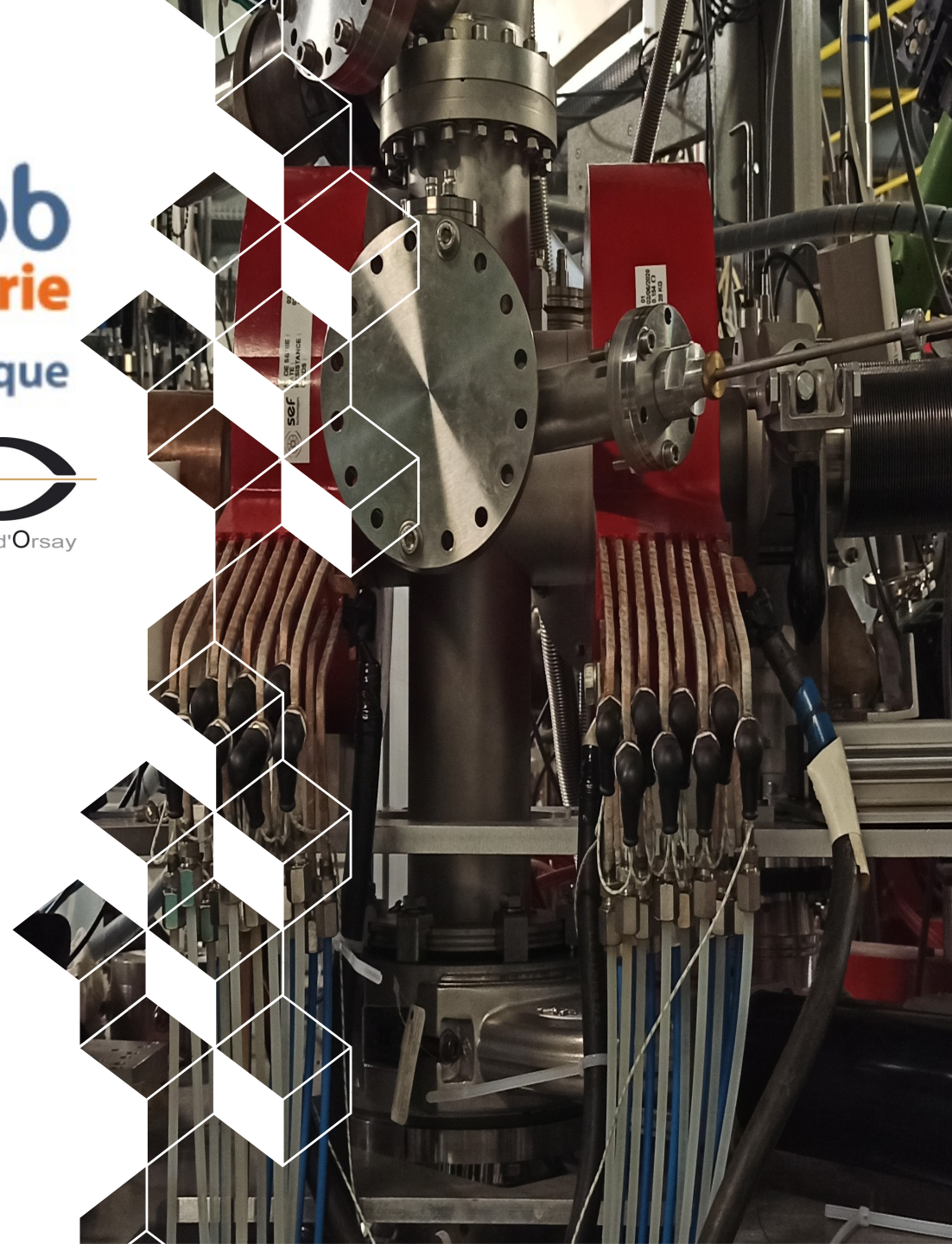




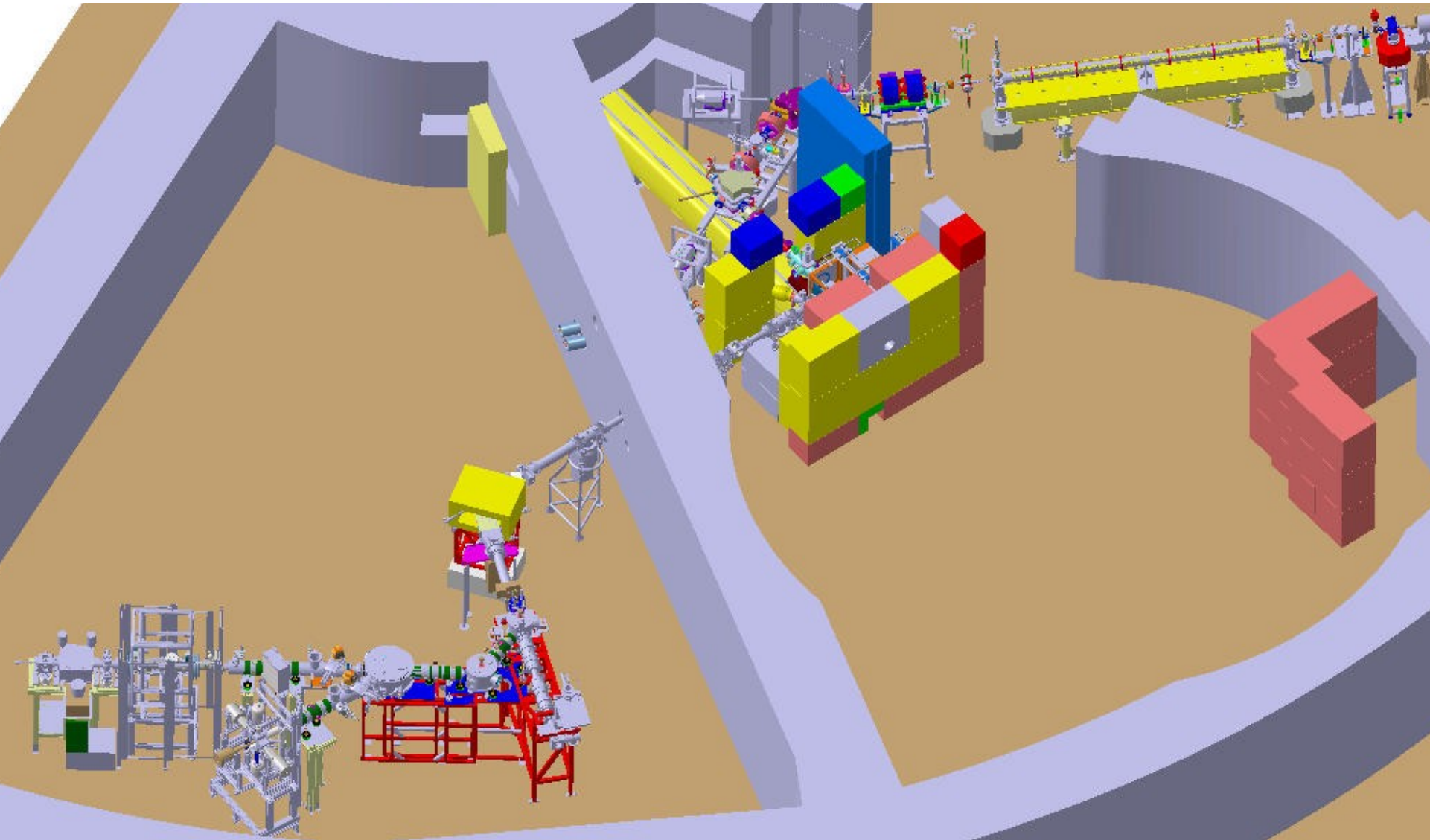
irfu



Investigating shape transition in neutron-rich nuclei through conversion electron spectroscopy at ALTO



