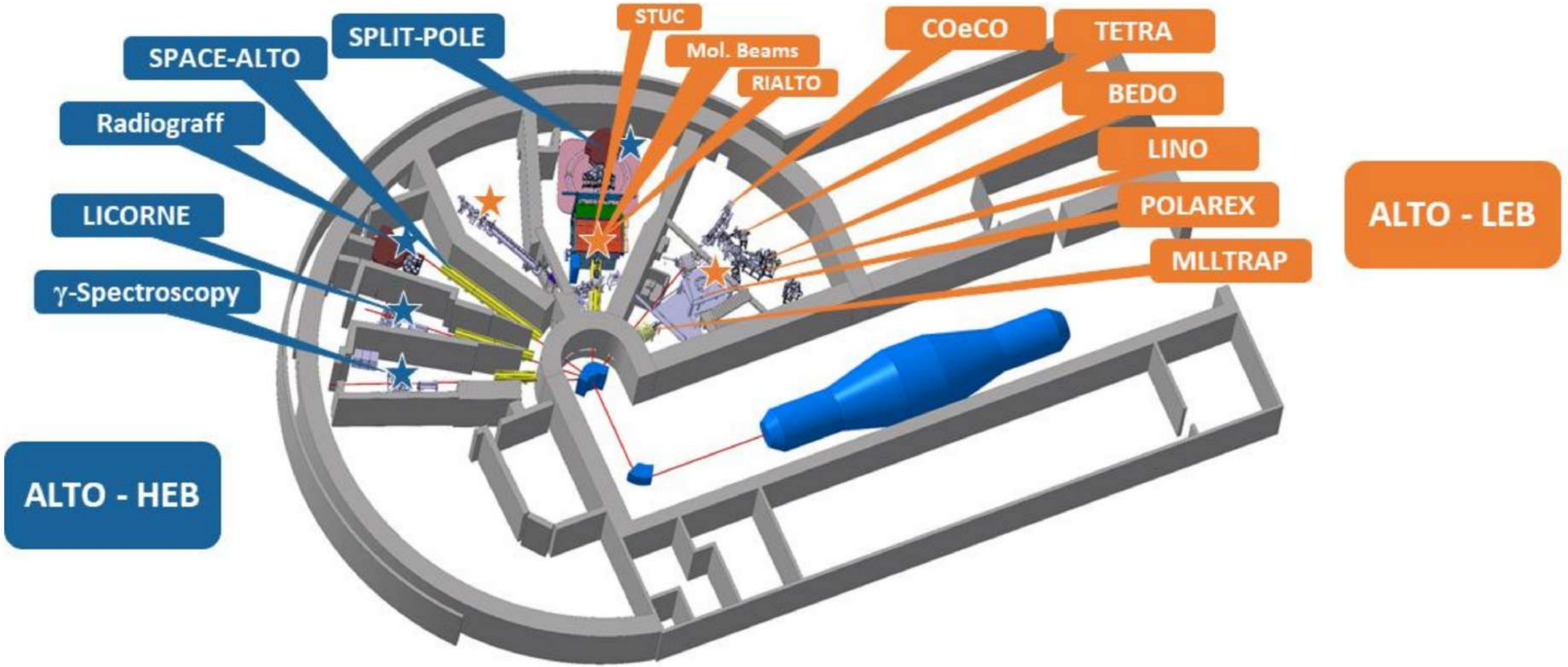
β-decay studies at ALTO and recent results

Guillem Tocabens



The ALTO facility



ALTO Low-Energy Branch

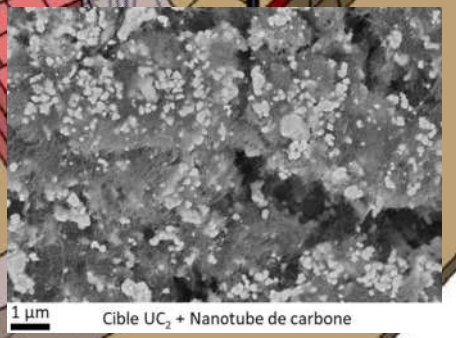
- Robotic front-end
- R&D on release properties of UCx targets
- New beams (Ag, Zn, Cd)

RIALTO

Electron Linac
50 MeV

Kicker-Bender
(35°)

Target-ion
source vault



Mass separator
(magnet dipole)

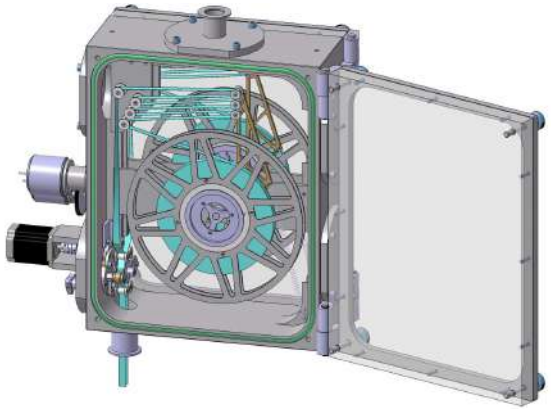
ALTO - LEB

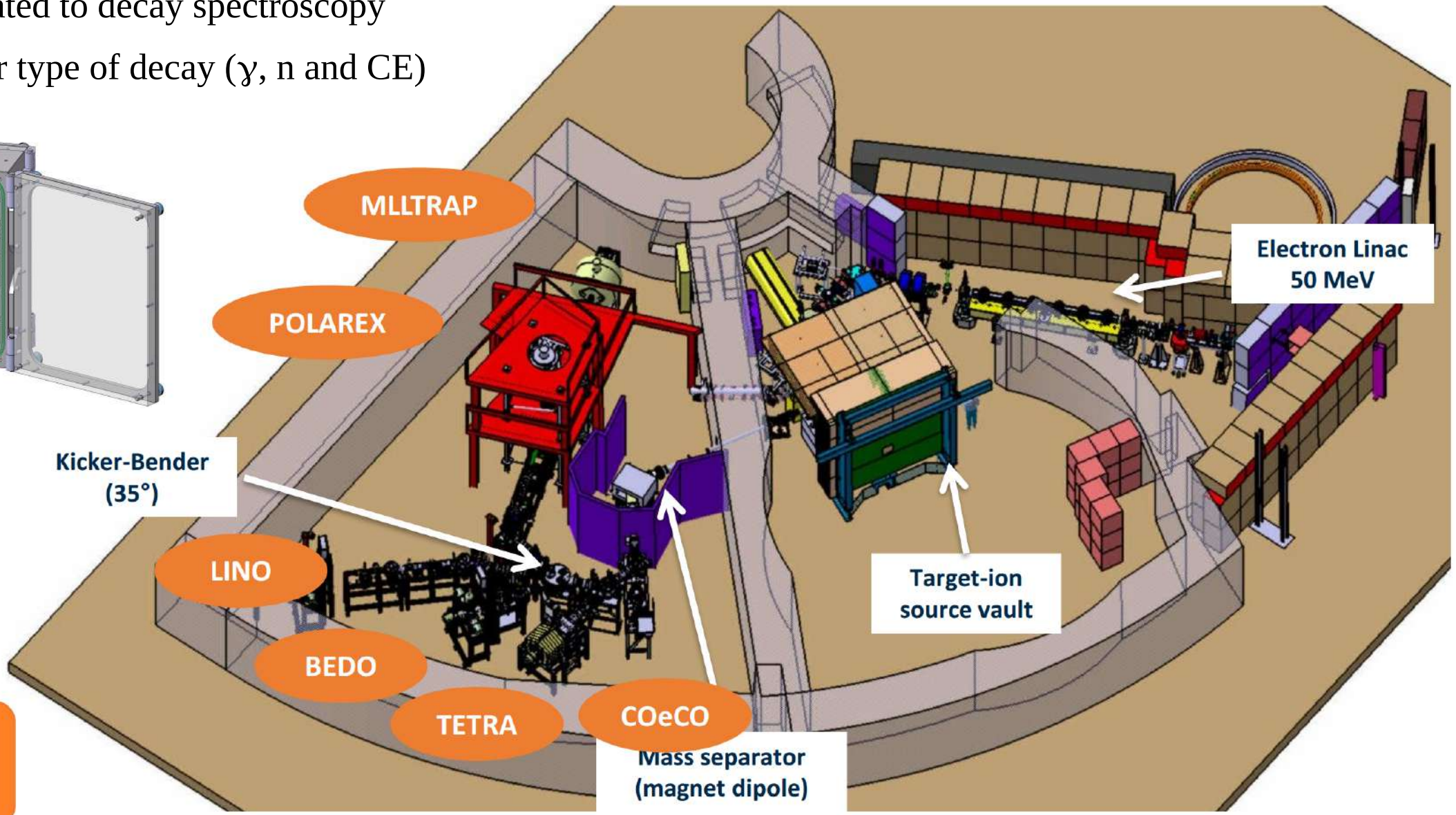
Observation

Production

ALTO Low-Energy Branch

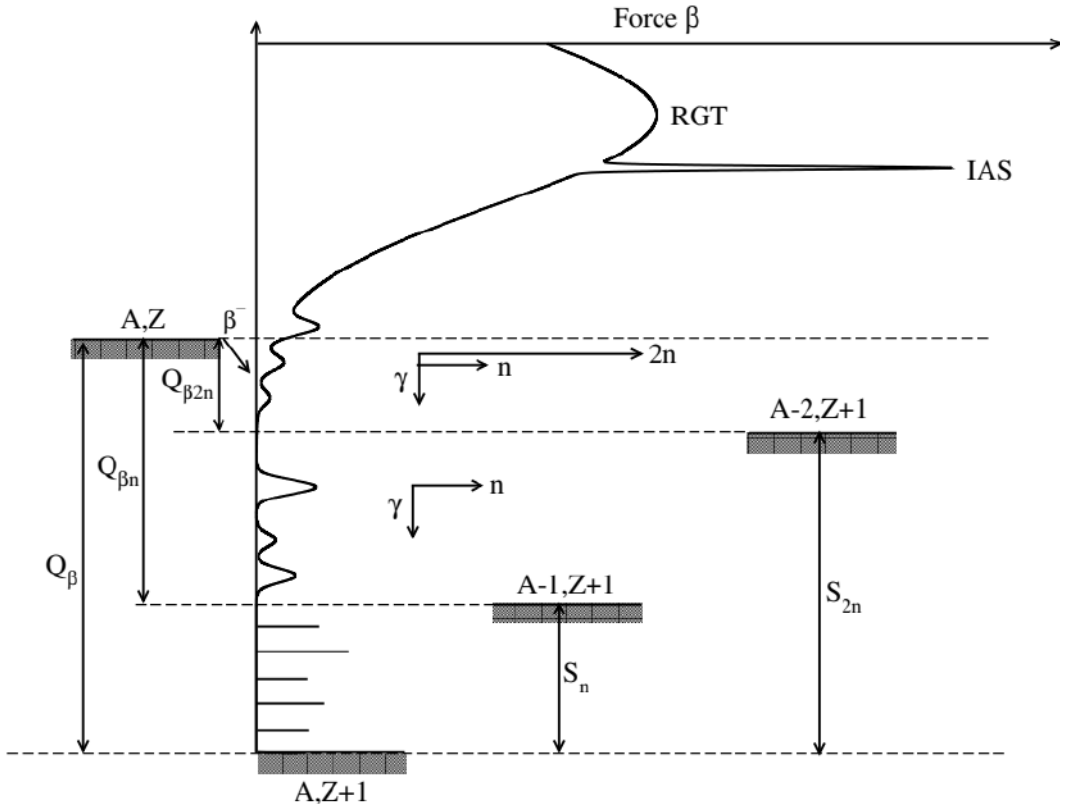
- 3 lines dedicated to decay spectroscopy
- One setup per type of decay (γ, n and CE)

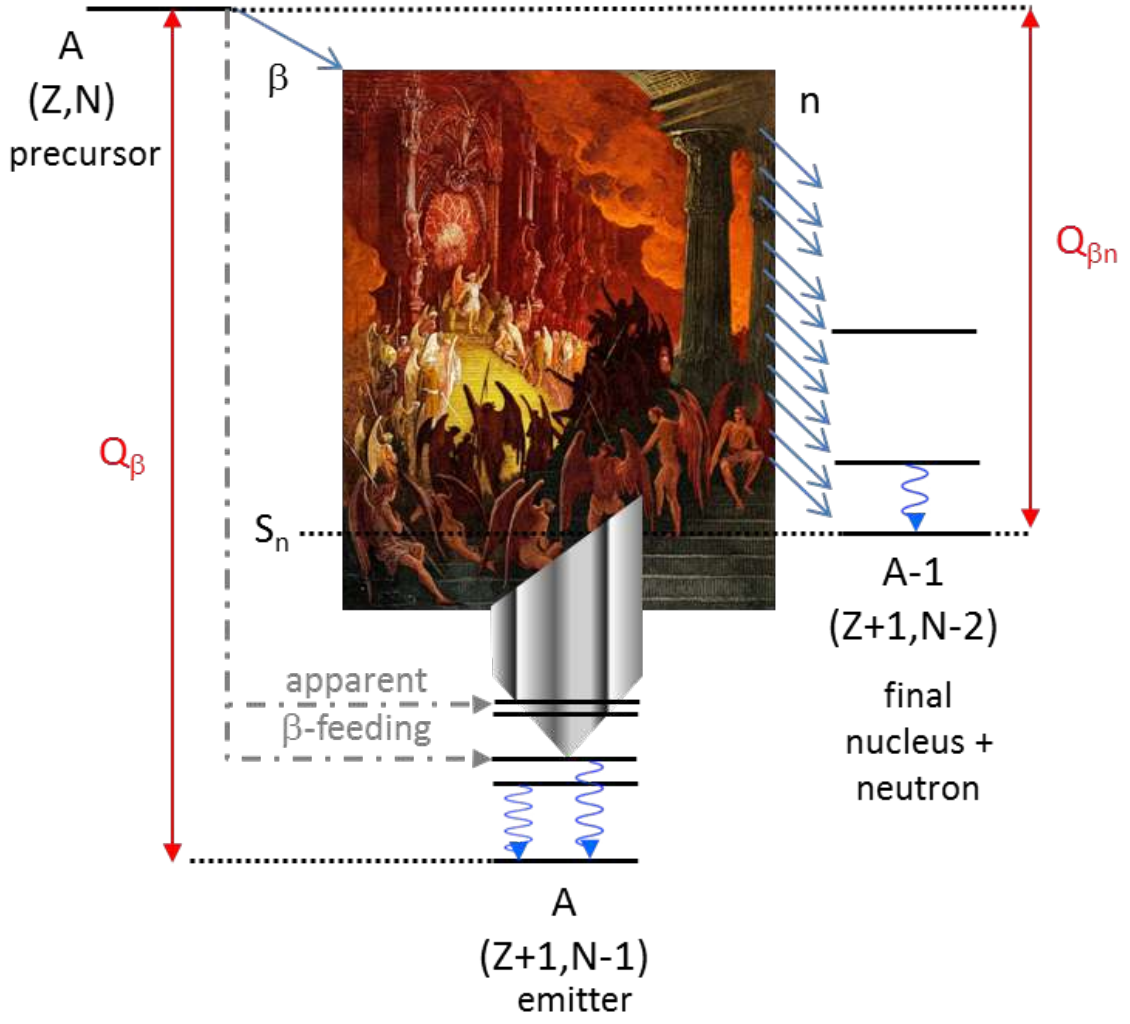




Structure close to and above S_n

Pandemonium Vs structure in β-decay properties



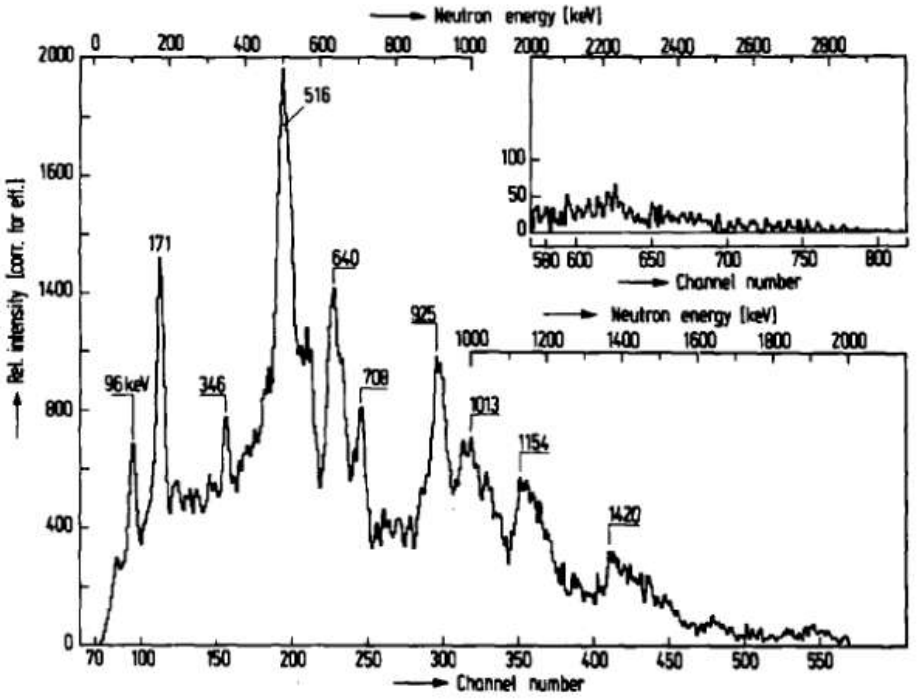


- *Hot*, unstructured system above S_n
- Statistical effect leads to overestimation of β-feeding

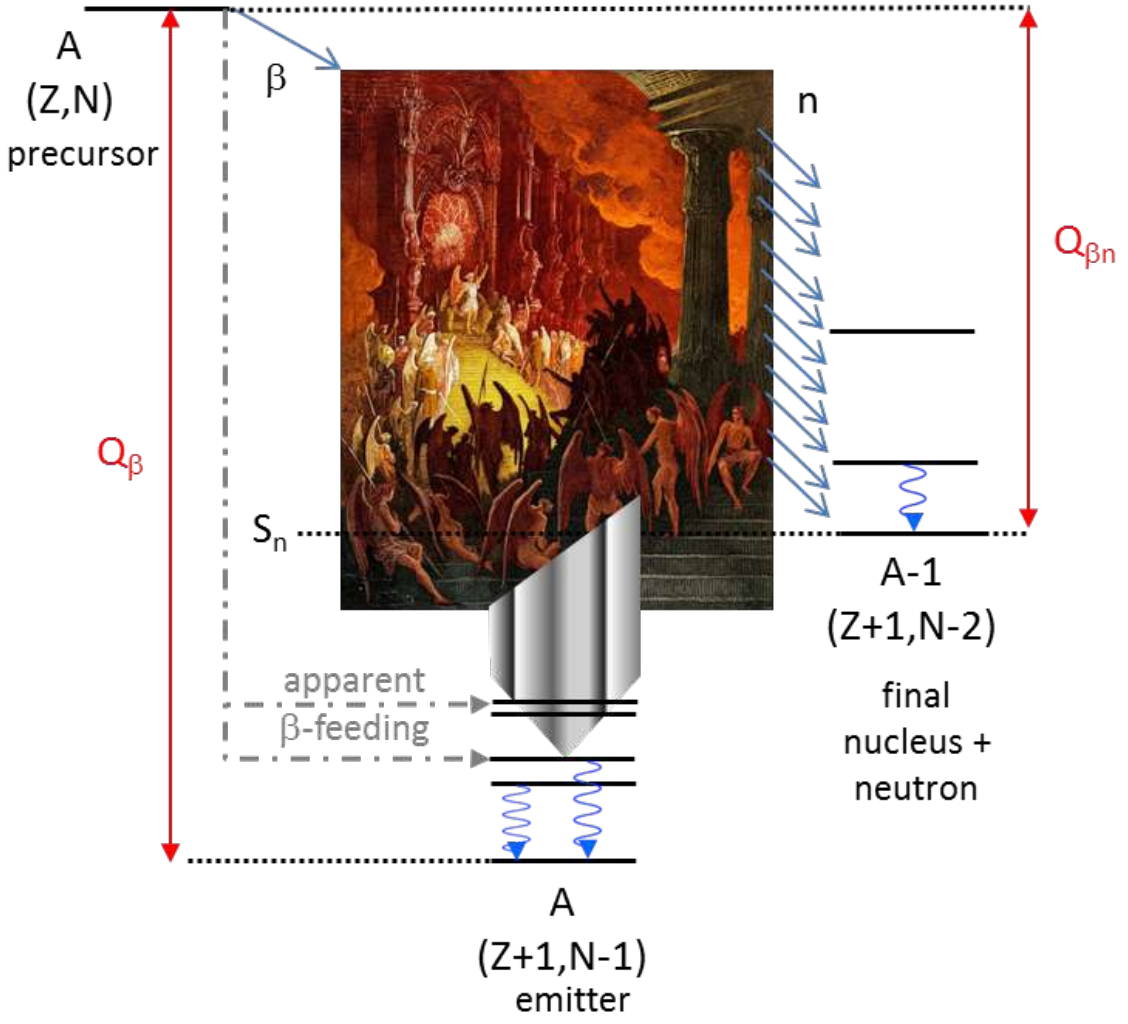
Hardy, PLB 71, 307 (1977)

Structure close to and above S_n

Pandemonium Vs structure in β-decay properties



Kratz *et al.*, Nucl. Phys. A, 317(2):335-362 (1979)