# ALTO radioactive beams



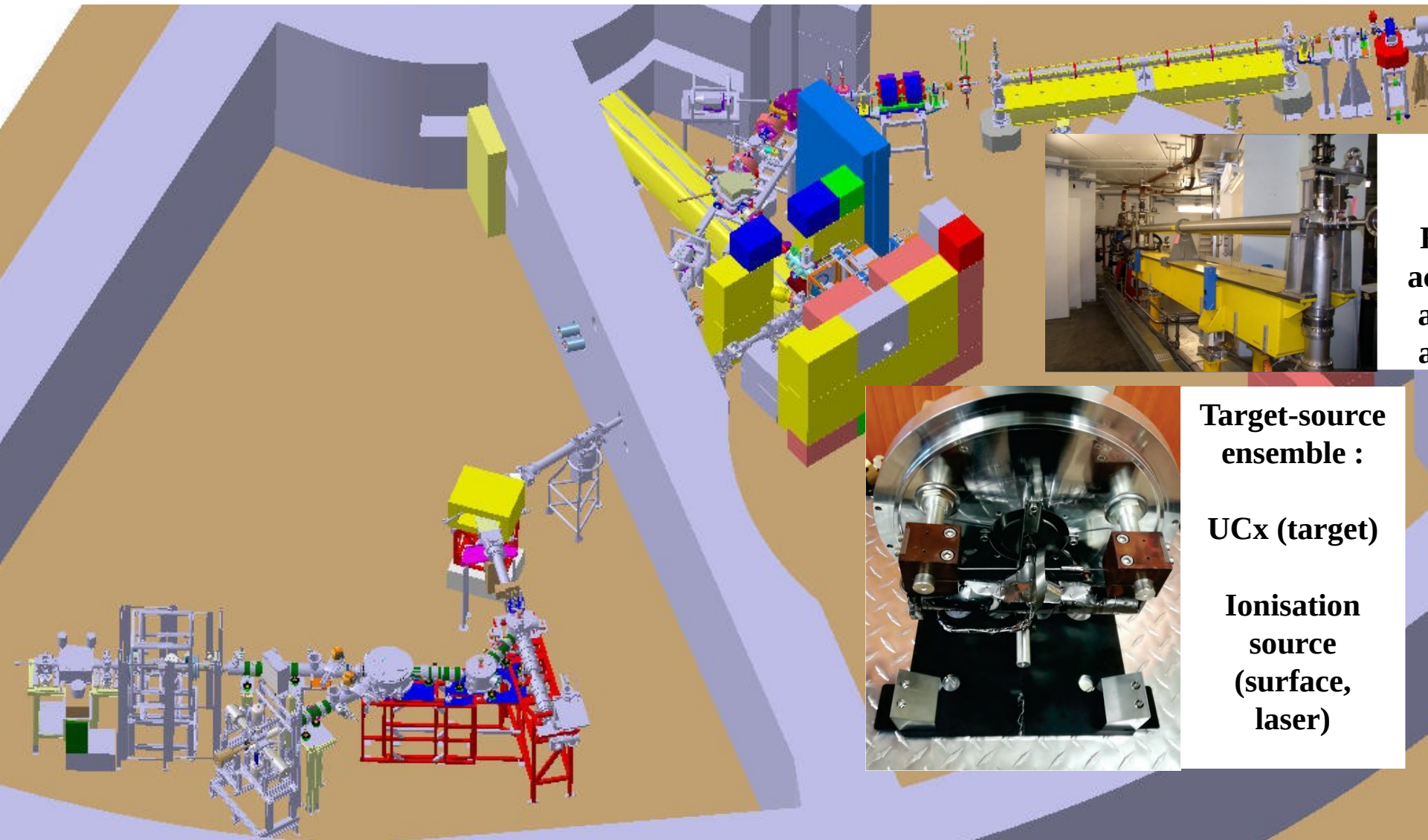
# ALTO radioactive beams



**LINAC**

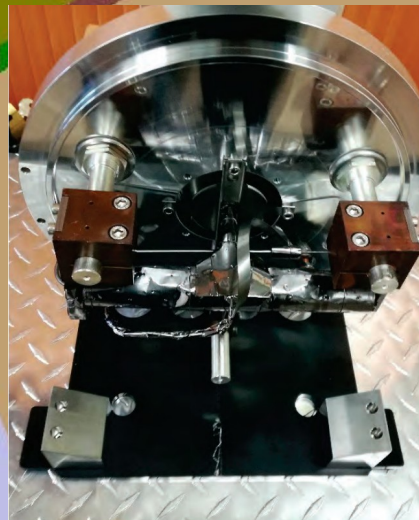
**Electrons  
accelerated  
at 50MeV  
and 10 $\mu$ A**

# ALTO radioactive beams



**LINAC**

**Electrons  
accelerated  
at 50MeV  
and 10 $\mu$ A**

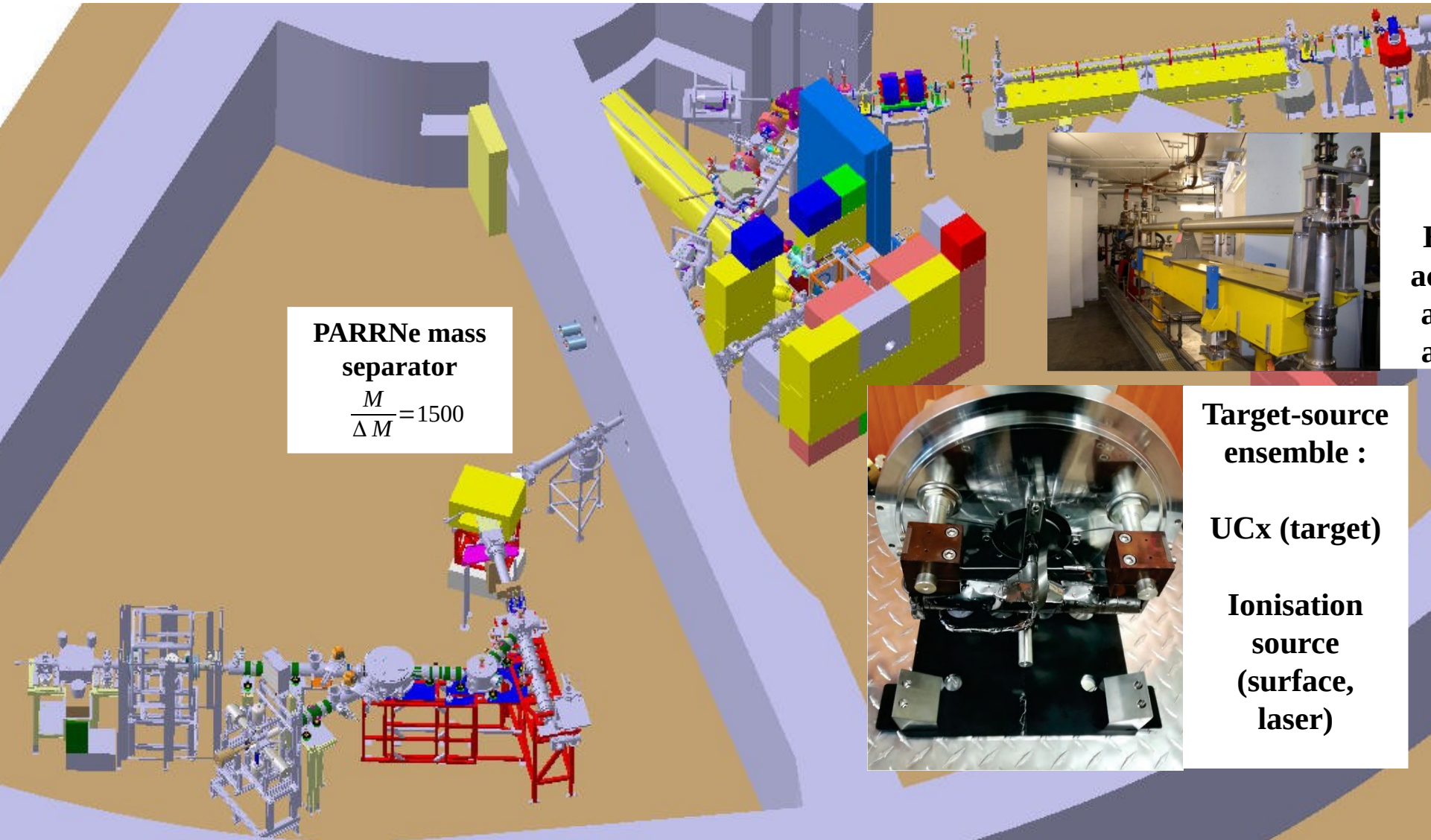


**Target-source  
ensemble :**

**UCx (target)**

**Ionisation  
source  
(surface,  
laser)**

# ALTO radioactive beams



**PARRNe mass separator**  
 $\frac{M}{\Delta M} = 1500$