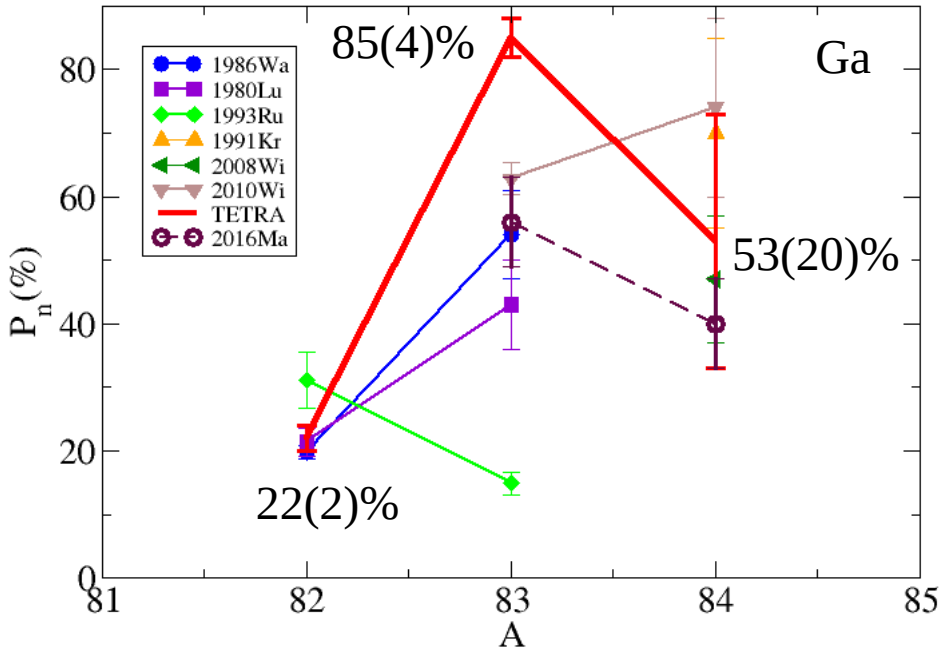


Hardy, PLB 71, 307 (1977)

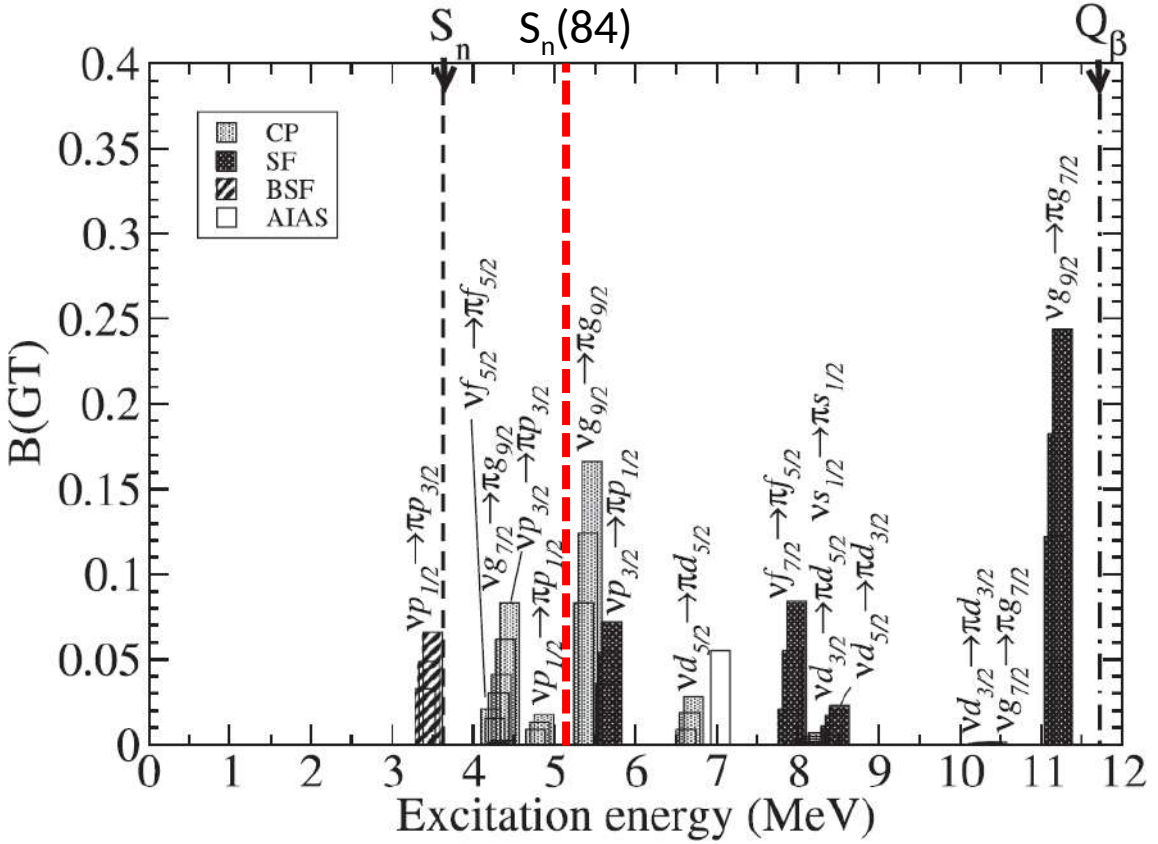
- *Hot*, unstructured system above S_n
- Statistical effect leads to overestimation of β-feeding
- First neutron spectra show peak structures

Structure close to and above S_n

Strong P_n oscillation in Ga isotopes close to N = 50



1986Wa: Reeder, Warner et al Rad Eff 94 (1986)
1980Lu: Lund et al Z Phys A 294 (1980)
1993Ru: Rudstam et al Atom. Nat. Nucl. Dat. Tab. 340 (1991)
1991Kr: Kratz et al Z Phys A 340 (1991)
2008Wi: Winger et al Sanibel Conf Proc (2008)
2010Wi: Winger et al. PRC 81 (2010)
2016Ma: Madurga et al. PRL 117 (2016)

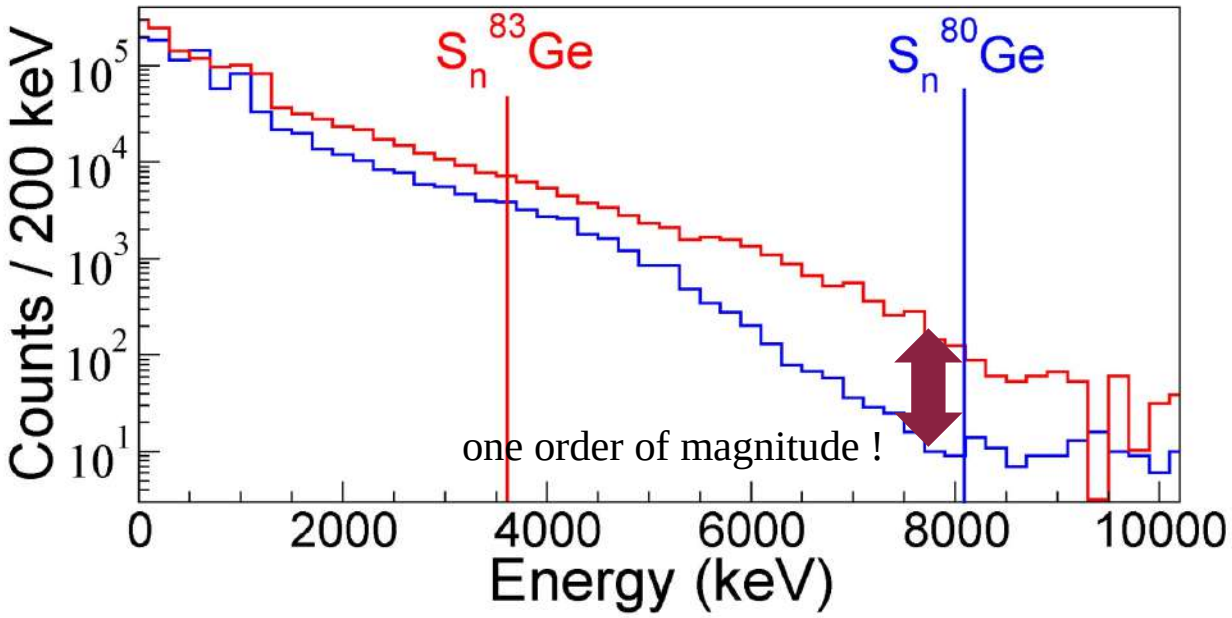


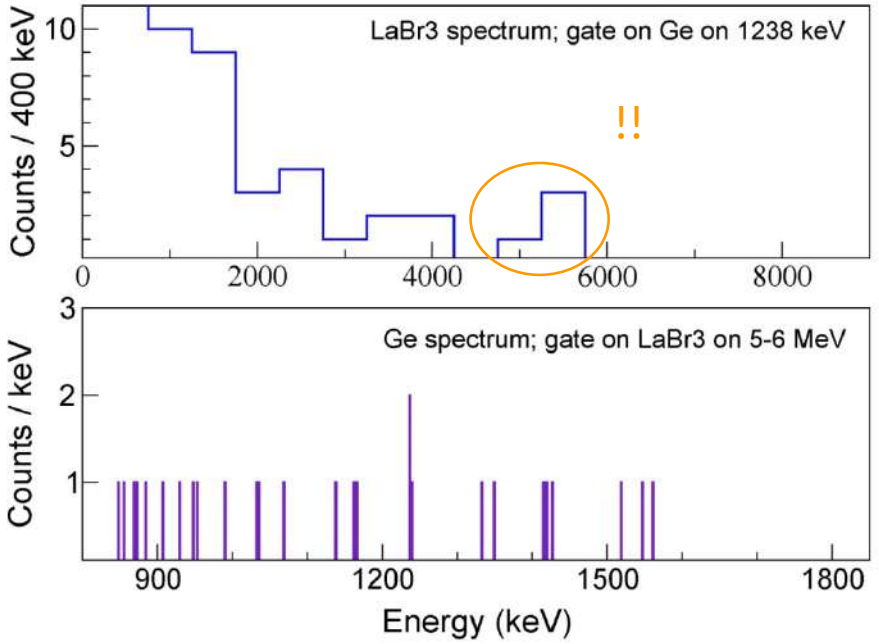
Verney *et al.*, Phys. Rev. C 95, 054320 (2017)

- As Q_β increases, P_n should too
- S_n increase at N = 53 excludes low-lying components in β-strength function

Structure close to and above S_n

Structure above S_n in ^{83}Ge



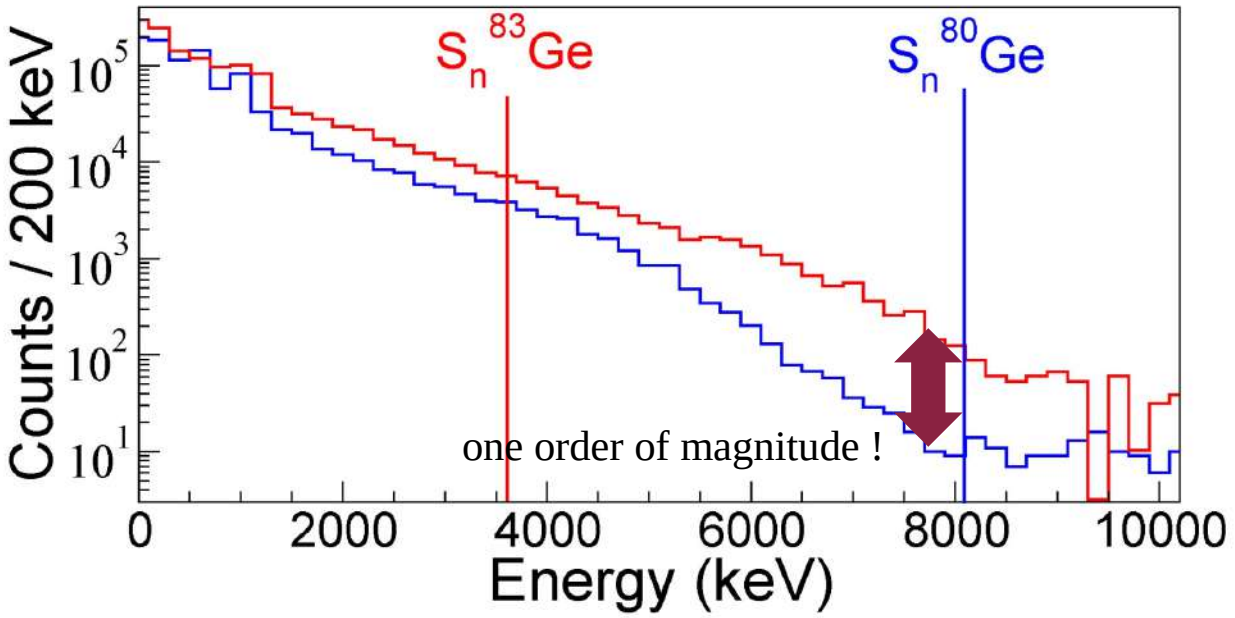


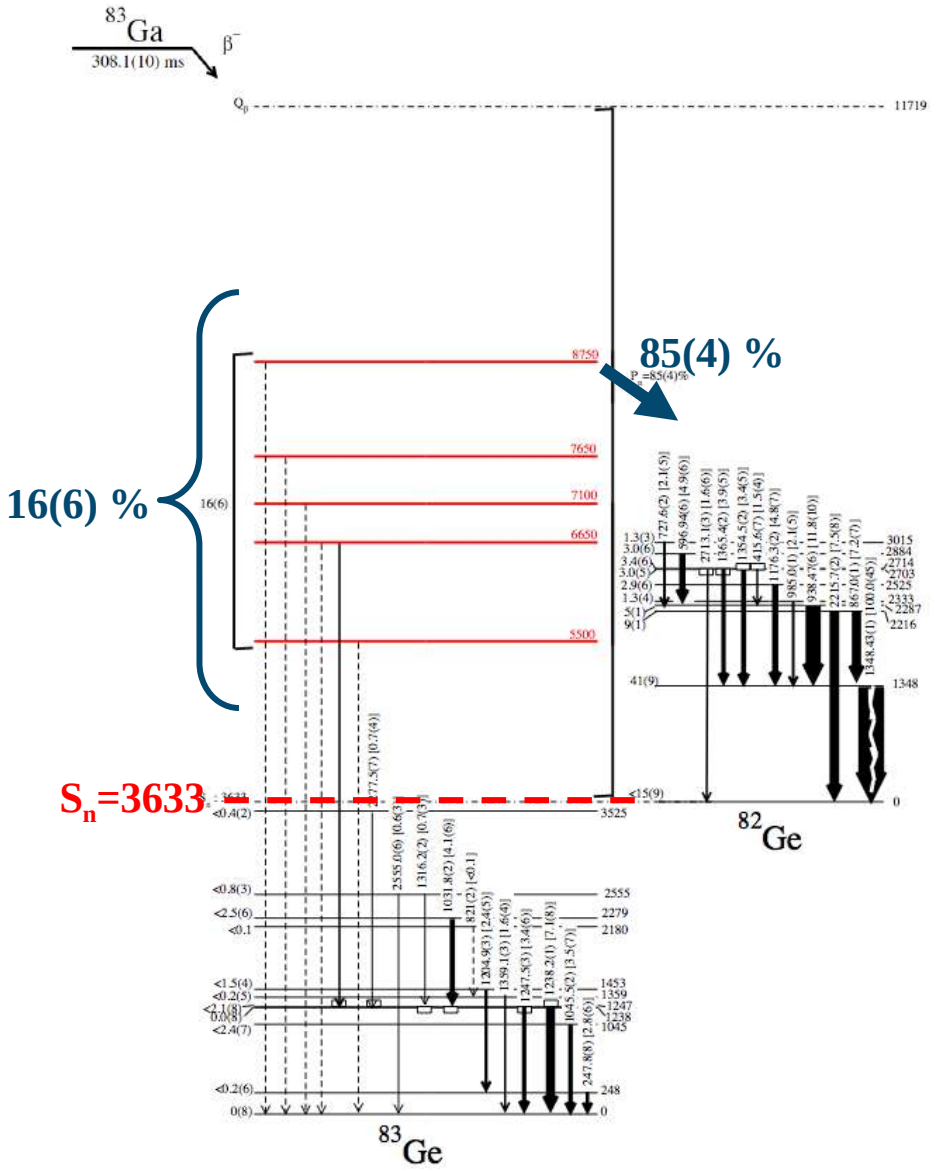
- γ-spectrum shows activity above S_n
- γ-rays between 4.5 – 6 MeV in coincidence with ^{83}Ge 1238 keV line

A. Gottardo *et al.*, Physics Letters B 772 (2017) 359–362

Structure close to and above S_n

Structure above S_n in ^{83}Ge

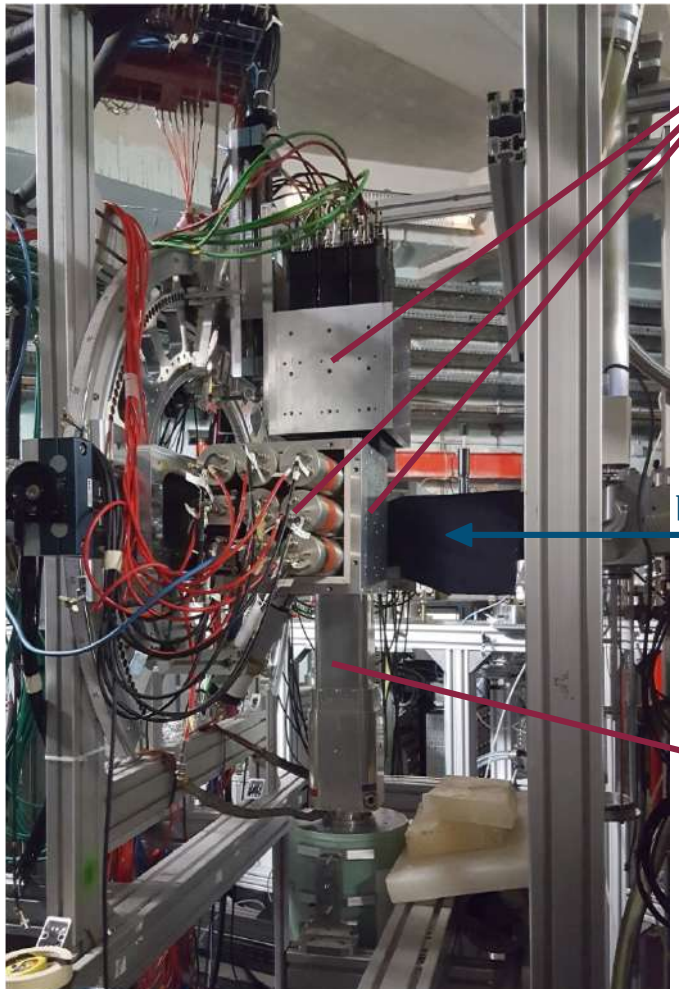


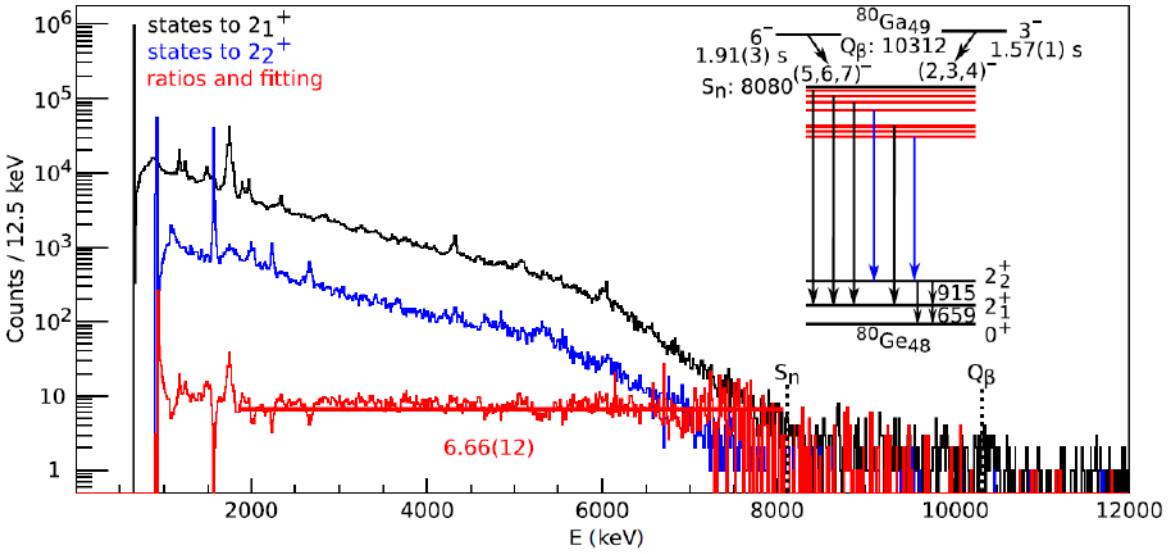


A. Gottardo *et al.*, Physics Letters B 772 (2017) 359–362

- γ-spectrum shows activity above S_n
- γ-rays between 4.5 – 6 MeV in coincidence with ^{83}Ge 1238 keV line
- Deconvoluted $LaBr_3$ spectrum shows structures above S_n accounting for 16% of the total intensity