**LINAC**

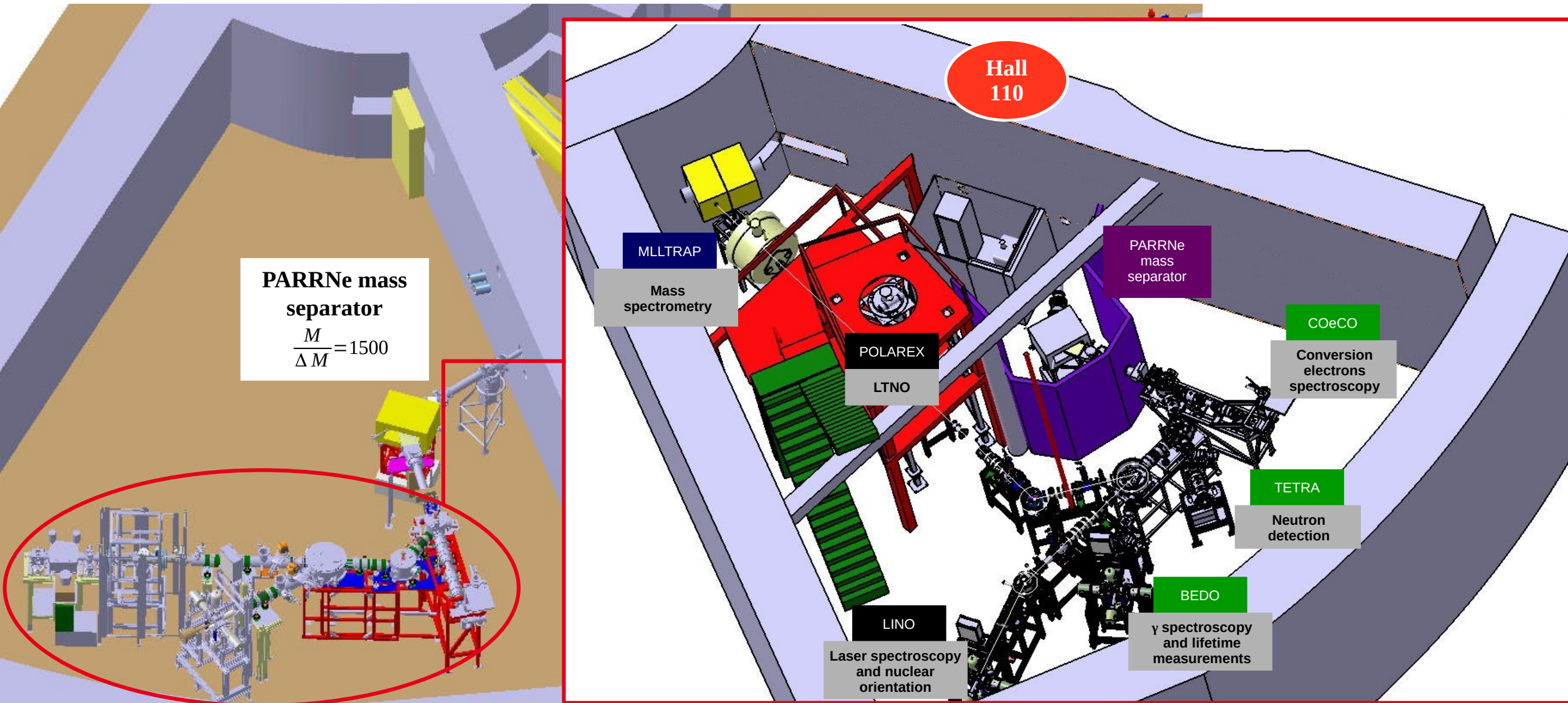
**Electrons accelerated at 50MeV and 10 $\mu$ A**

**Target-source ensemble :**

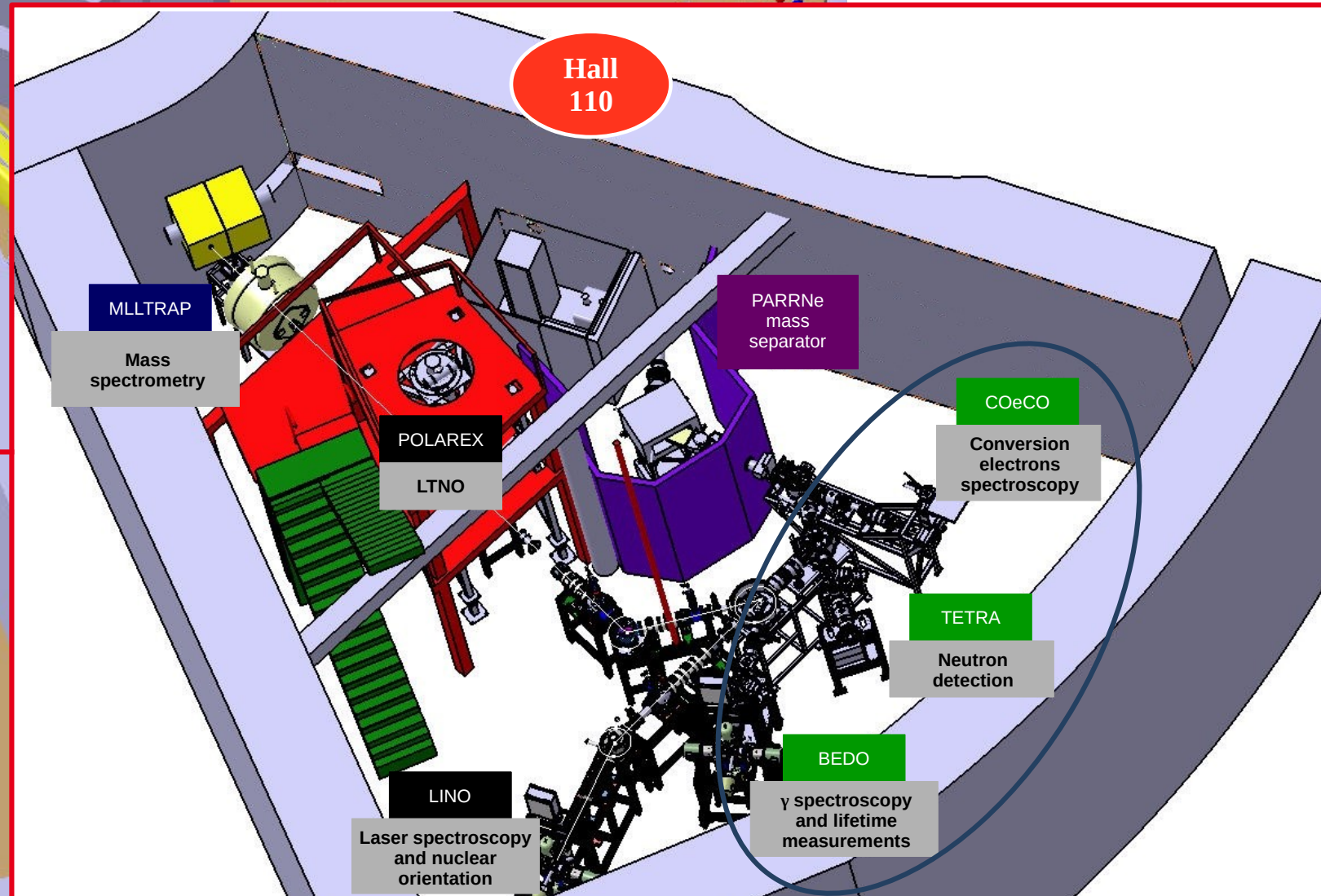
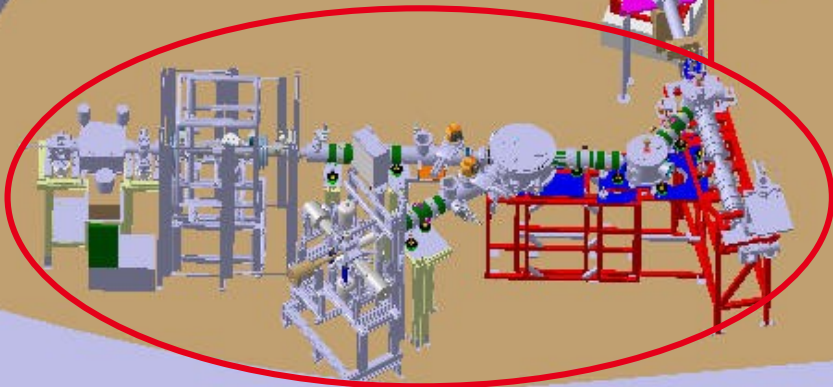
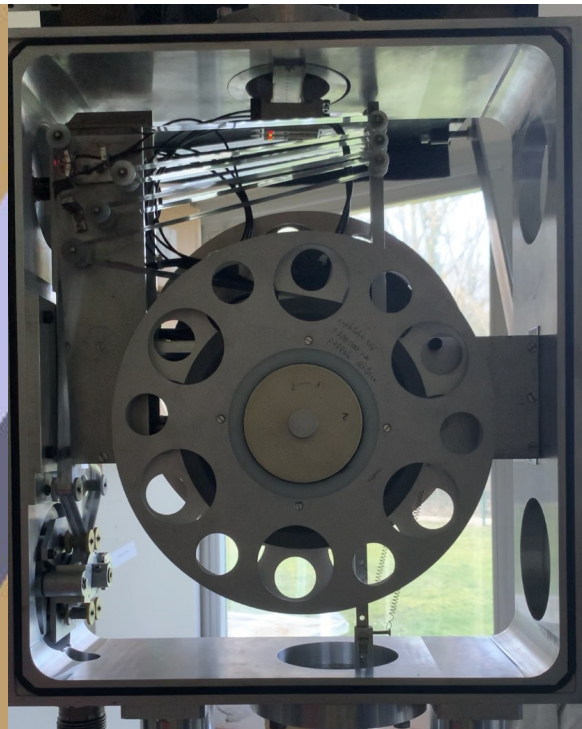
**UCx (target)**

**Ionisation source (surface, laser)**

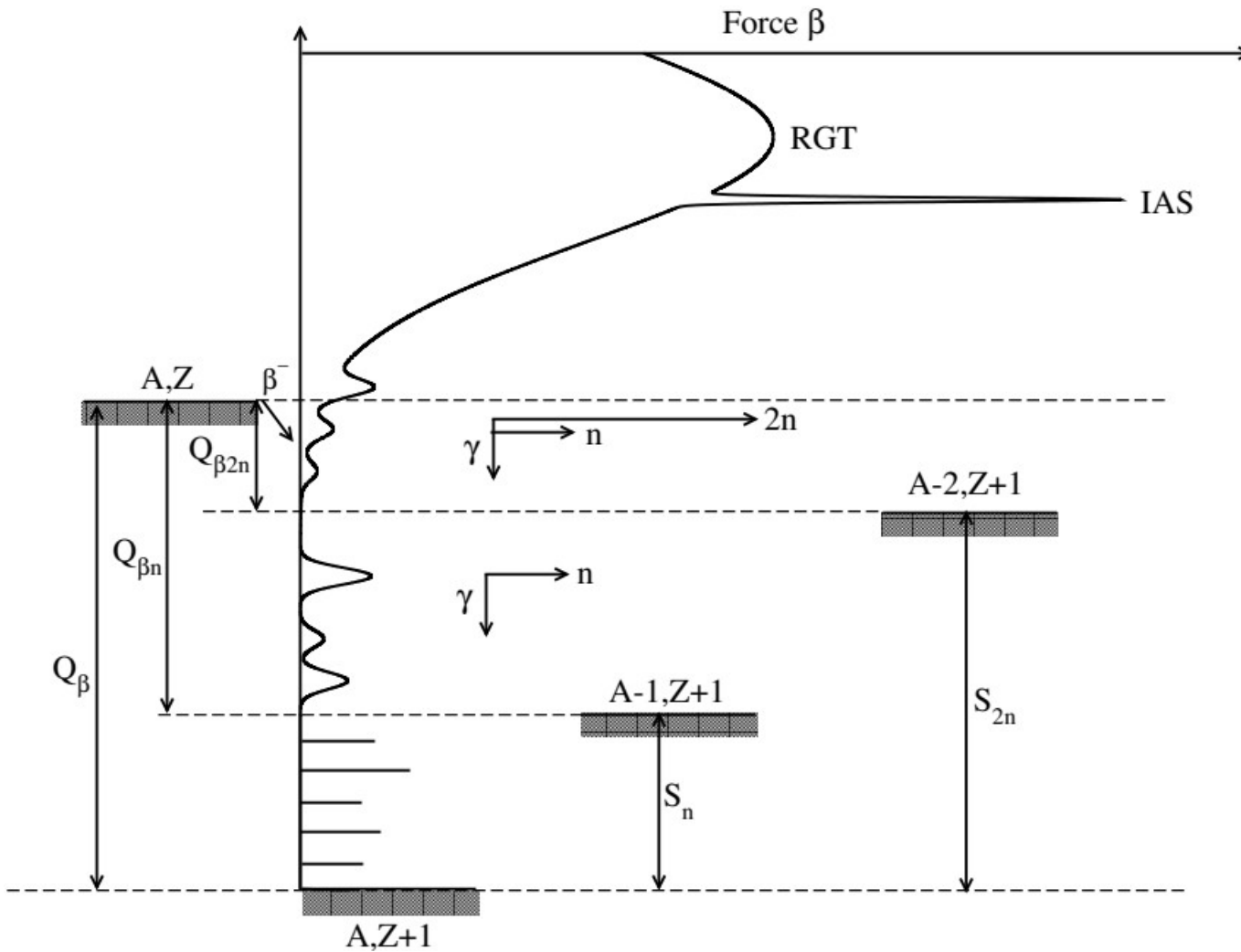
# ALTO radioactive beams



# ALTO