Decay spectroscopy of ^{80}Ga using PARIS





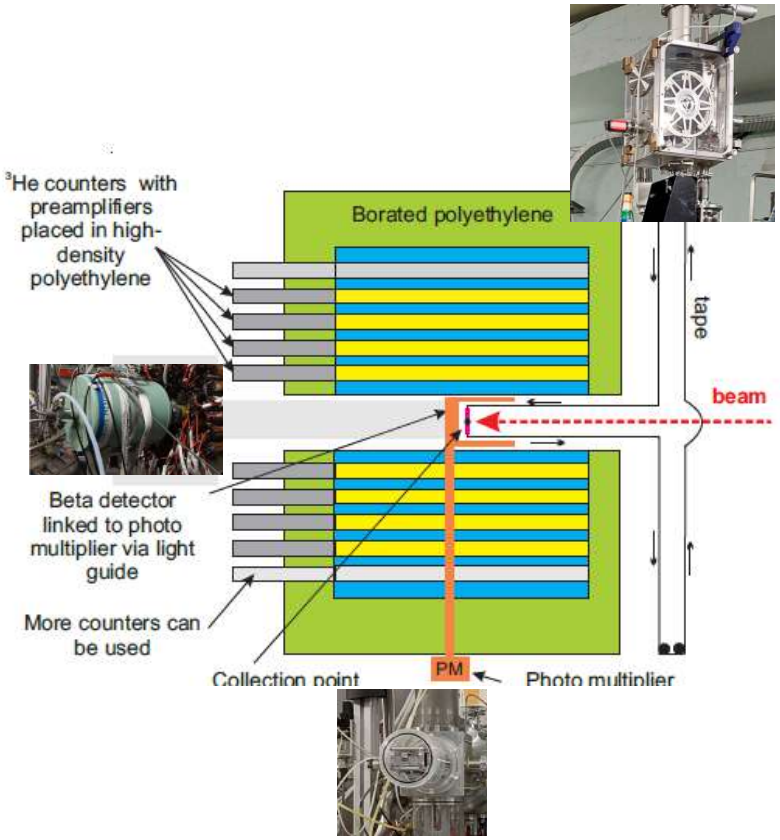
Li *et al.*, Phys. Rev. C 111, 034303 (2025)

- Decay of ^{80}Ga also shows correlation between deformation of precursor and selectivity to highly deformed 2^+ state

Full ɣ-spectroscopy just published :
Li *et al.*, Phys. Rev. C 112, 044306 (2025)

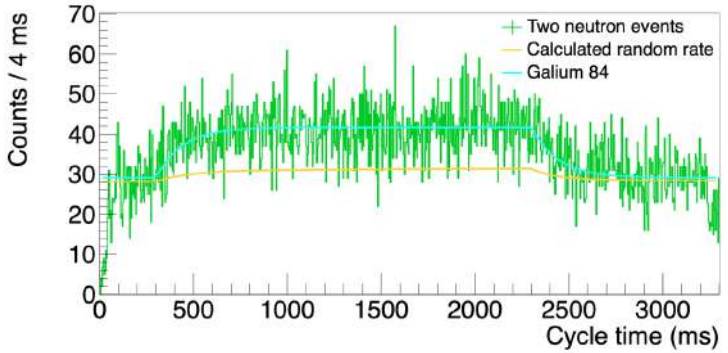
Part of 3 PhDs works :
defended { Lama Al Ayoubi, Ren Li
on-going → Elia Nseir

Mean neutron energy measurement with TETRA

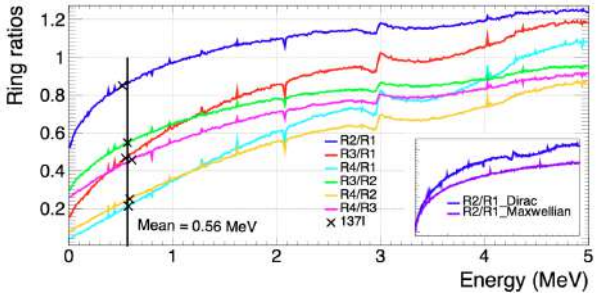


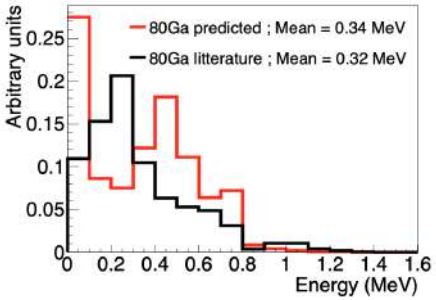
- Neutron counter
- n moderation with HDPE
- n + ^{3}He → p + ^{3}H + 765 keV
- ~ 52% efficiency
- Low threshold
- No energy information

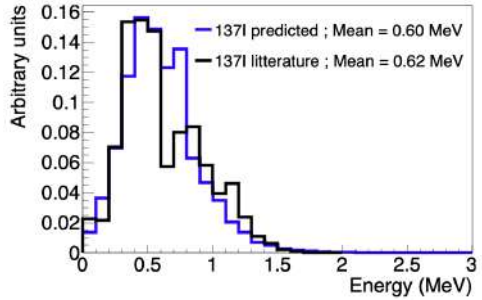
P_n and P_{2n} measurements of ^{84}Ga



- P_{2n} measured for the second time only
- P_{2n} = 1.45(38) % in agreement with previous measurement (BRIKEN, P_{2n} = 1.86(6)(11))



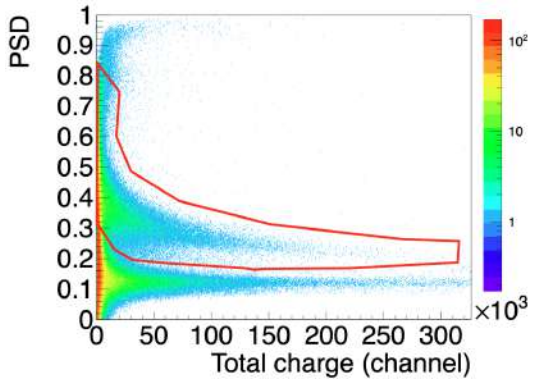




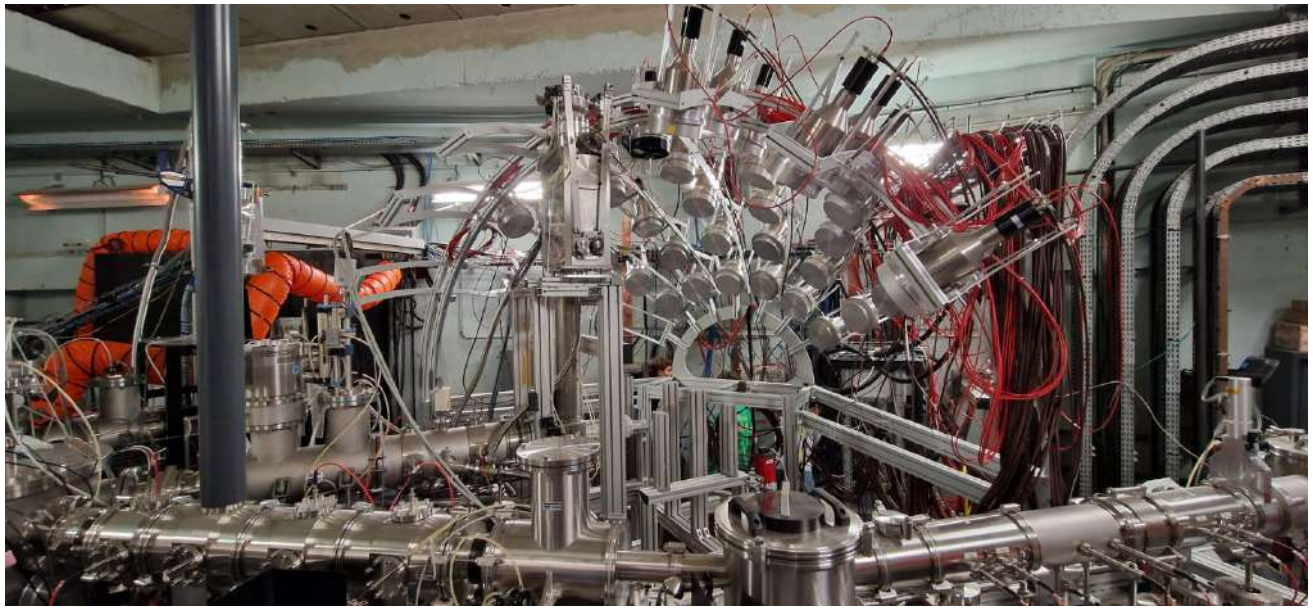
- Reconstruction of mean n energy using ring-ratios
- New method to reconstruct the neutron emission spectrum
- Bayesian method of deconvolution of the TETRA response

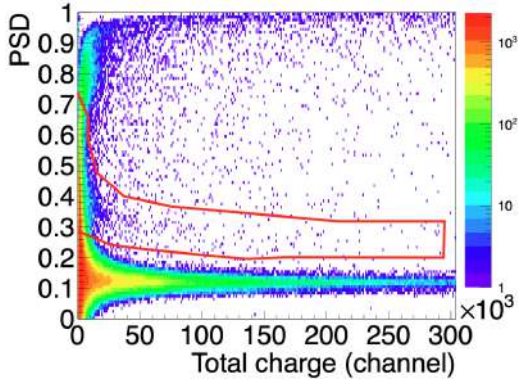
Part of Emile Cantacuzène PhD work, N.I.M in preparation

Strengthening BEDO with MONSTER (n-ToF)



PSD as a function of total charge, neutrons in red (^{252}Cf source)





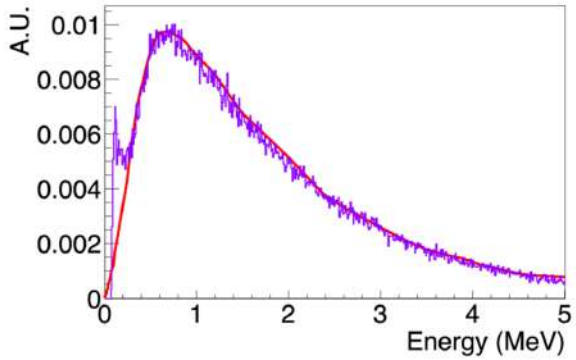
PSD as a function of total charge, neutrons in red (^{82}Ga source)

n energy spectrum of ^{82}Ga

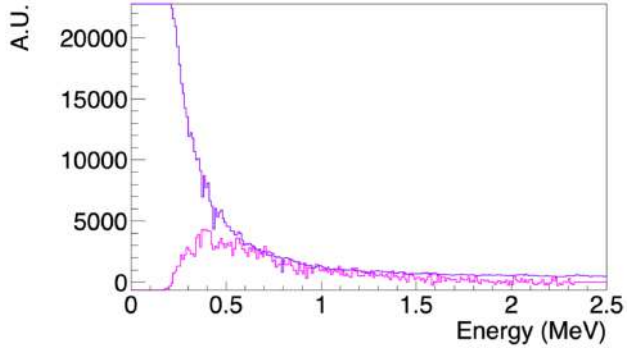
(~ 8h of data)

- Good neutron/gamma identification with MONSTER
- Proof of functioning at ALTO for future reference
- High energy threshold (~ 100 keV)
- P_n largely under-estimated :
  12% (MONSTER) Vs 24% (TETRA)

Part of Emile Cantacuzène PhD work



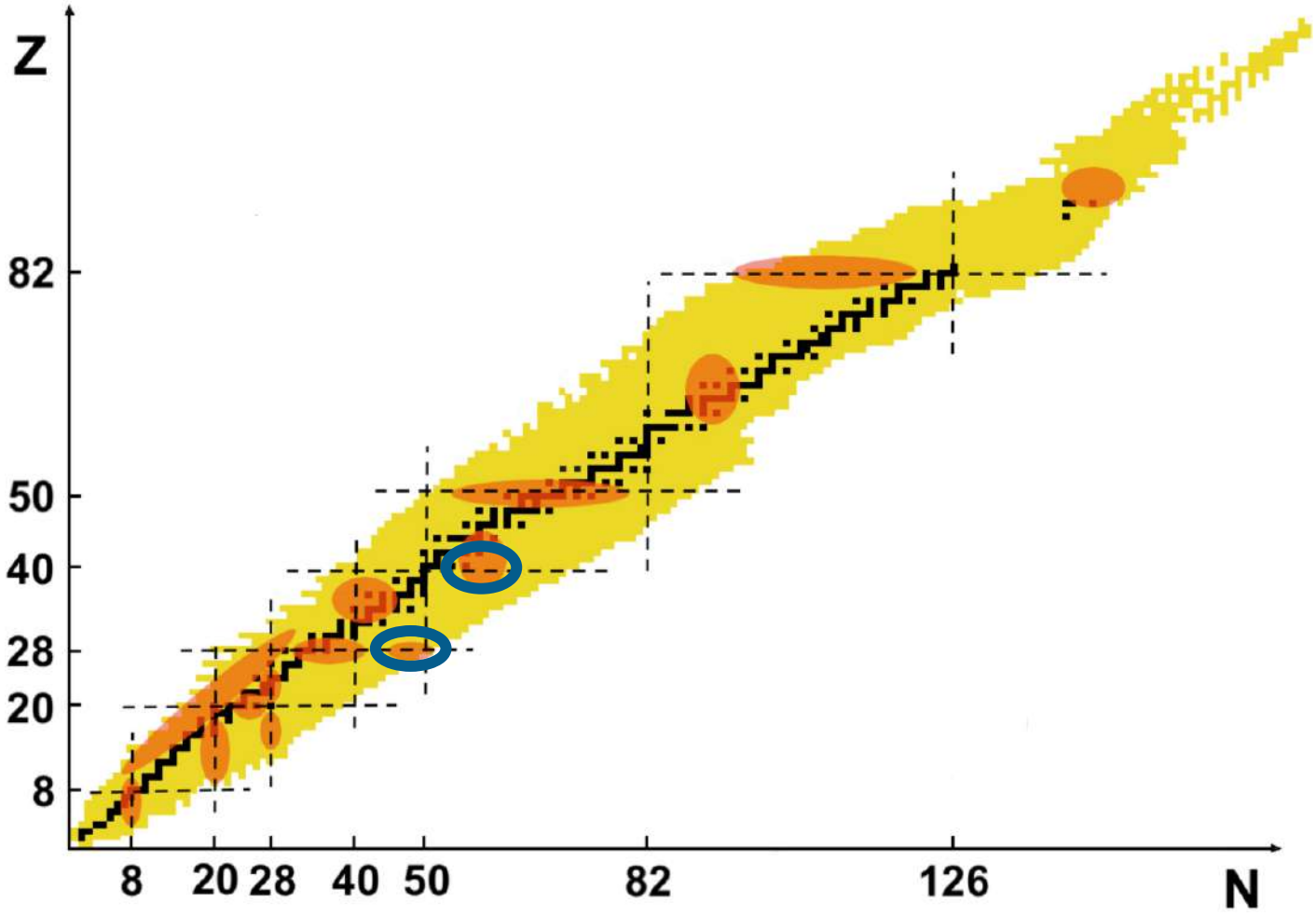
n energy spectrum (^{252}Cf) compared to the IAEA spectrum corrected by MONSTER efficiency



n energy spectrum (^{82}Ga, pink) compared to the spectrum obtained from the Bayesian method (violet)

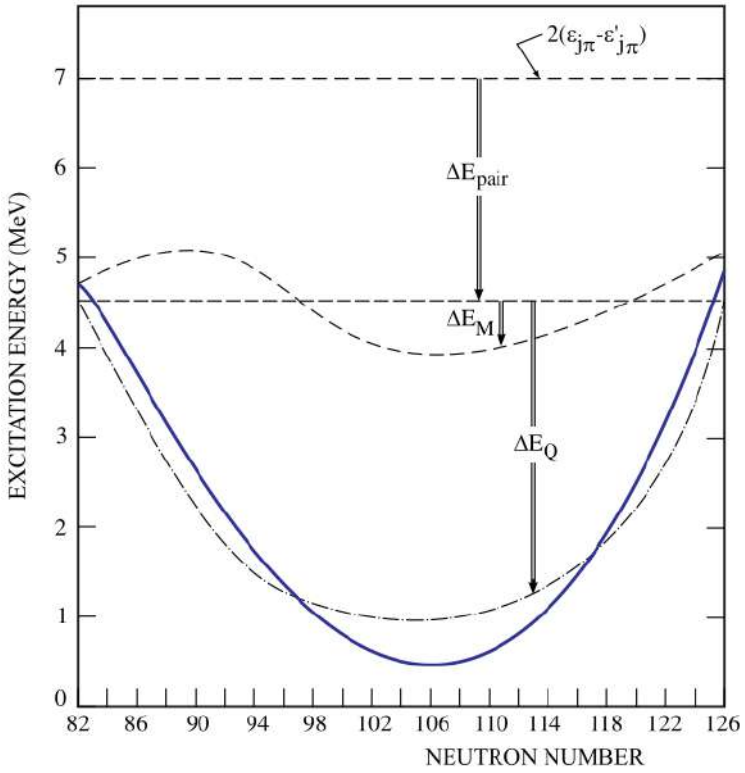
Shape coexistence at low energy

Two main regions of interest at ALTO



Adapted from K. Heyde, J. L. Wood, Shape coexistence in atomic nuclei, Rev. Mod. Phys. 83, 2011

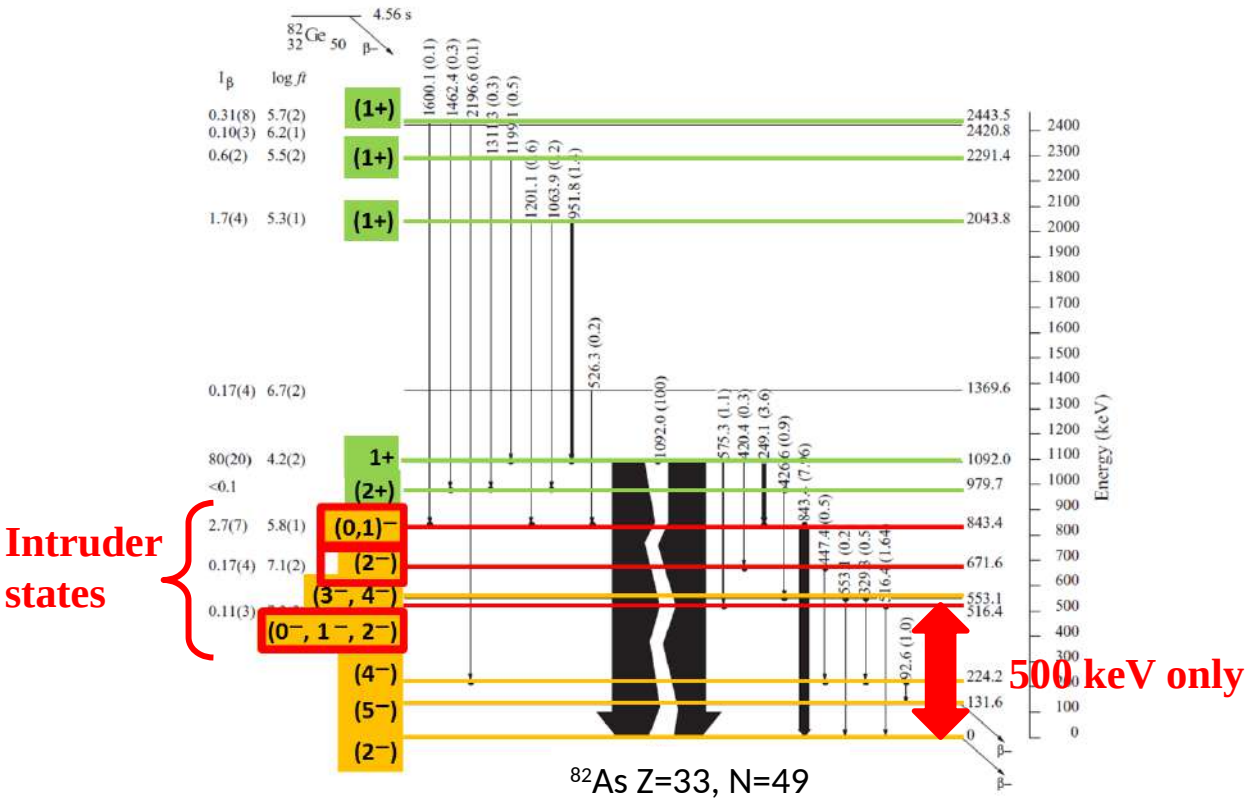
- A widely spread phenomenon, occurring around shell closures
- In a shell-model view, can be seen as a 2p-2h intruder configuration, for which the gain given by correlations is higher than the gap