radioactive beams

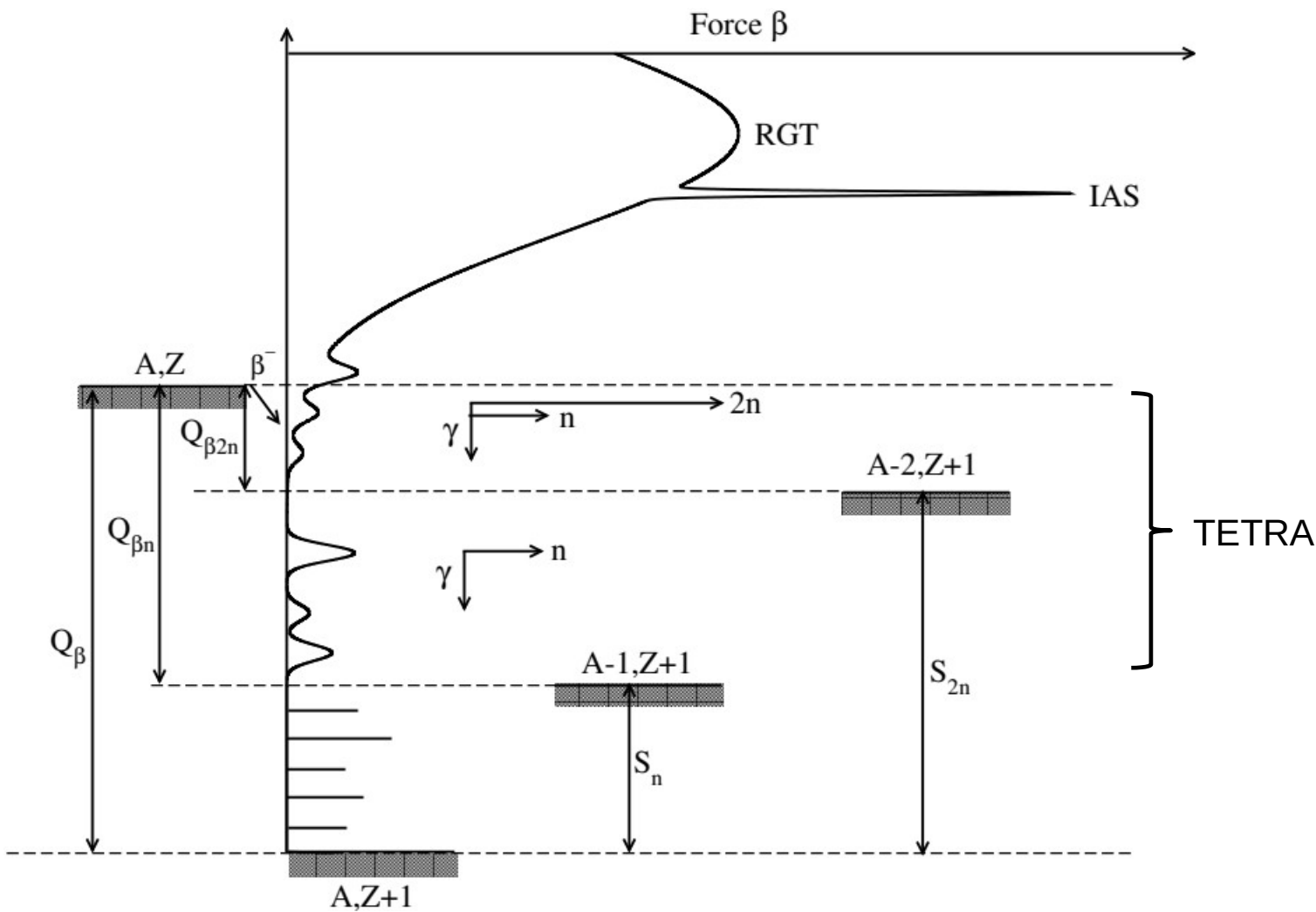


# Three $\beta$ -delayed spectroscopy setups