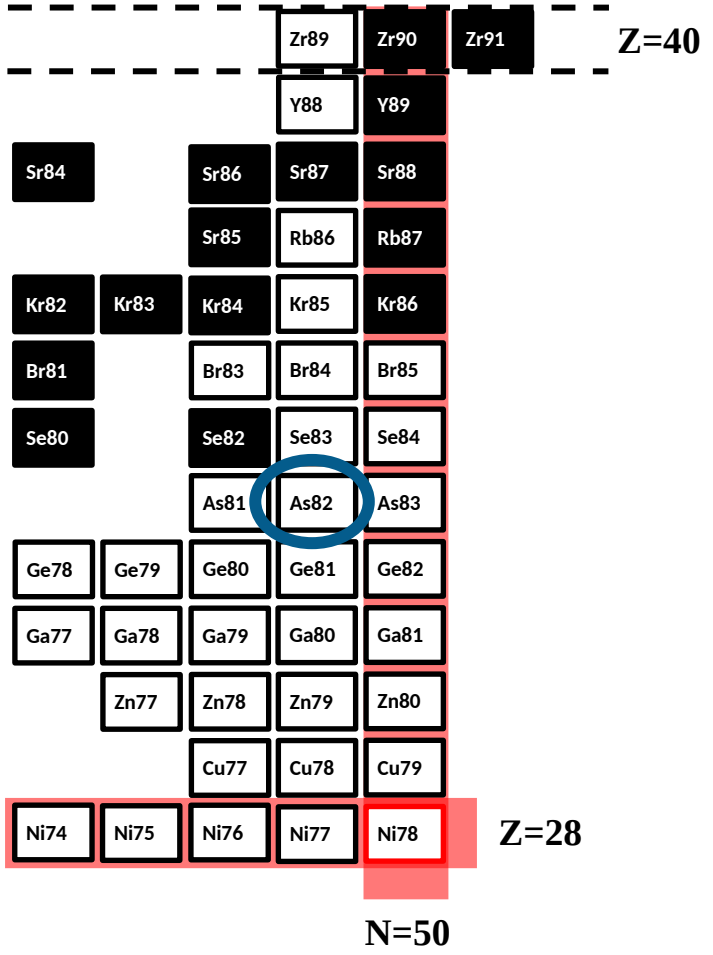


Shape coexistence at low energy

Low-lying, low-spin, negative parity states in ^{82}As

- Discovered in β-decay experiment with BEDO





A. Etilé *et al.*, Phys. Rev. C 91 064317 (2015)

Shape coexistence at low energy

Low-lying, low-spin, negative parity states in ^{82}As

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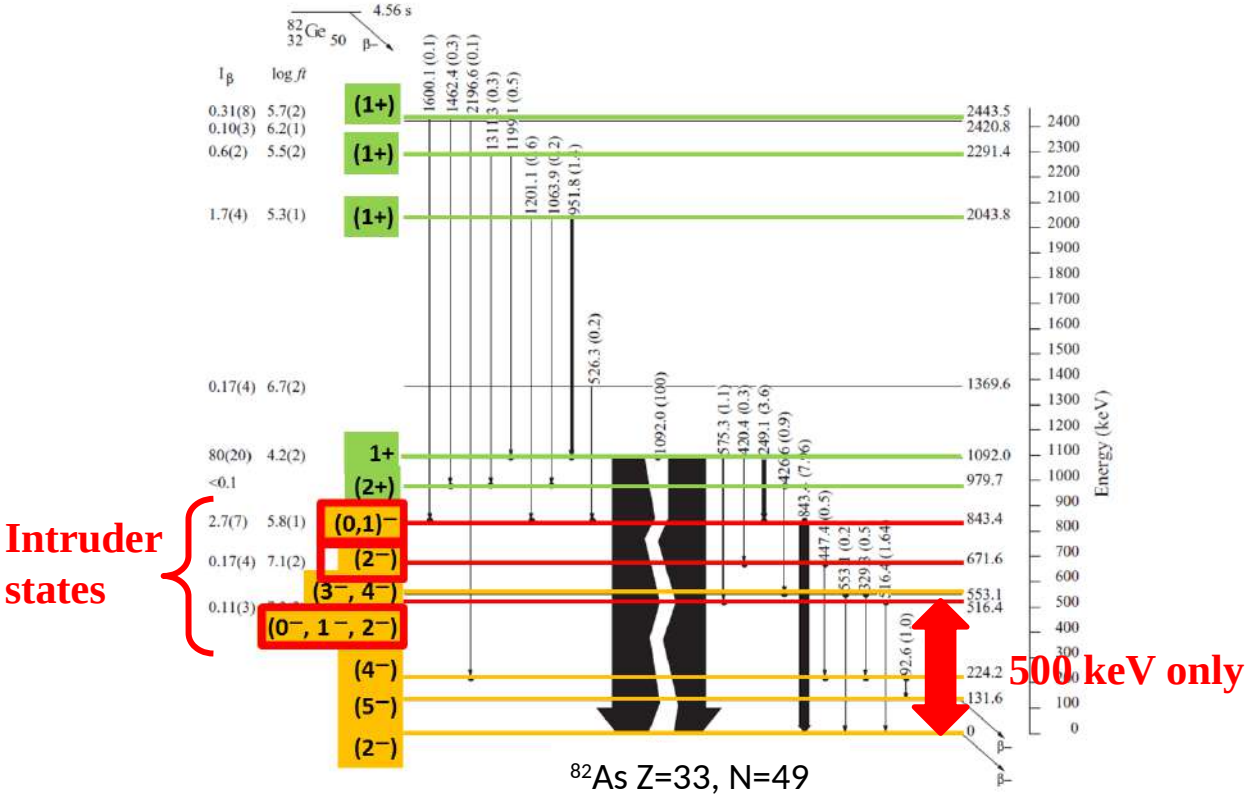
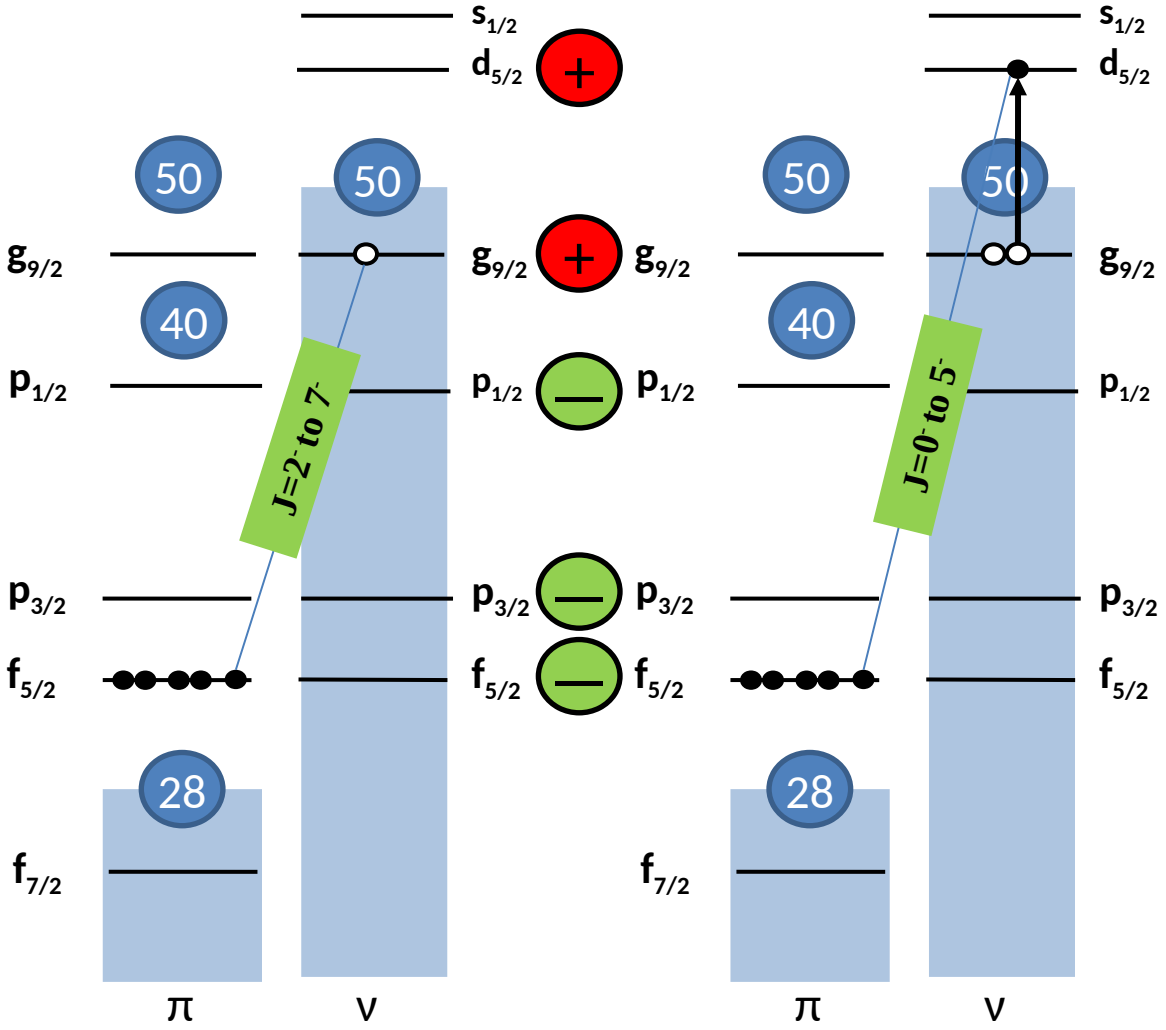
- Intruder configuration, neutron promotion across N = 50 gap



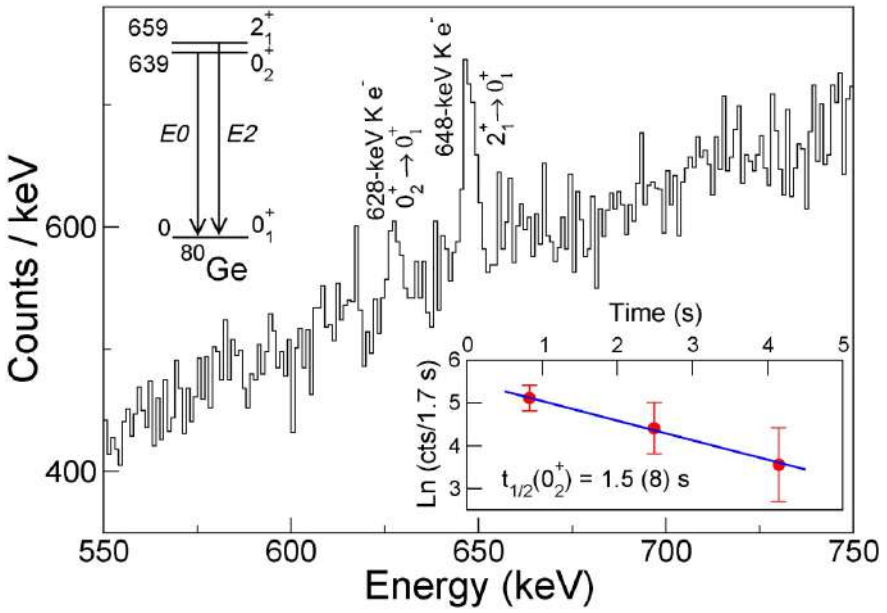


A. Etilé *et al.*, Phys. Rev. C 91 064317 (2015)

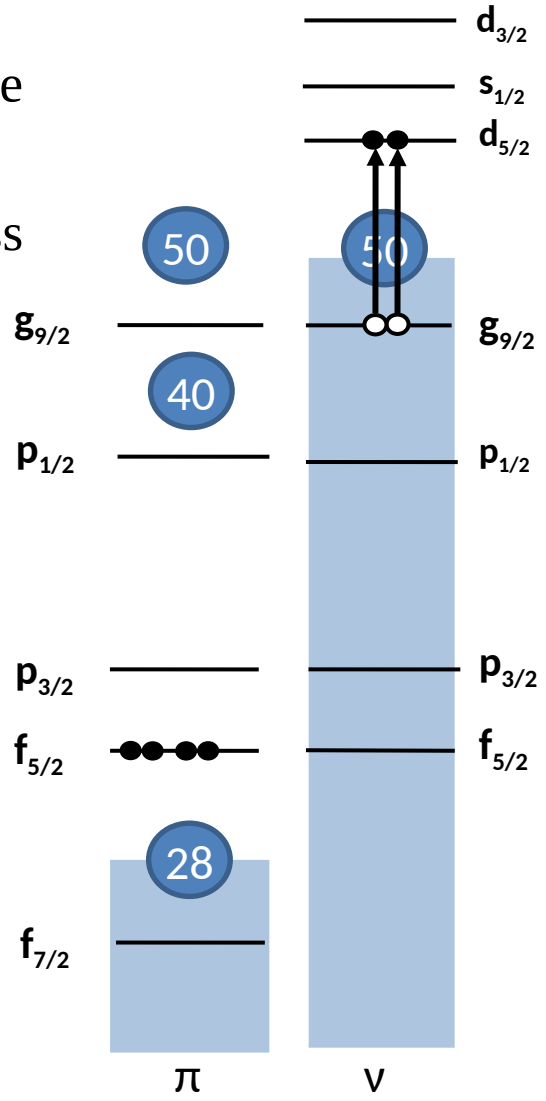
Shape coexistence at low energy

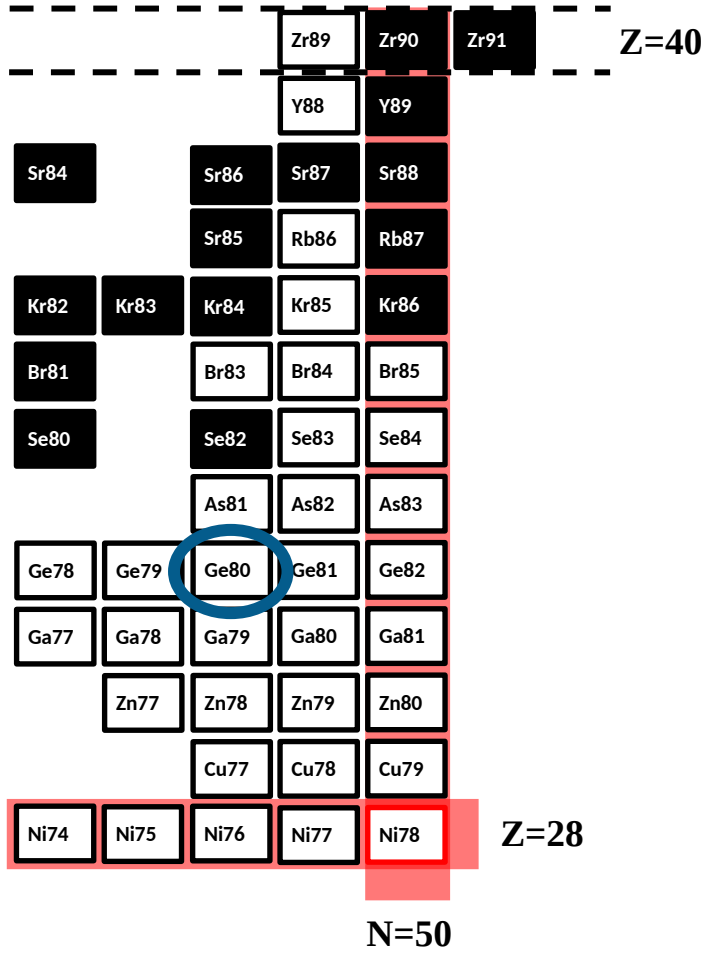
Low-lying 0^+ state in ^{80}Ge

- Discovered by adding a Si(Li) detector to the identification station
- Intruder configuration, pair promotion across N = 50 gap

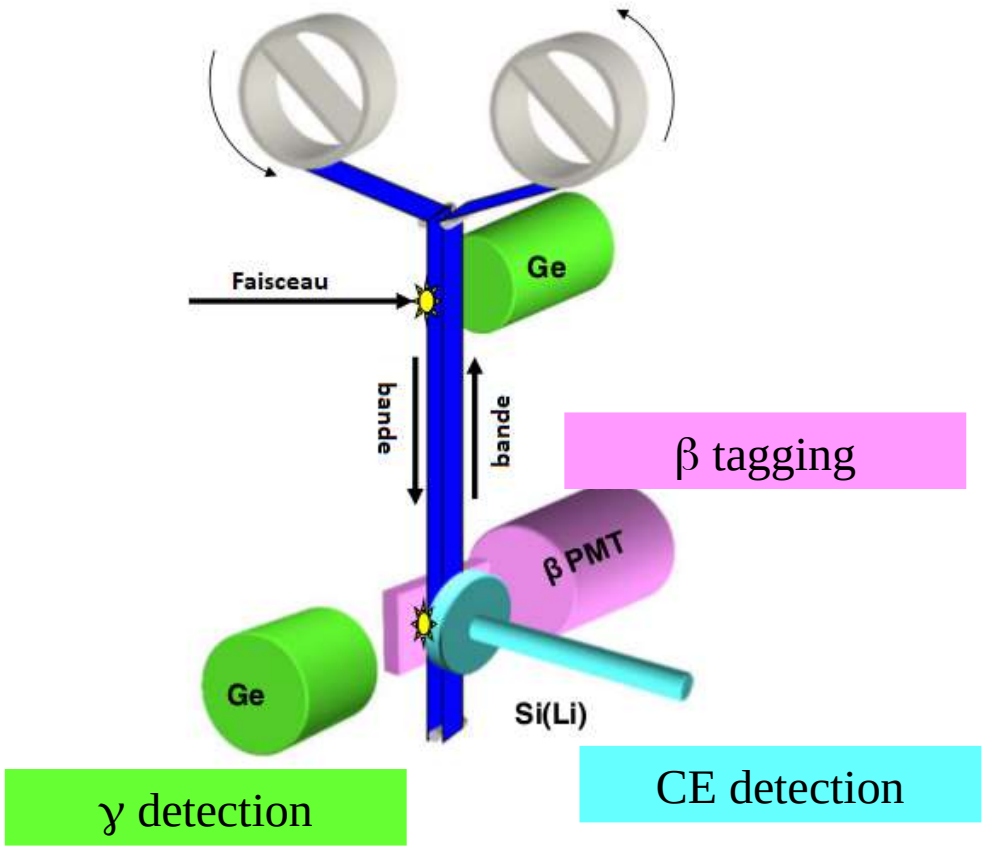


A. Gottardo *et al.*, Phys. Rev. Lett. 116, 182501 (2016)

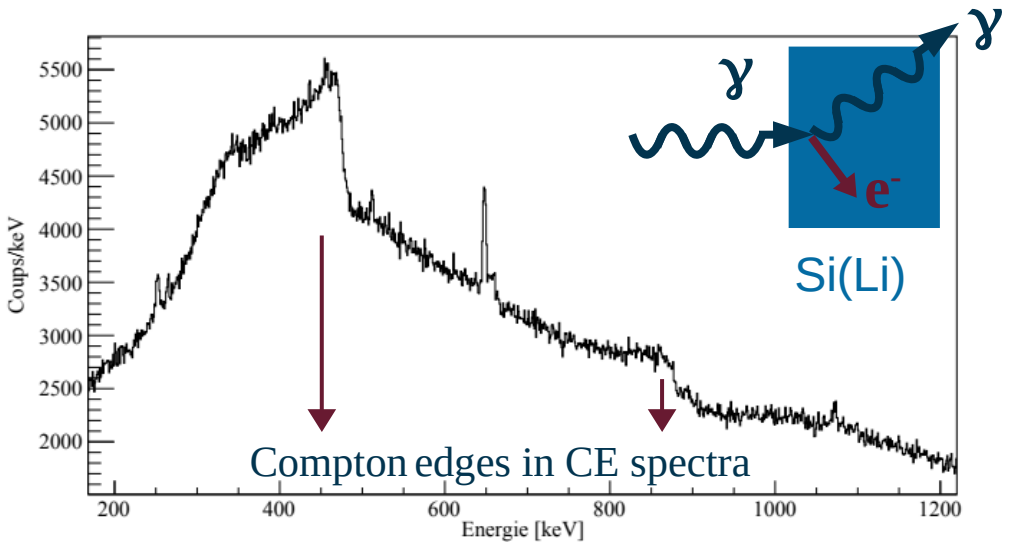




Conversion electron spectroscopy at ALTO



- Rather rudimentary setup, Si(Li) added to the identification station
- Two-step collection and measurement setup (short lifetimes inaccessible)
- Very close geometry at the detection point (important γ background in CE spectra)

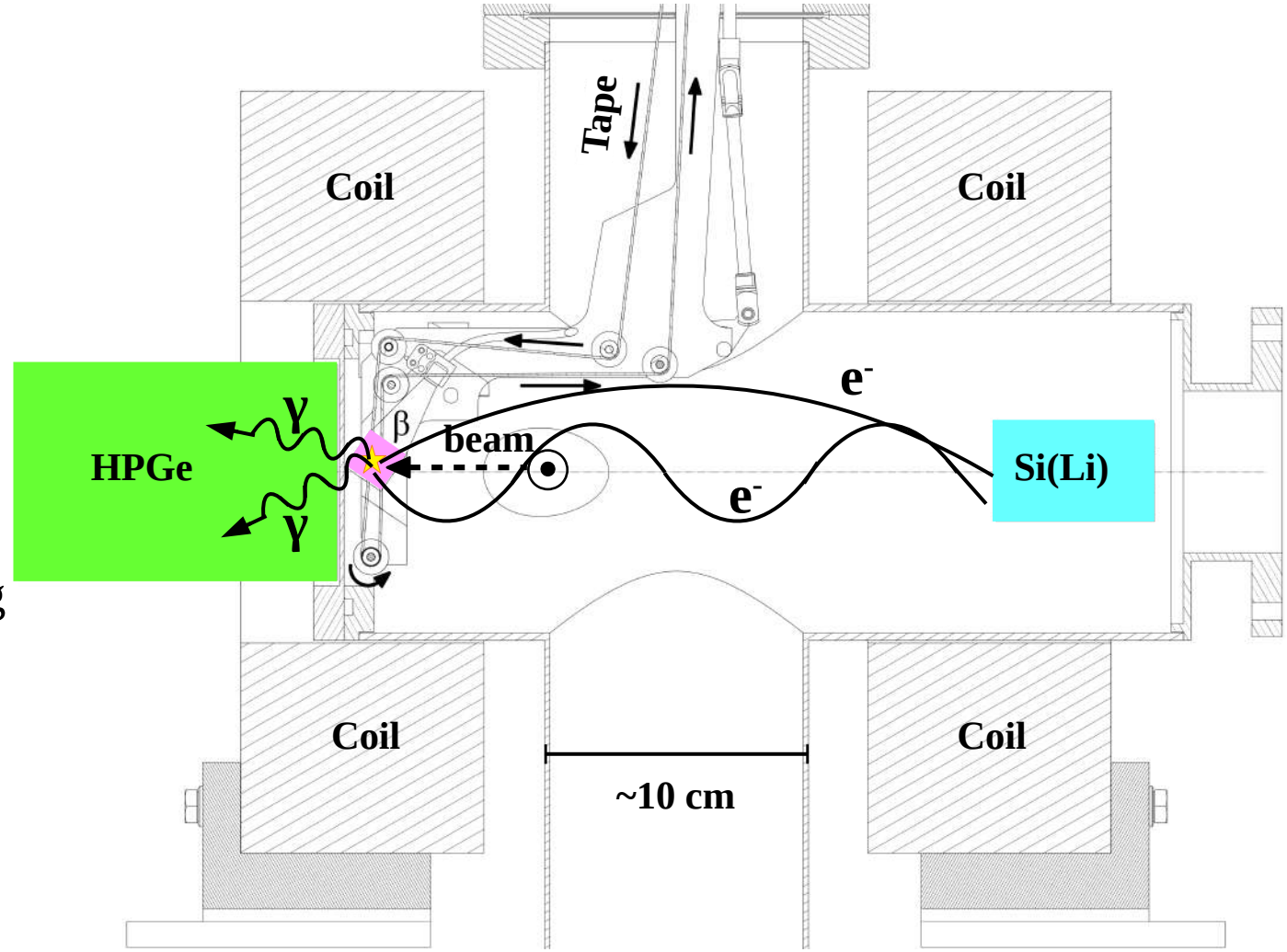


COeCO : COnversion electrons Chasing at Orsay

Upgraded setup with magnetic transporter similar to ELLI (Jyväskylä)

J. M. Parmonen, NIM-A 306, 504-511 (1991)

- Two copper coils close to Helmholtz configuration
- Beam collected on tape (center of first coil)
- Plastic scintillator surrounds tape for β tagging
- Conversion electrons are guided following magnetic field towards the Si(Li) detector (center of second coil)
- Tape is unwound to remove the source



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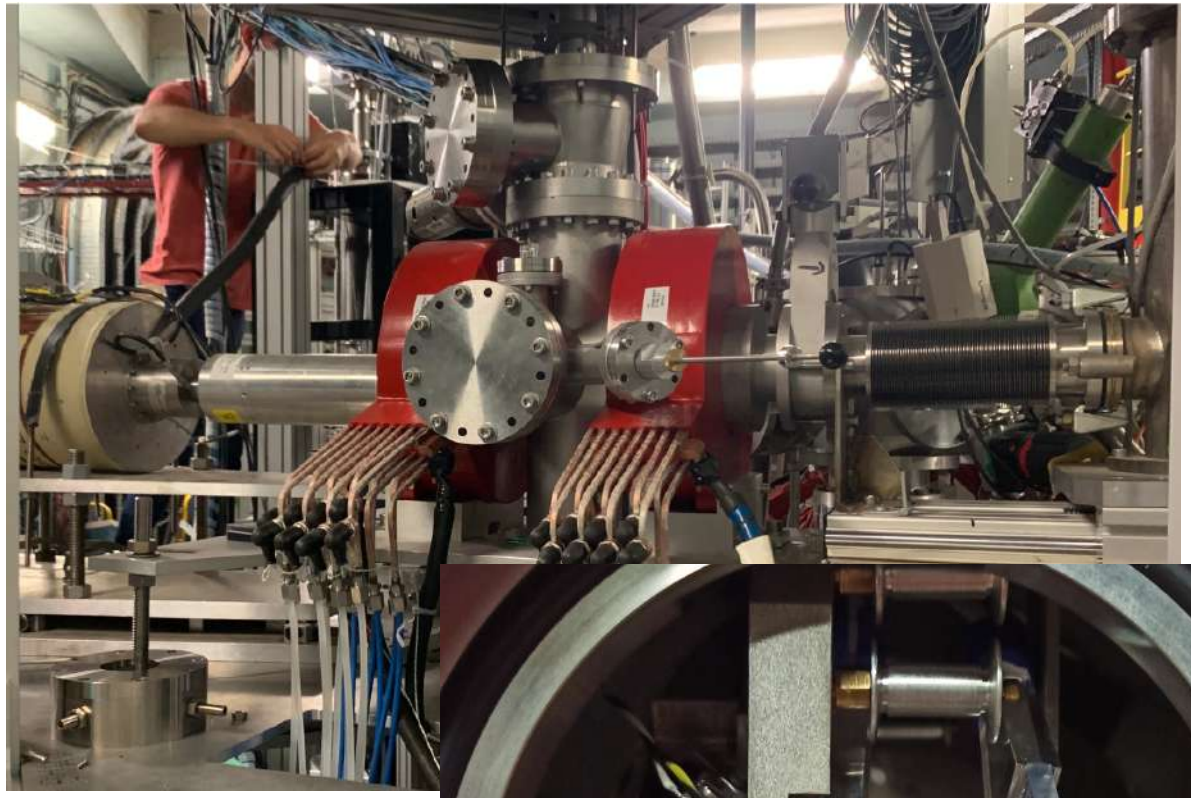
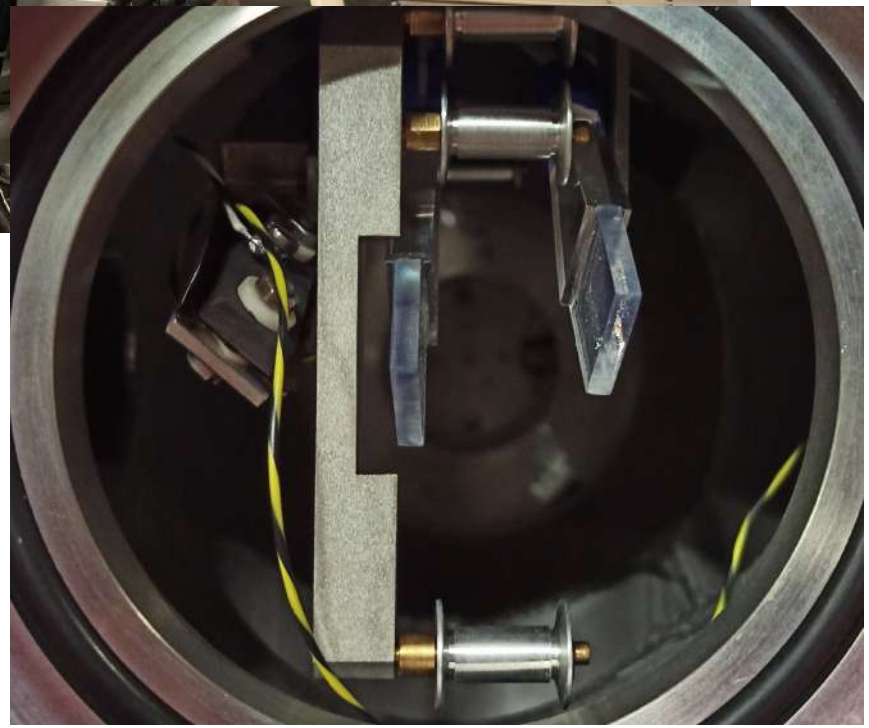
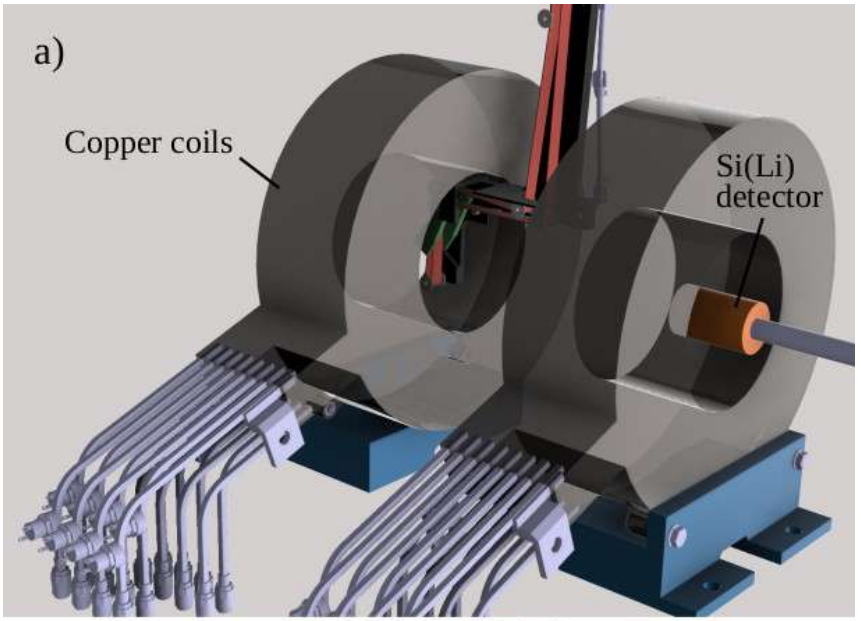
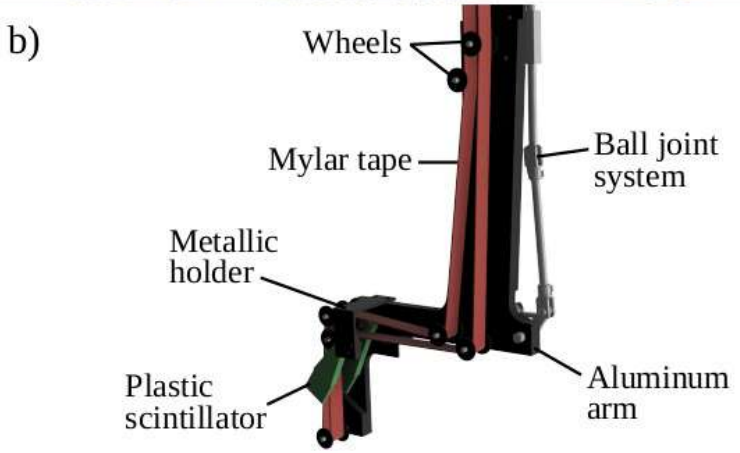




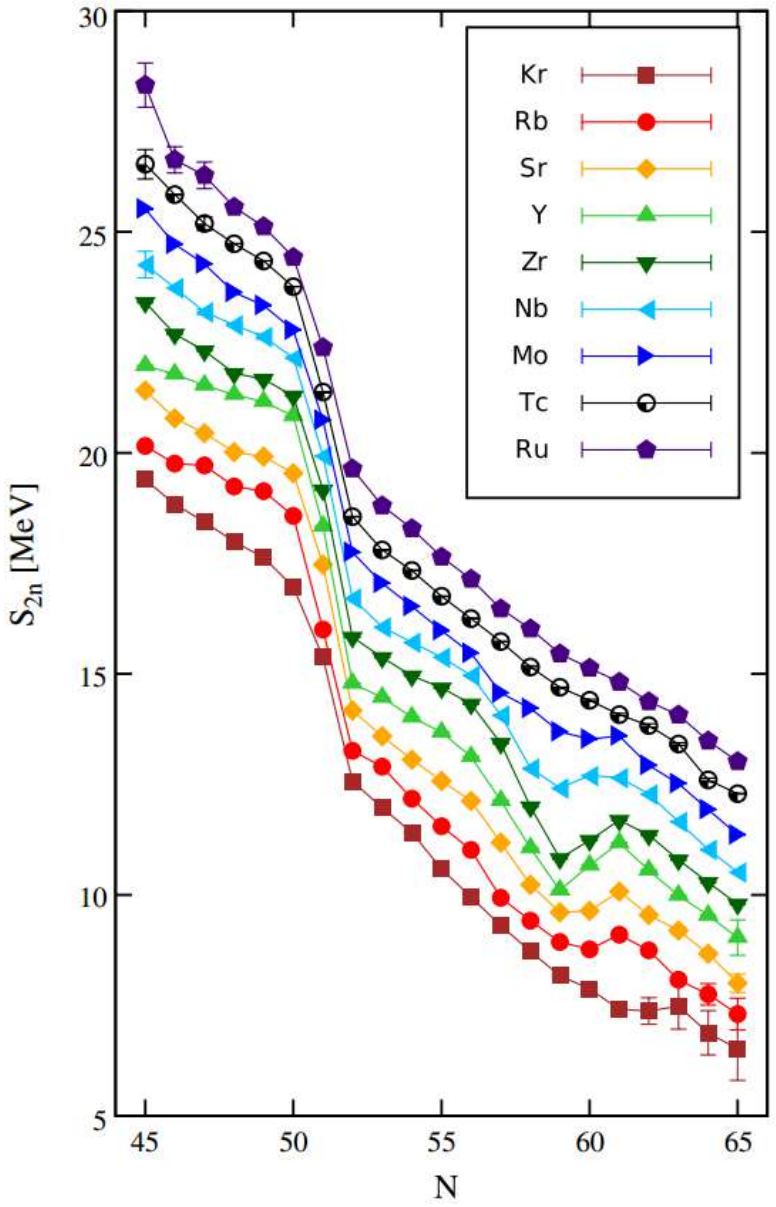




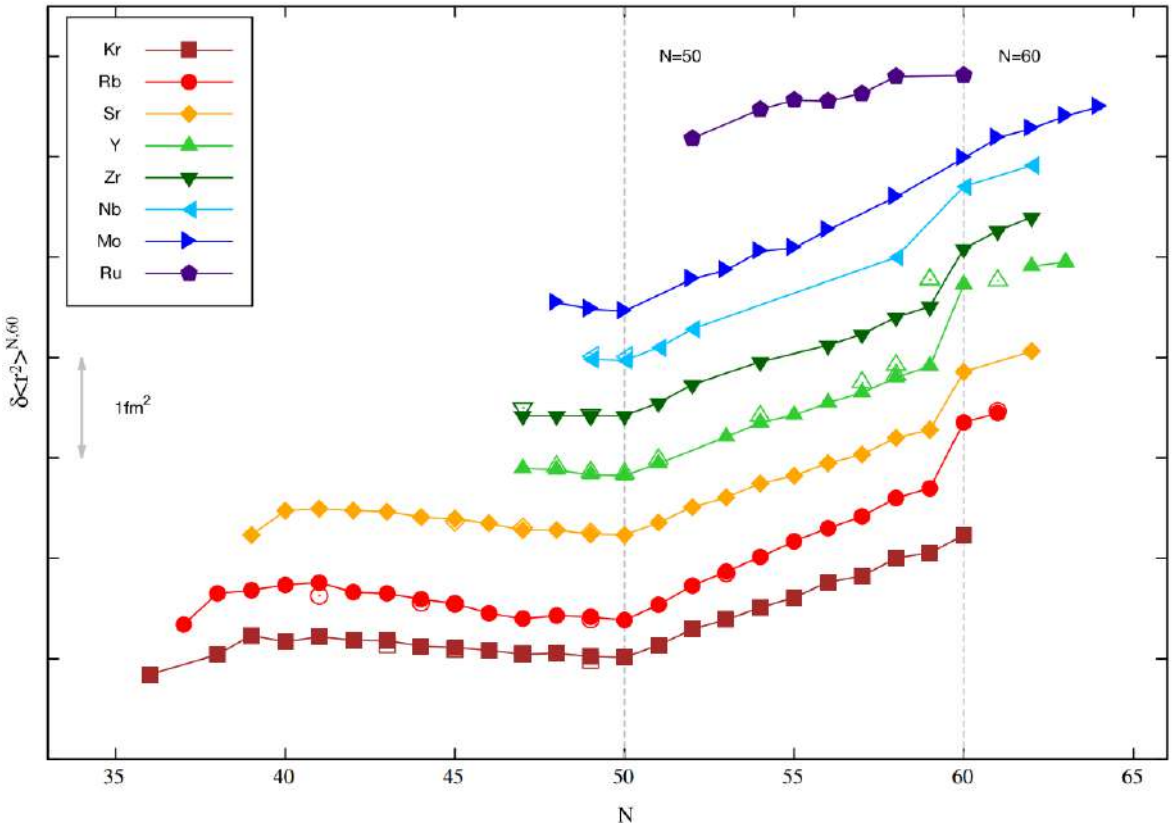
G. Tocabens *et al.* NIM A, 1064 (2024) 169345

The region around N = 60

P. Campbell et al., Prog. Part. Nucl. Phys. 86 (2016) 127

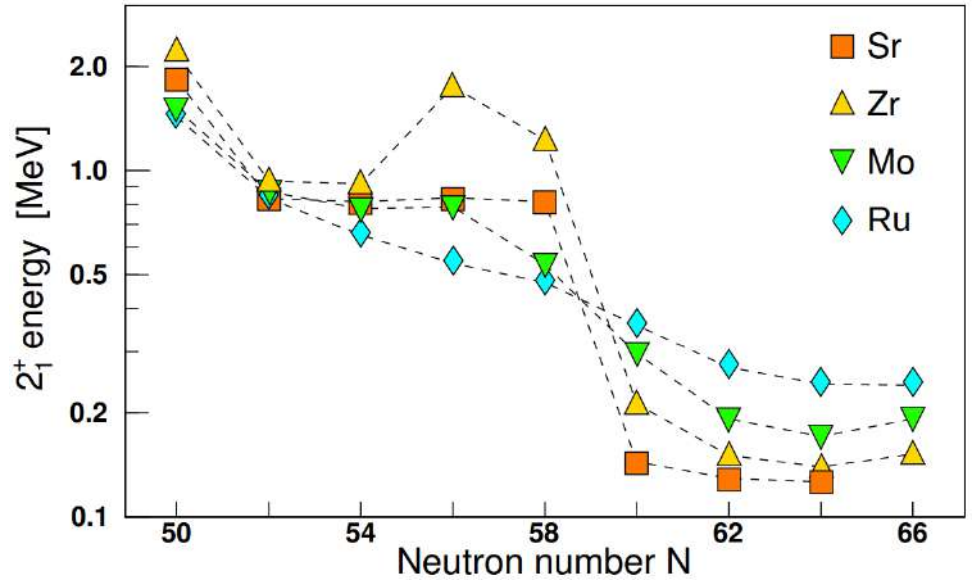


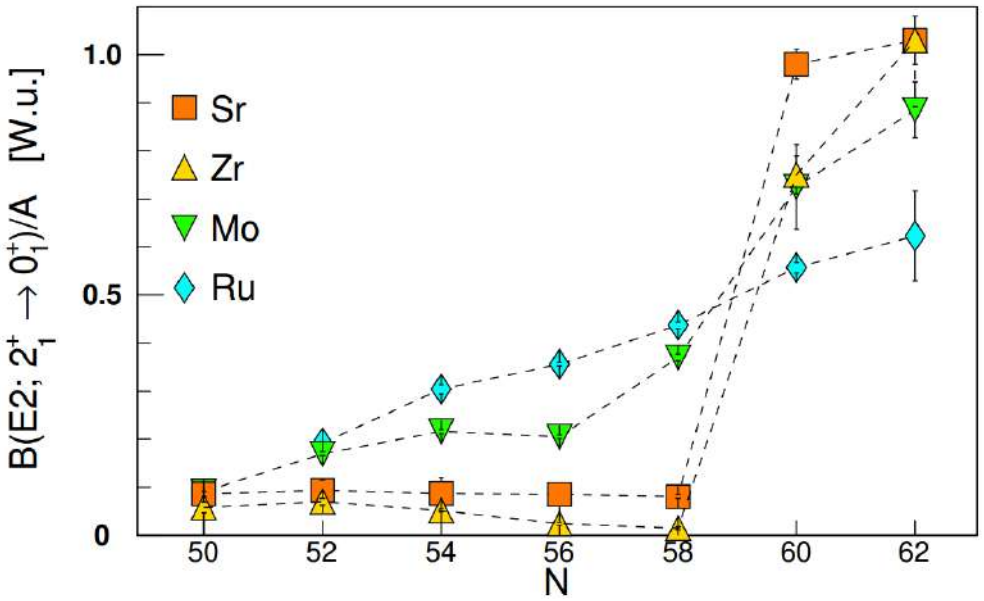
- Sharp increase in S_{2n} and $\langle r^2 \rangle$ interpreted as a change in the ground-state structure exactly at N = 60
- Considerable experimental and theoretical efforts