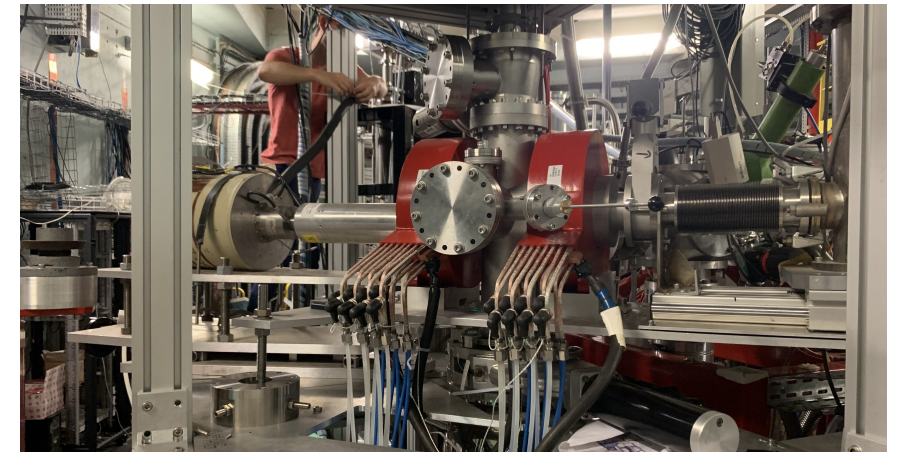
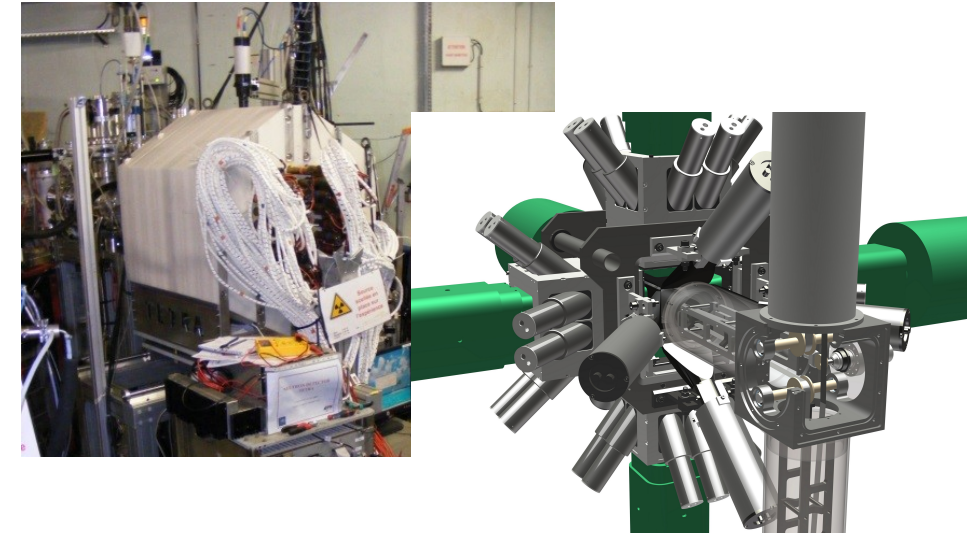
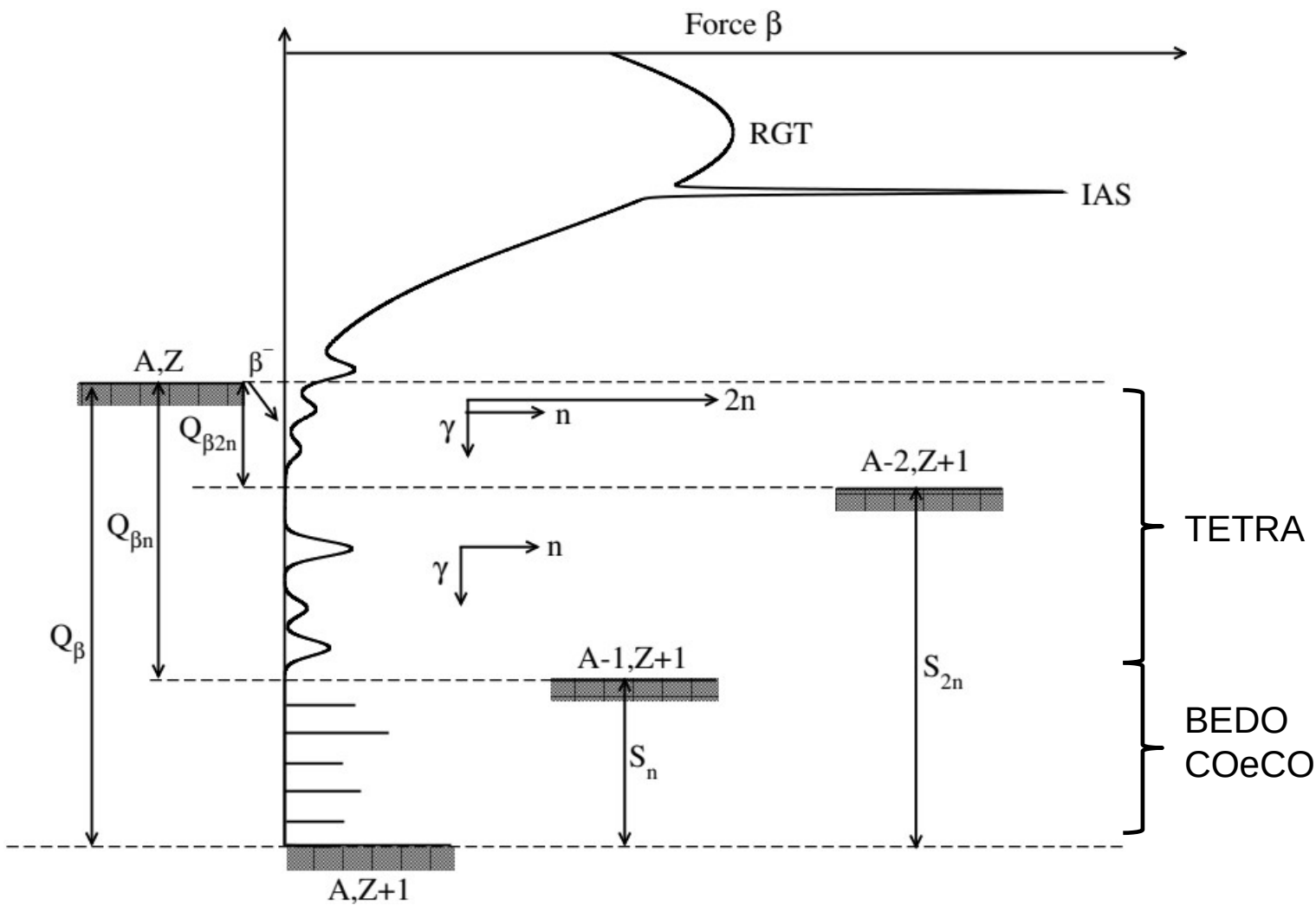