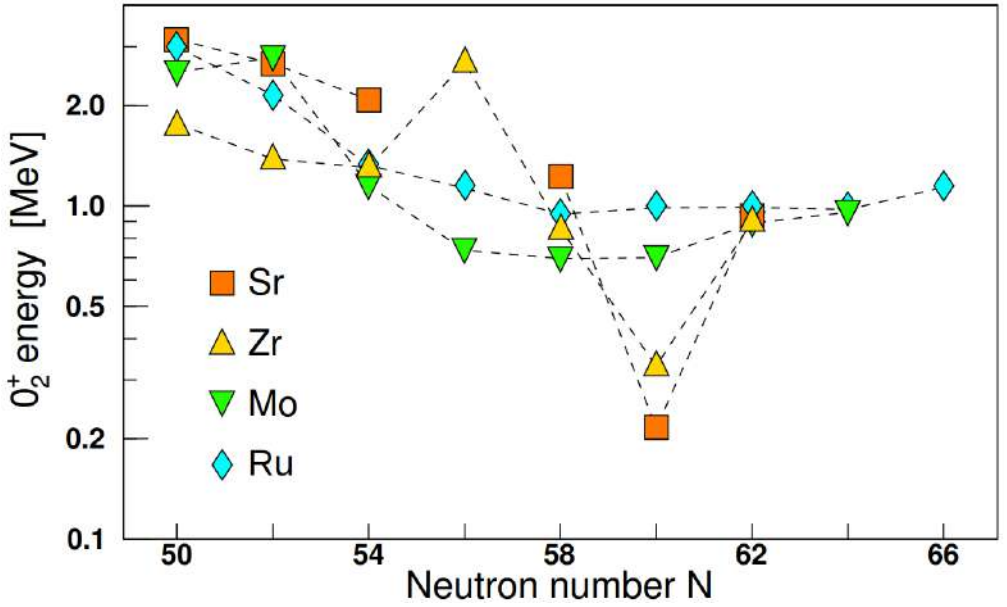
The N = 60 onset of deformation

P. E. Garrett et al., Phys. Rev. C 106, 064307 (2022)





- Sudden decrease (increase) in the 2_1^+ energy (B(E2; $2_1^+ \rightarrow 0_1^+$)) for Sr and Zr isotopes at N = 60
- Several low-lying 0_2^+ states observed in Sr, Zr, Mo and Ru isotopes



The N = 60 onset of deformation

P. Federman and S. Pittel,
Phys. Rev. C 20, 820 (1979)

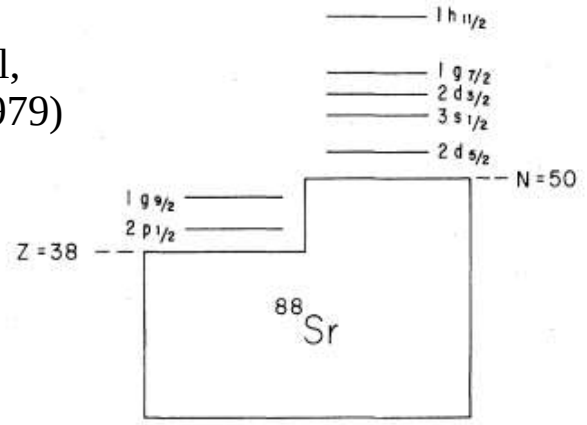
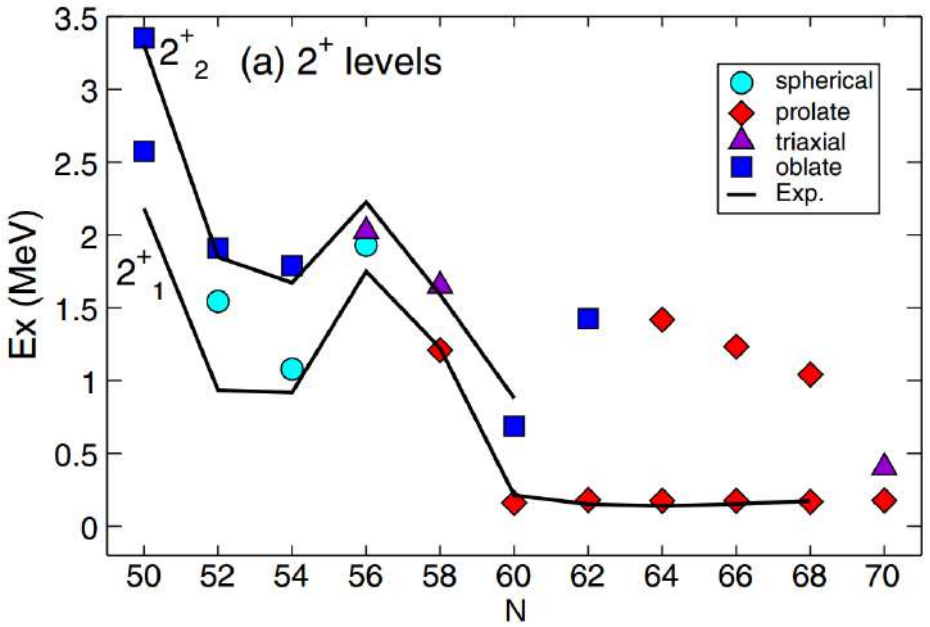
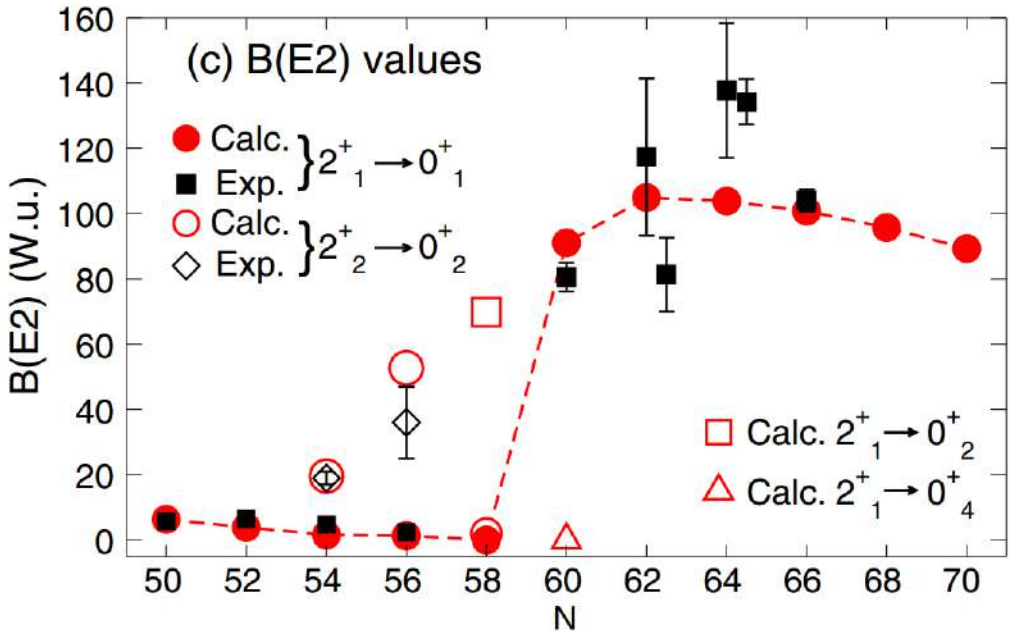


FIG. 3. Single-particle levels appropriate to a description of nuclei in the Zr-Mo region. An ^{88}Sr core is assumed.

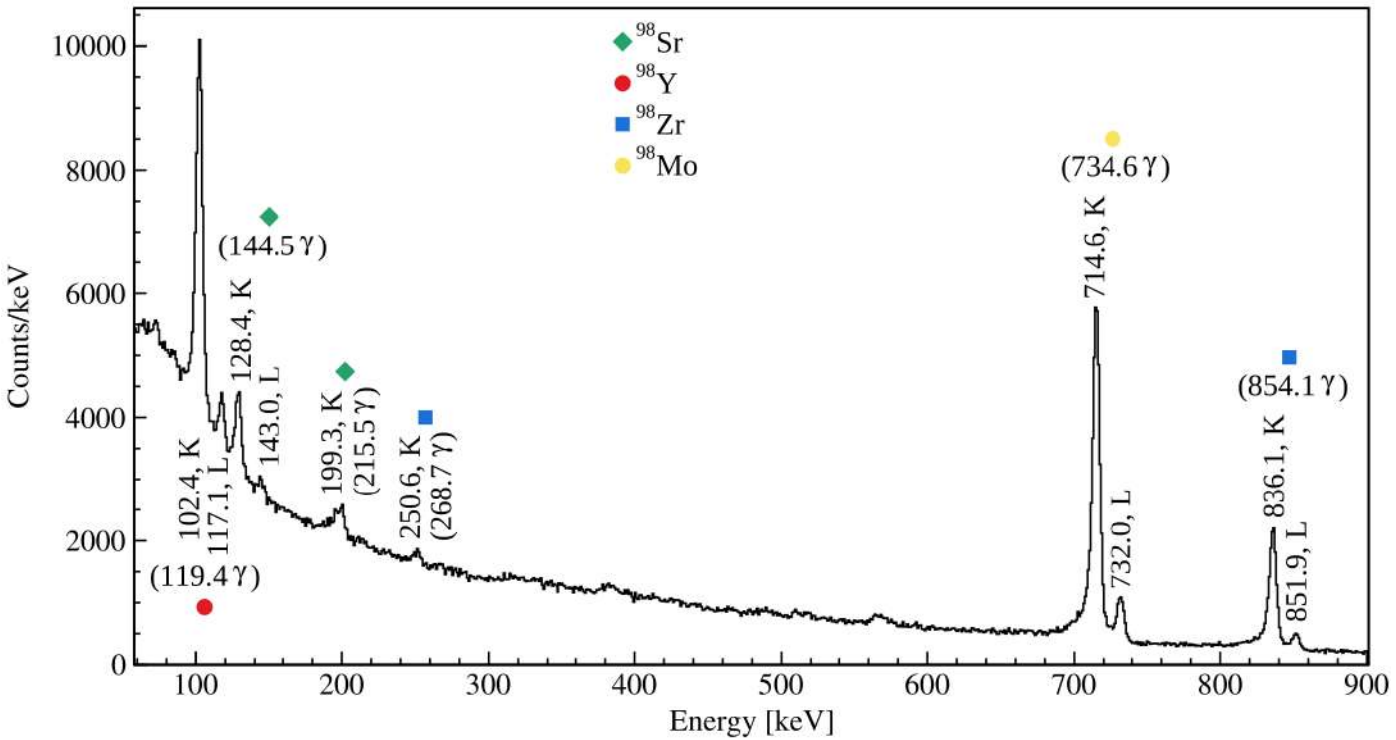
- Within shell-model, interplay between spin-orbit partners $\pi g_{9/2}$ and $\nu g_{7/2}$ explains the sudden inversion of configurations
- Monte-Carlo Shell-Model calculations reproduce the sudden deformation increase at N = 60

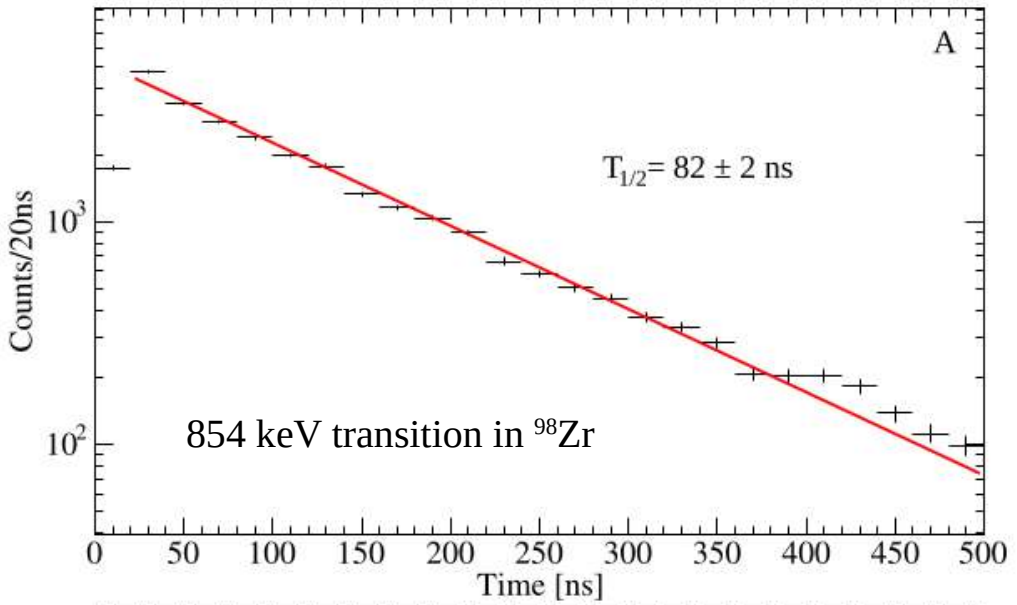


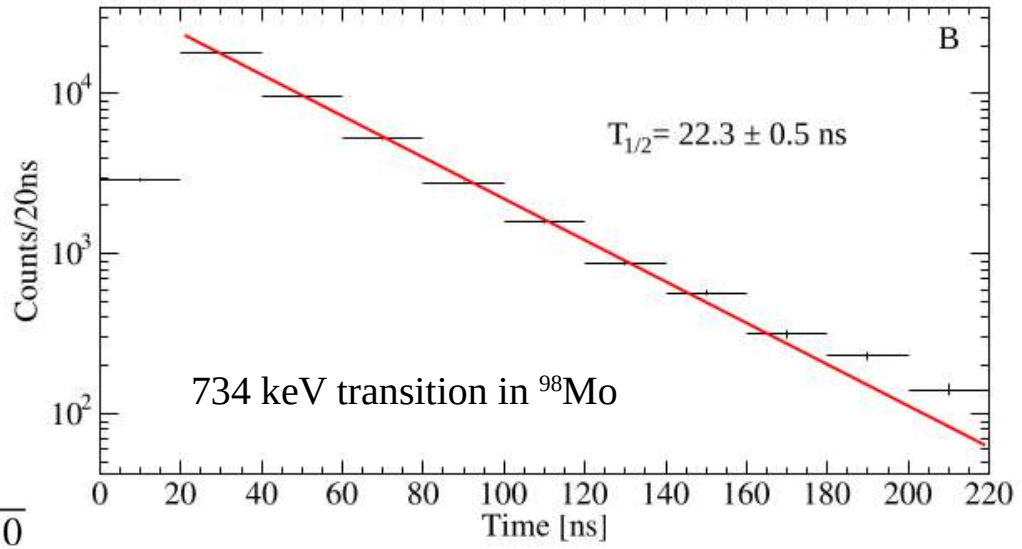


T. Togashi et al., Phys. Rev. Lett. 117, 172502 (2016)

^{98,100}Zr study through β-decay at ALTO



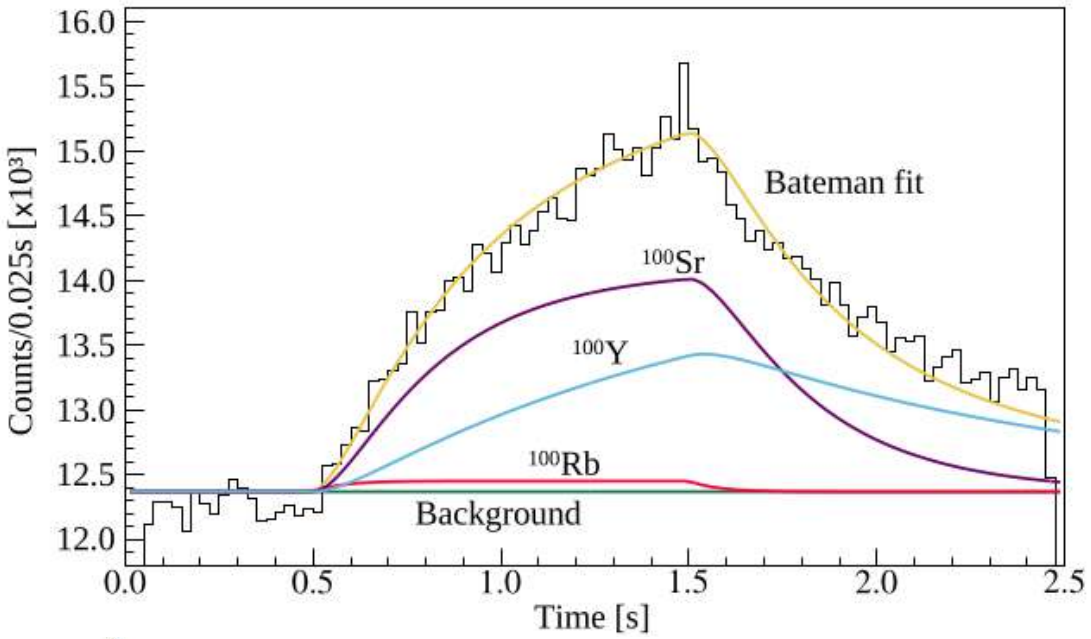


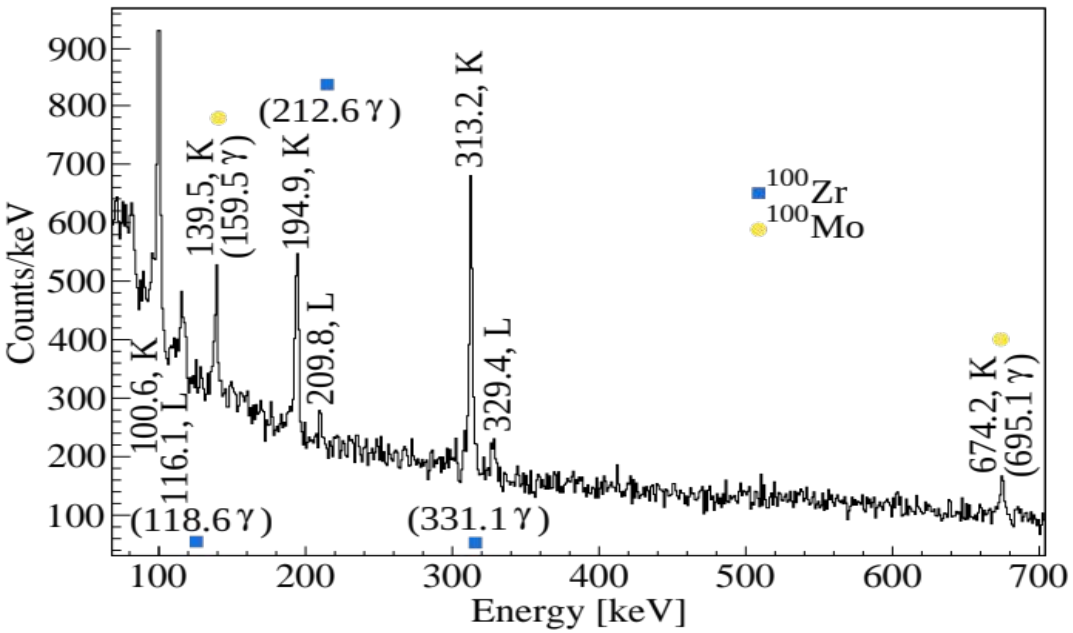


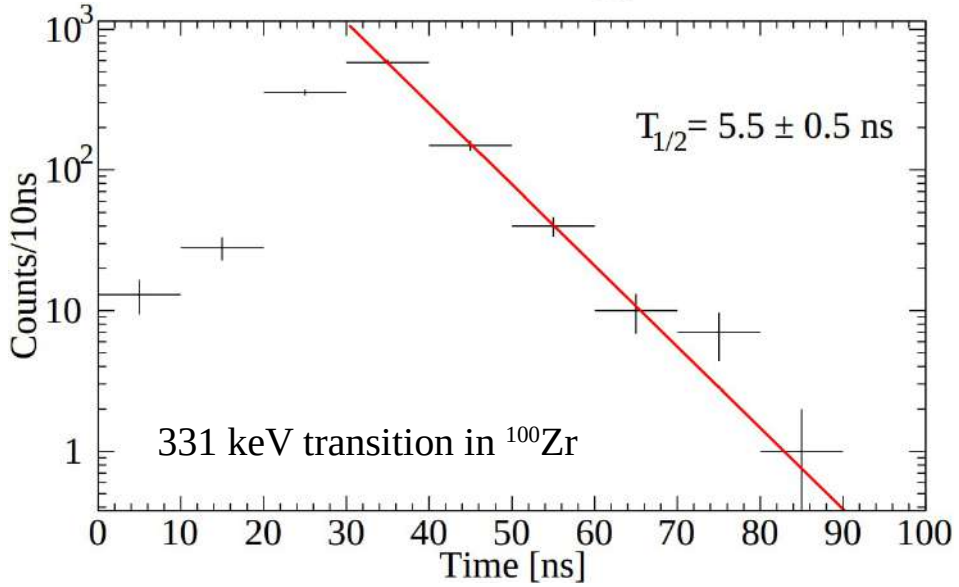
- Measurement done on a fixed tape (high activity of daughter)
- Intense E0 transitions from *long-lived* 0_2^+ state in Mo and Zr
- Delayed β-CE coincidences allowed to measure the half-life of both 0_2^+ states (much longer for Zr)
- New $\rho_0(0_2^+ \rightarrow 0_1^+)$ = 8.6(2) m.u. (lit. 11.1(12) m.u.)

$$\rho^2 = \frac{\ln(2)}{\Omega_{\text{tot}} T_{1/2}^{E0}}$$

^{98,100}Zr study through β-decay at ALTO







- Same work was done at mass 100 for 0_2^+ in ^{100}Zr
- Half-life in good agreement with literature value
- This time, branching ratio is needed to compute transition strength ρ_0
- New $\rho_0(0_2^+ \rightarrow 0_1^+)$ = 70(16) m.u. (lit. 102(5) m.u.)

Shape transition at N = 60

- Both new ρ_0 values where interpreted using a simple two-states mixing model with axially deformed configurations

$$|0_f^+\rangle = \cos\theta|A\rangle + \sin\theta|B\rangle,$$

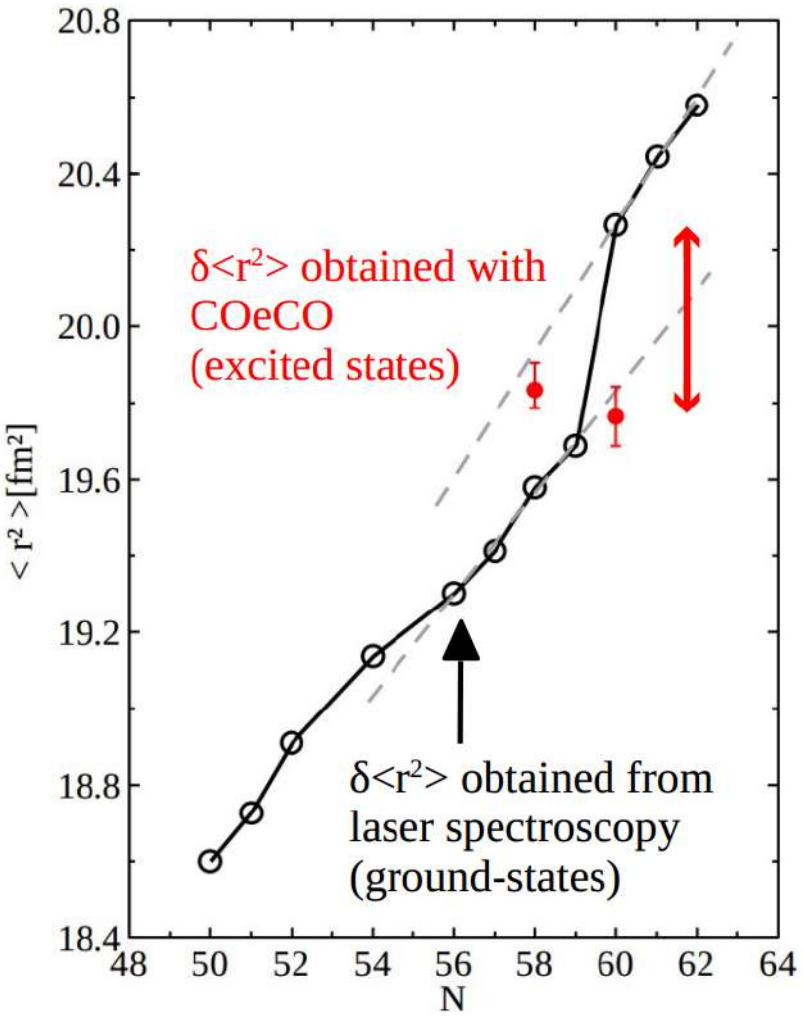
$$|0_i^+\rangle = -\sin\theta|A\rangle + \cos\theta|B\rangle$$

- In such a model, transition strength can be linked to the change in mean-square charged radius between the states

$$\rho^2 = \langle 0_f^+|\hat{T}(E0)|0_i^+\rangle$$

$$\rho^2 = \frac{Z^2}{R_0^4}\cos^2\theta\sin^2\theta[\Delta\langle r^2\rangle]^2$$

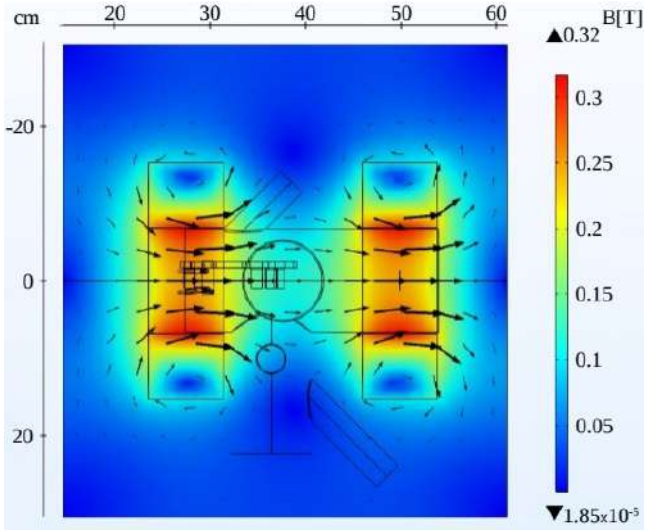
- Mixing angle θ was taken from the work of D. Kalaydjieva, obtained through an extensive β-decay study performed at TRIUMF with the GRIFFIN spectrometer



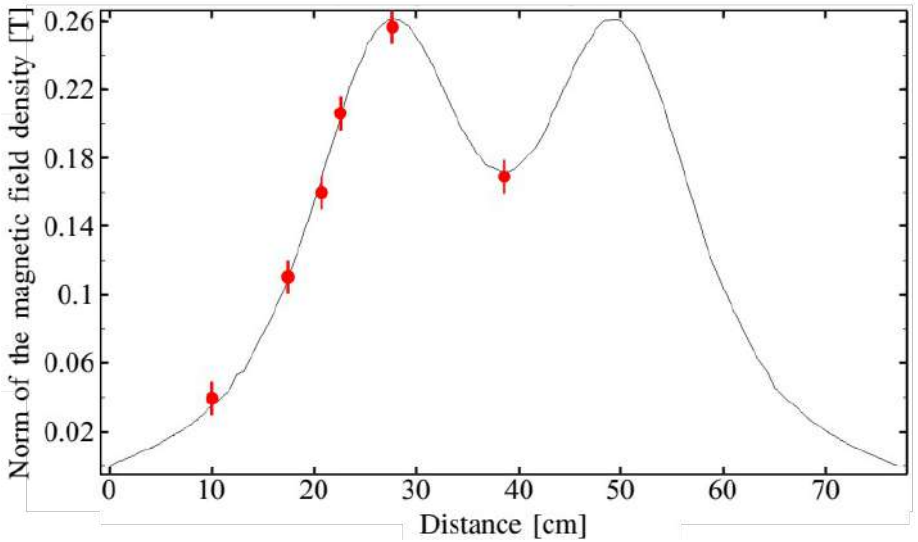
Conclusions

- Continuation of research program on structure above the neutron emission threshold
  - Two main results paving the way (P_n staggering in Ga, high-energy γ in ^{83}Ge, 2017)
  - Impact of shell-structure on β-decay shown from ^{80}Ga $\rightarrow$ ^{80}Ge (PARIS campaign)
  - New method for neutron mean energy measurements with TETRA
  - MONSTER experiment calls for more ambitious program at DESIR once FP are available
- Shape coexistence studied using conversion electron spectroscopy
  - New decay station dedicated to CE spectroscopy operationnal at ALTO
  - Two new values of $\rho_0(0^+ \rightarrow 0^+)$ in both ^{98}Zr and ^{100}Zr where found
  - Simple two-states mixing model seems to capture the shape transition at N = 60
  - This study calls for complementary work in the region, both experimentally and theoretically

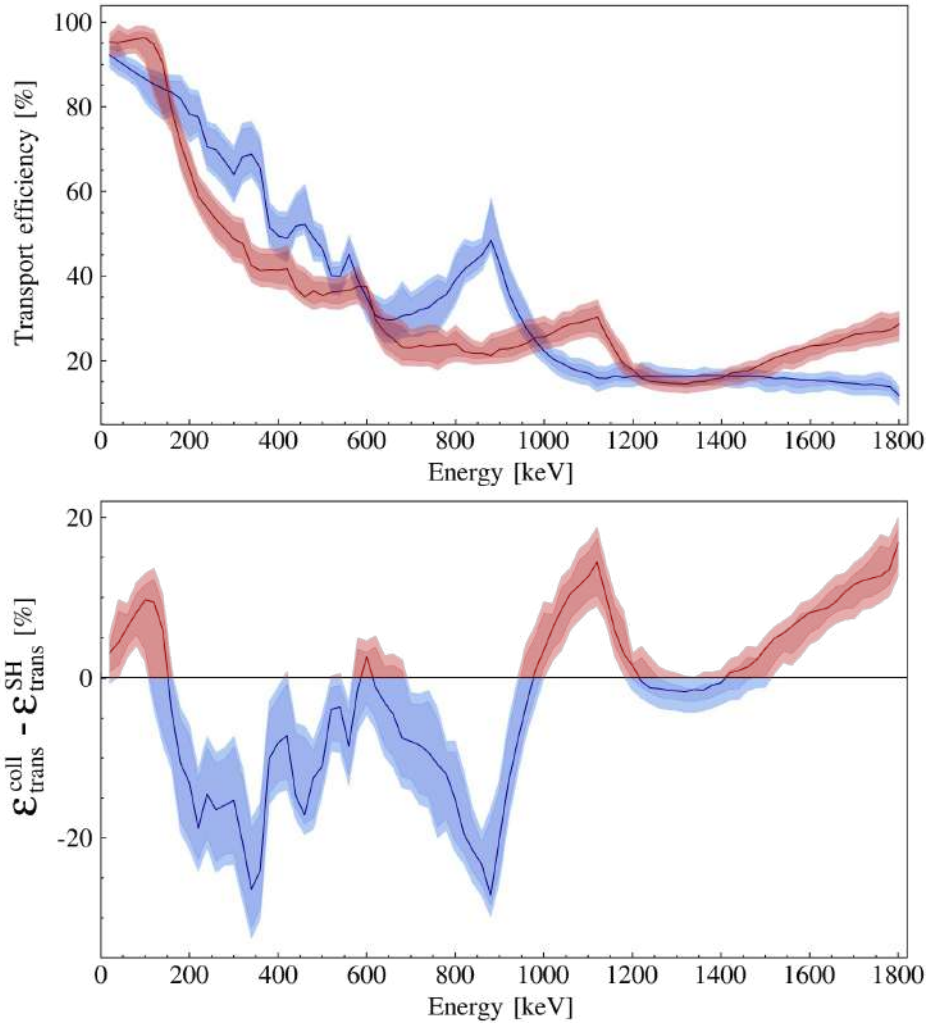
Simulations



Magnetic field

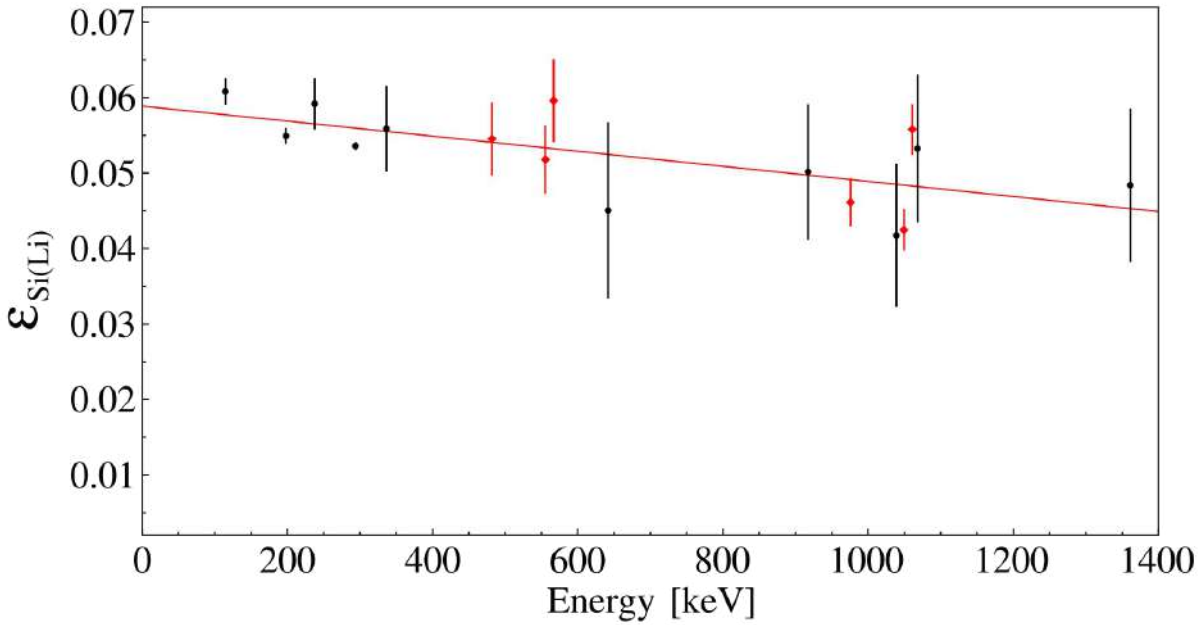


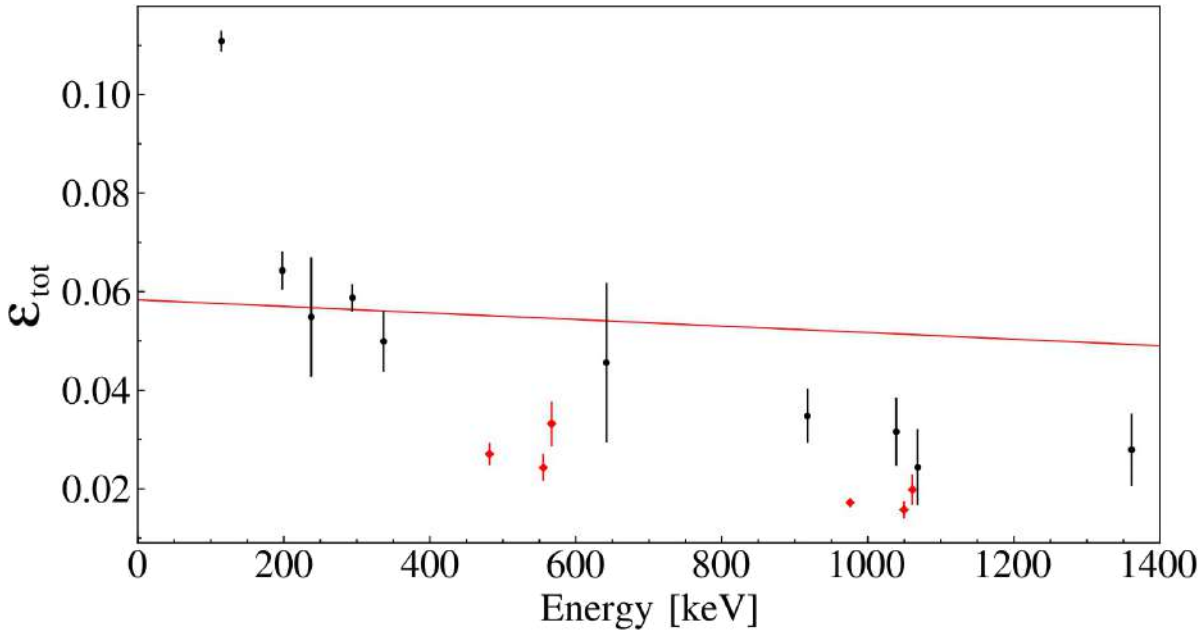
Magnetic field measurements along coil axis

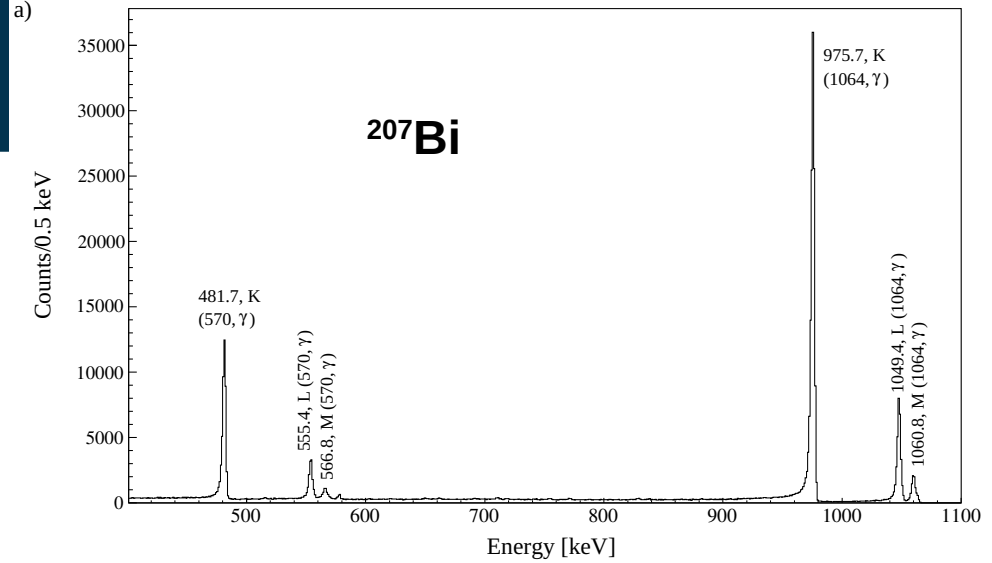


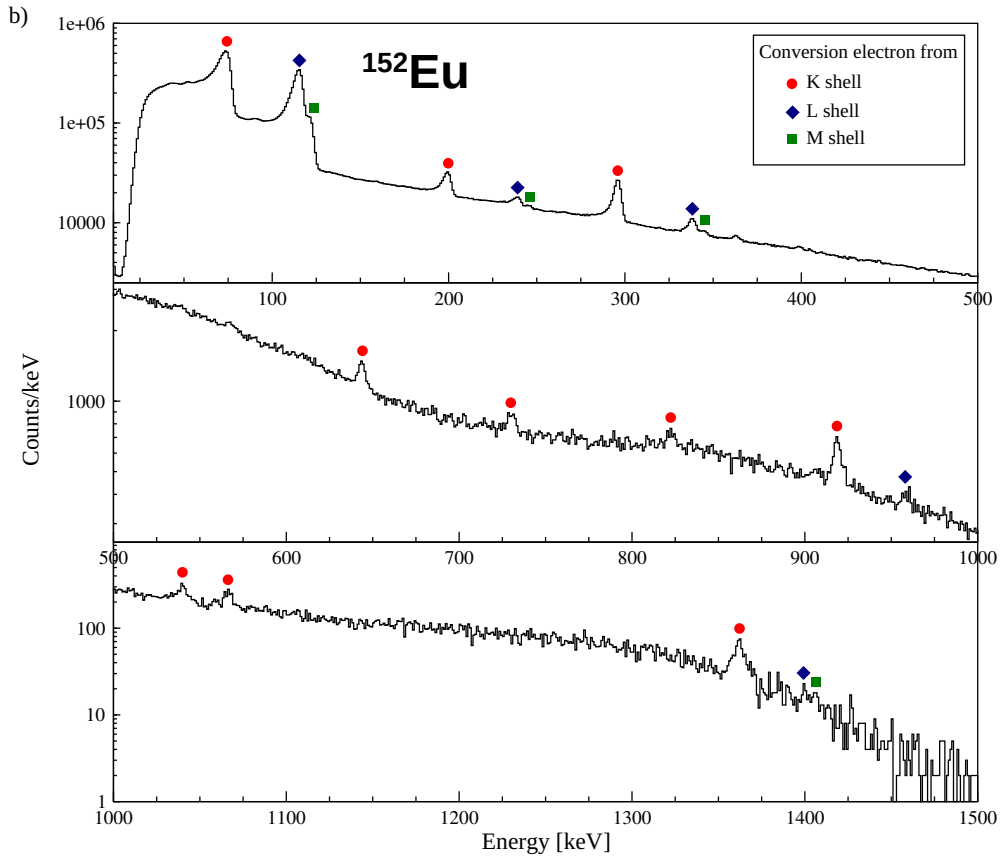
Transportation, at collection point (red) and at source holder point (blue)

COeCO efficiencies

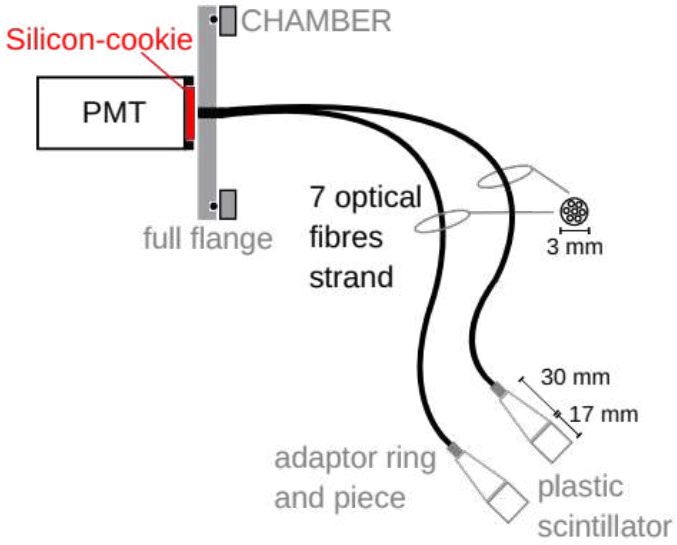


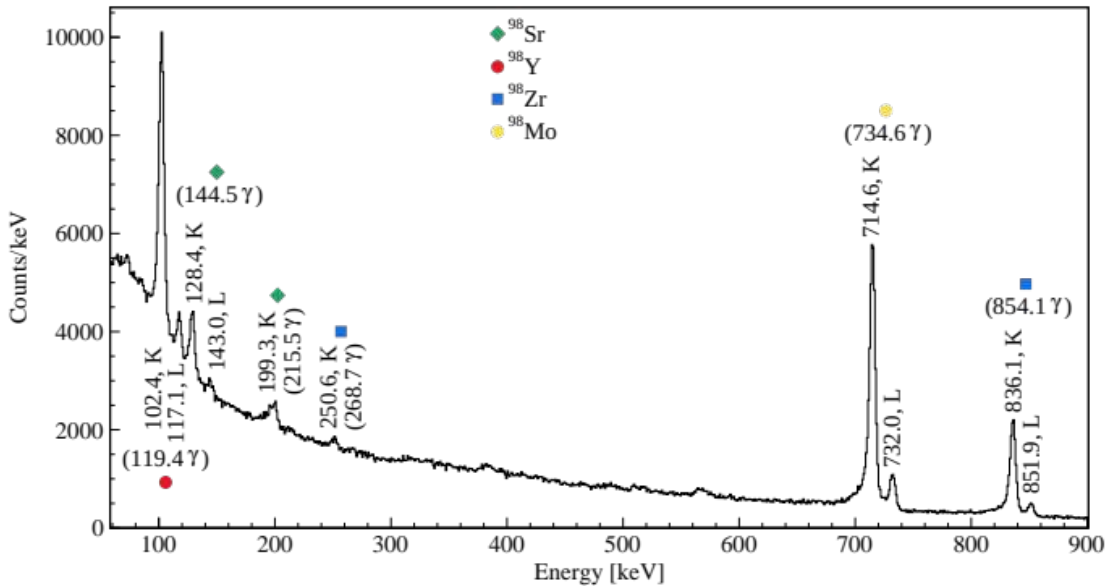


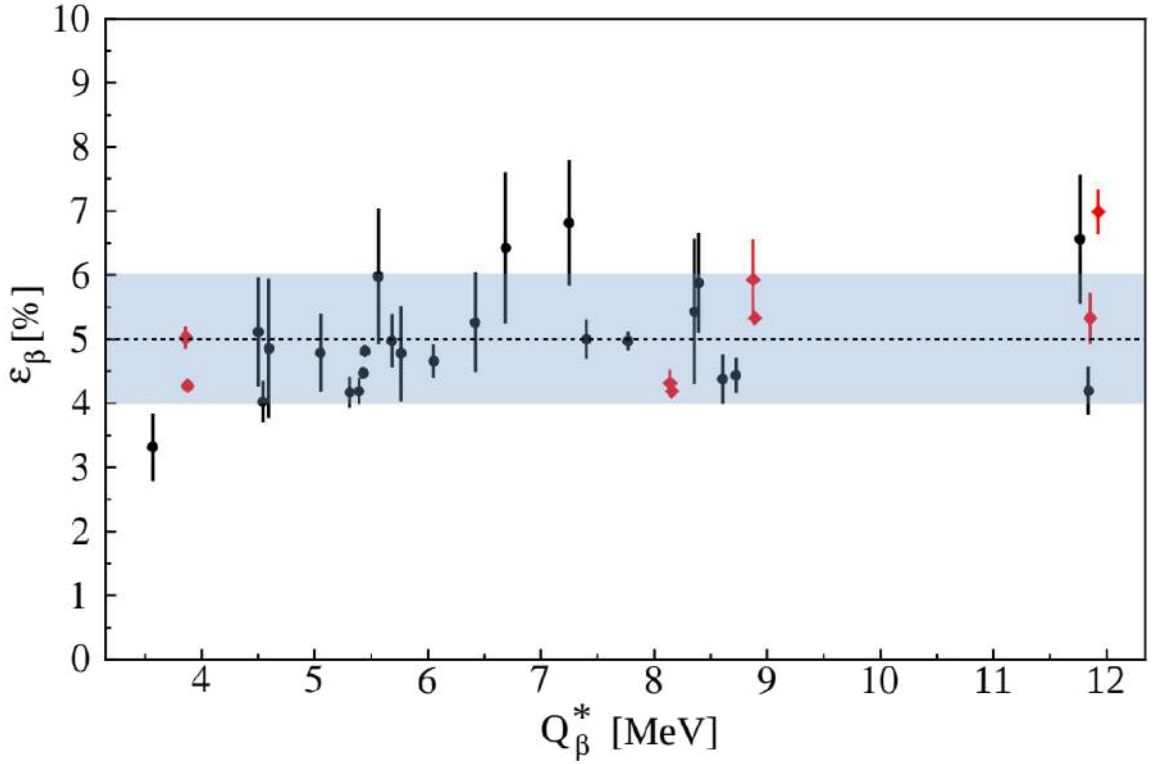




Plastic scintillator

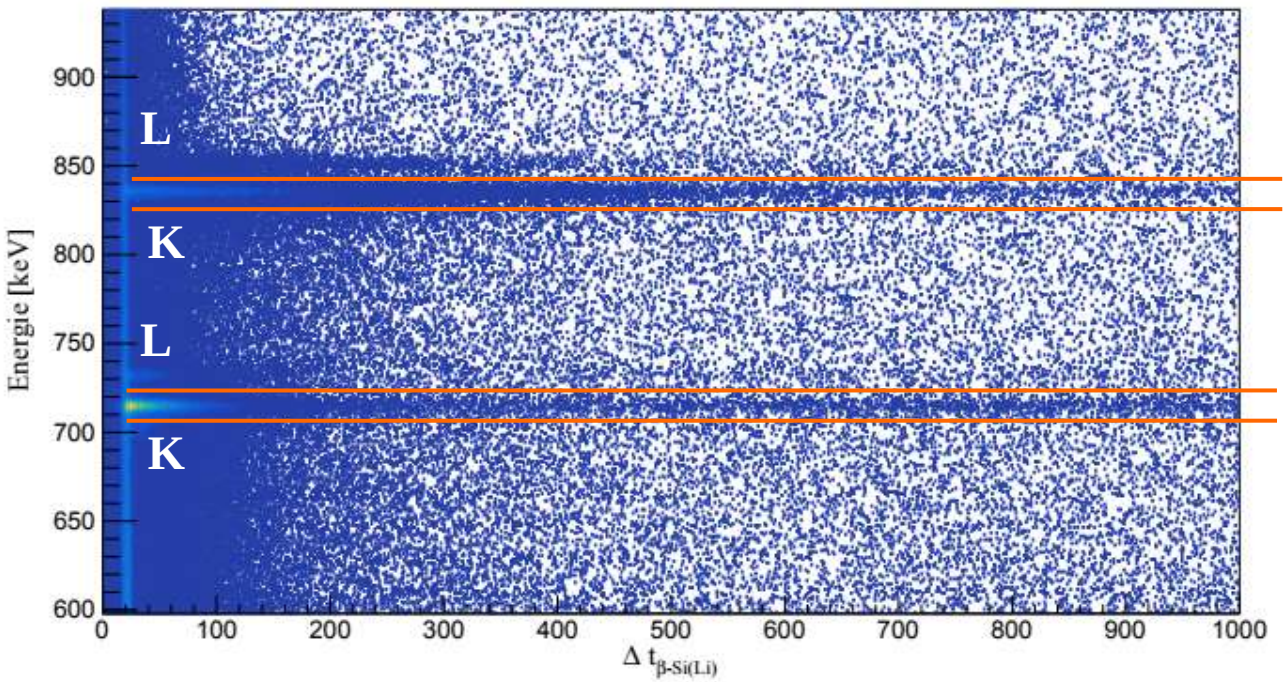


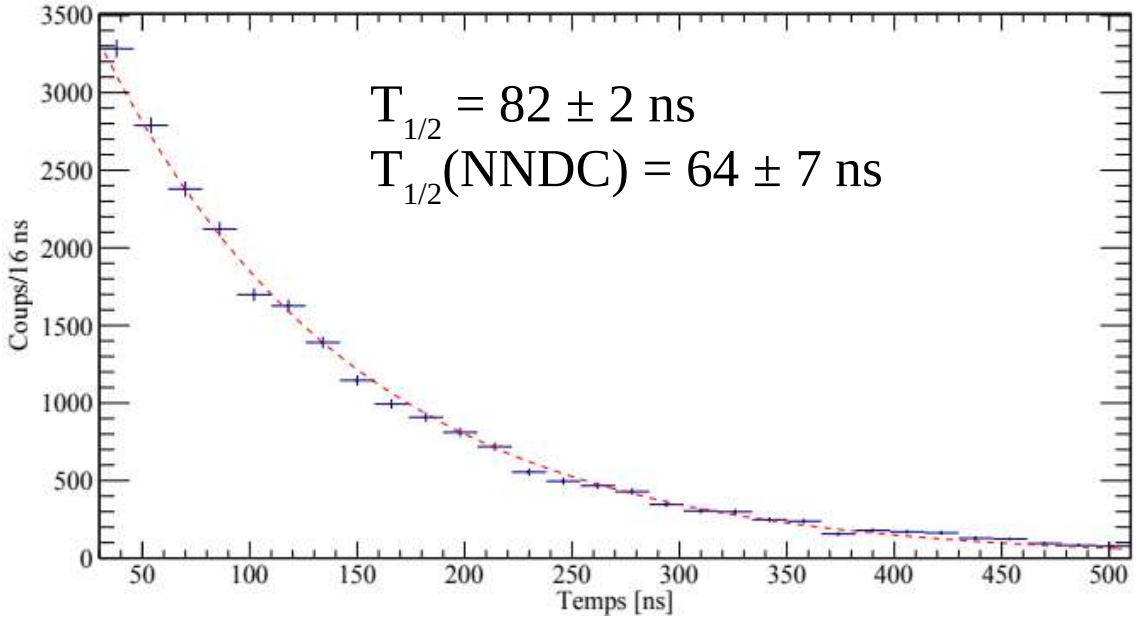


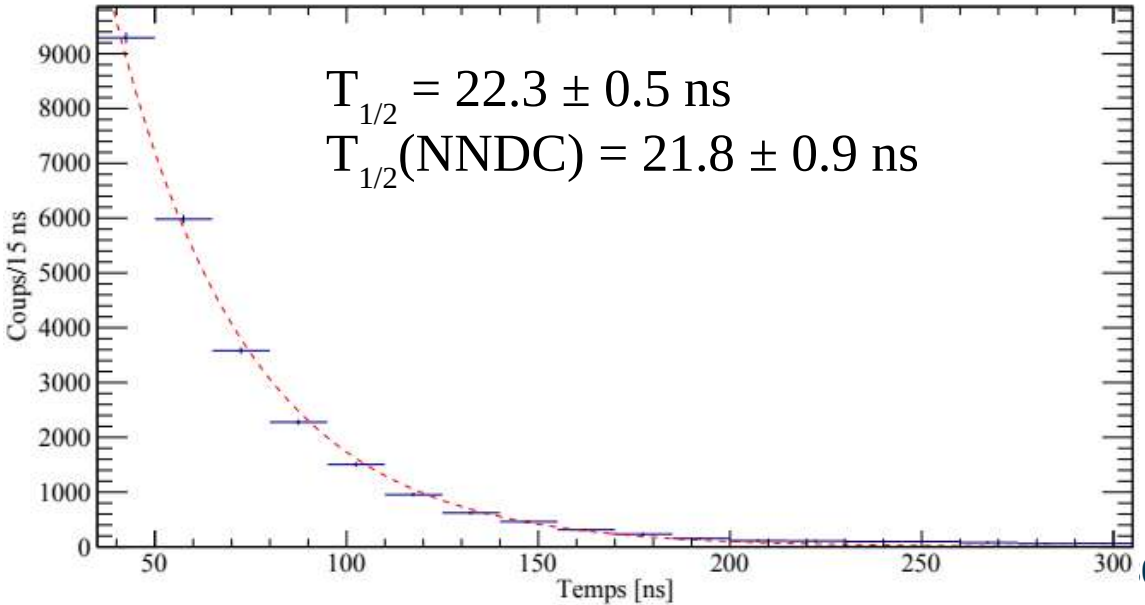


Efficiency measured with a ^{98}Rb source

$T_{1/2}$ measurements



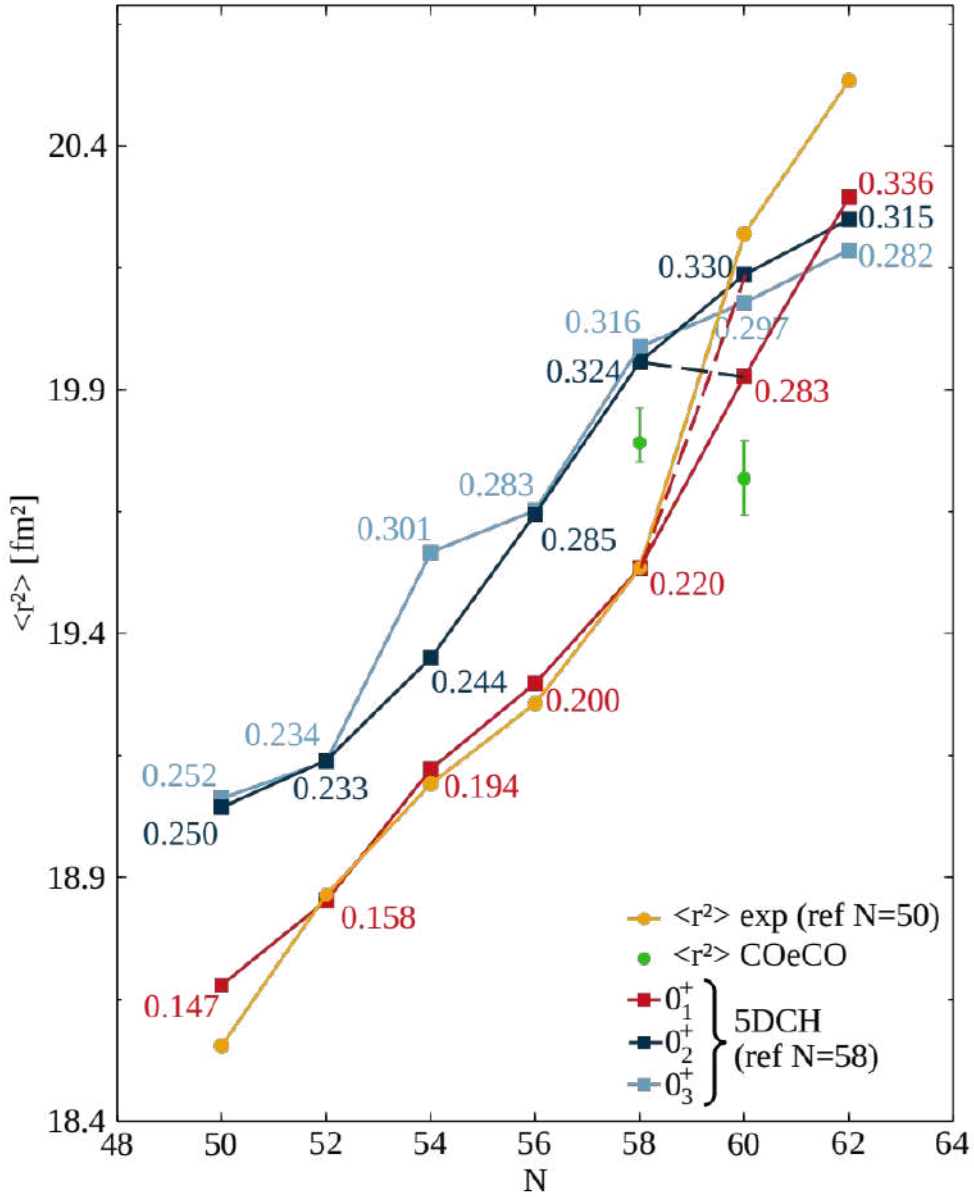




- Projection on the time difference between an event detected in the plastic scintillator and an event in the Si(Li) detector
- Max of the prompt peak is found and the decay is fitted to get $T_{1/2}$

Shape transition at N = 60

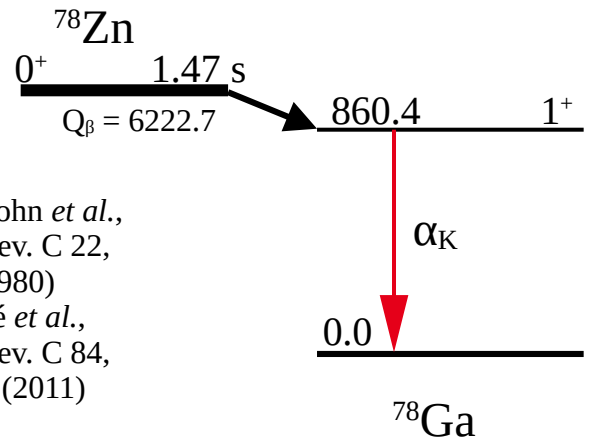
- Beyond mean-field calculations (5DCH on HFB constrained surface, with Gogny D1M interaction)
- Normalization at N = 58 to see the transition
- Inversion at N = 62 if we follow the given ordering, but states are close in energy (~800 keV, uncertainty on calculations is ~1 MeV)
- Good reproduction of the tendency, except for deformation (ground-states are ~spherical or weakly deformed, rather good for excited states)
- Beyond N = 60, radii and deformation are way off and everything looks the same



Proposal for COeCO

Intruder states and shape coexistence in the ^{78}Ni region

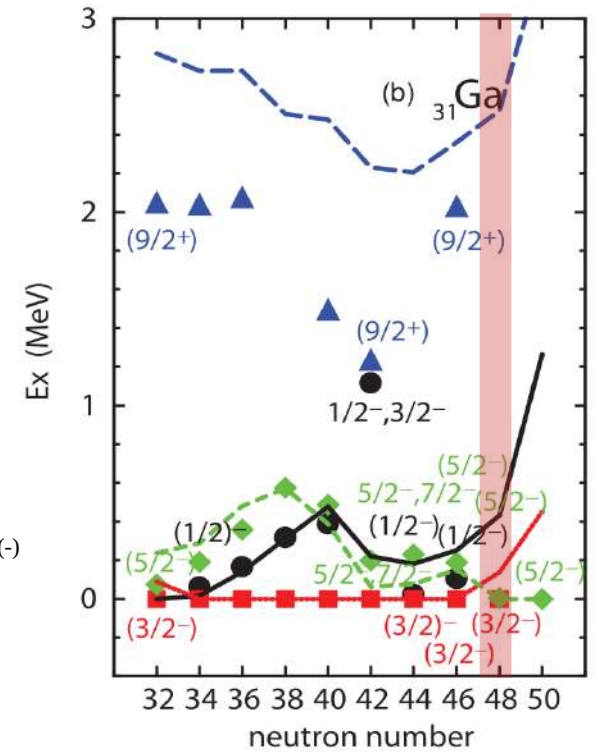
- Several hints for possible shape coexistence in the region
  - Low-energy 0^+ state (^{80}Ge, debatted), Phys. Rev . Lett. 116, 182501 (2016)
  - Low-spin, negative parity states (^{82}As), Phys. Rev. C 91, 064317 (2015)
  - High $\delta\langle r^2\rangle$ between isomeric and ground state (^{79}Zn), Phys. Rev . Lett. 116, 182502 (2016)
- Determination of spins and parities by conversion electron spectroscopy with COeCO
  - Ground state and excited states (ex : ^{78}Ga)
  - Extend comparison with theory (^{79}Ga)



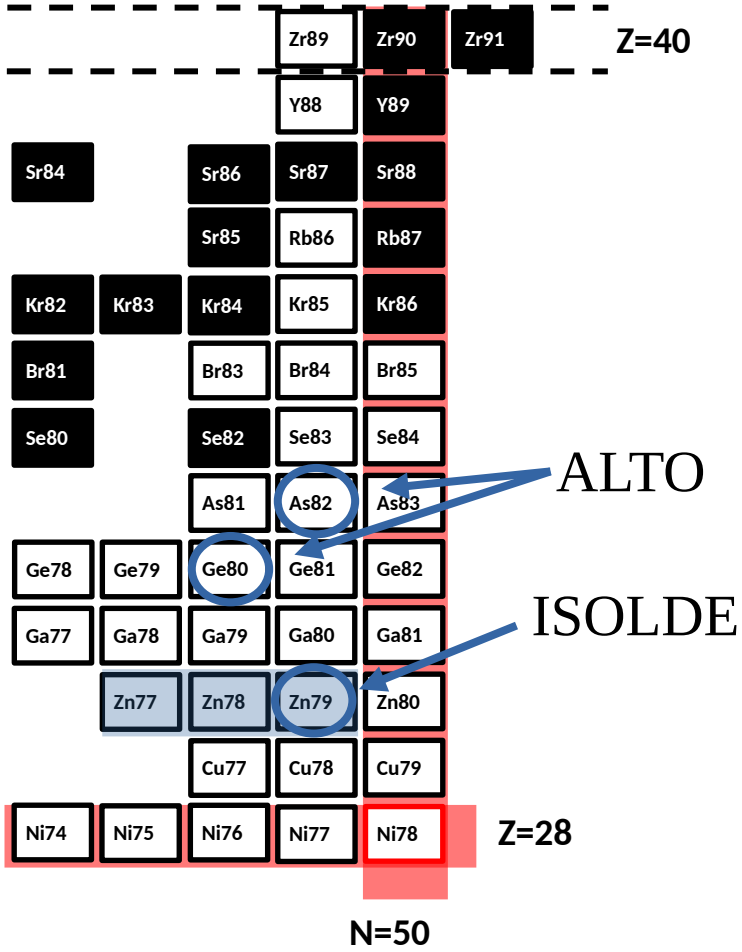
F. K. Wohn *et al.*, Phys. Rev. C 22, 2547 (1980)
E. Mané *et al.*, Phys. Rev. C 84, 024303 (2011)

β-decay : (3^+)

Laser-spectro : $2^{(-)}$



M. Honma et al., Phys. Rev. C 80, 064323 (2009)



Spokesperson : G. Tocabens