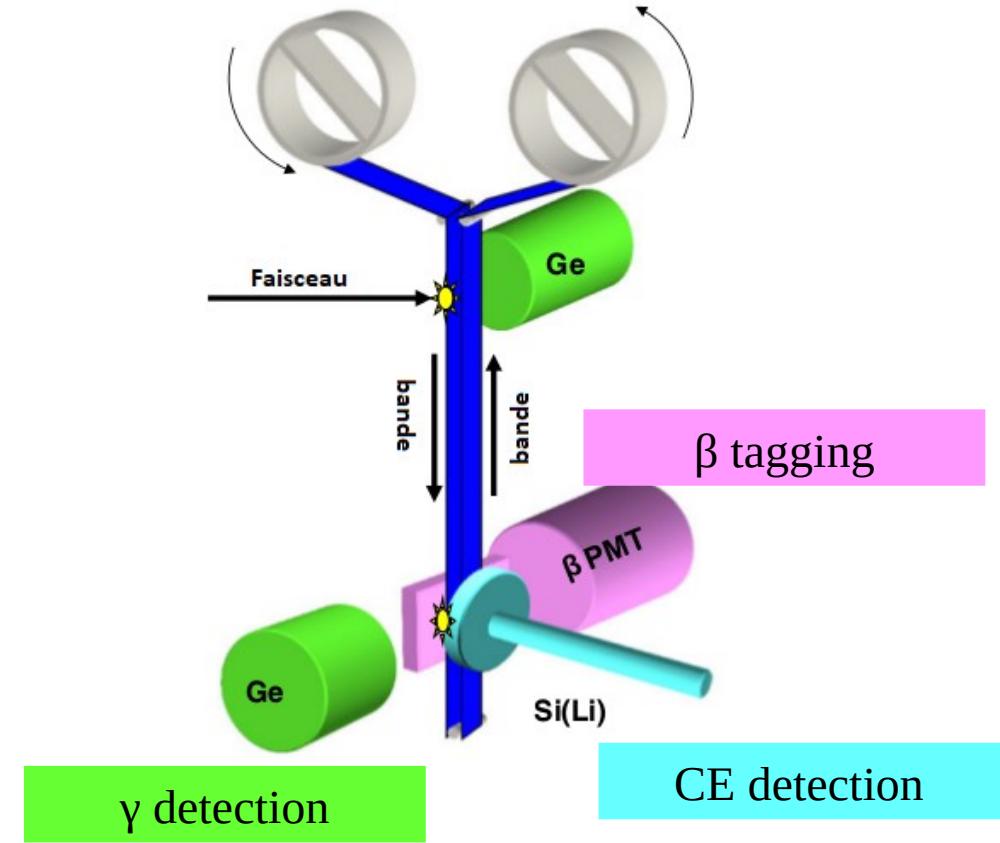
# Three $\beta$ -delayed spectroscopy setups



# Three $\beta$ -delayed spectroscopy setups



# Conversion electrons spectroscopy at ALTO pre-2022

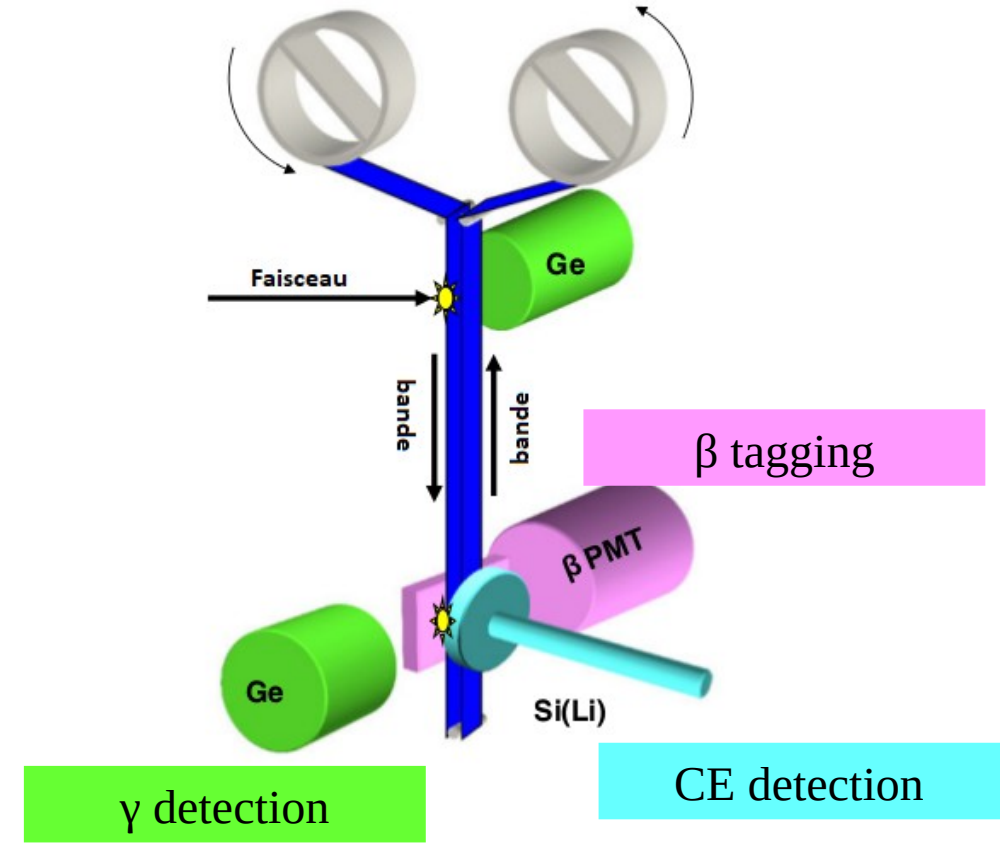


# Conversion electrons spectroscopy at ALTO pre-2022

Roughly 1s to bring the source in front of the detectors



Short lifetimes inaccessible



# Conversion electrons spectroscopy at ALTO pre-2022

Roughly 1s to bring the source in front of the detectors

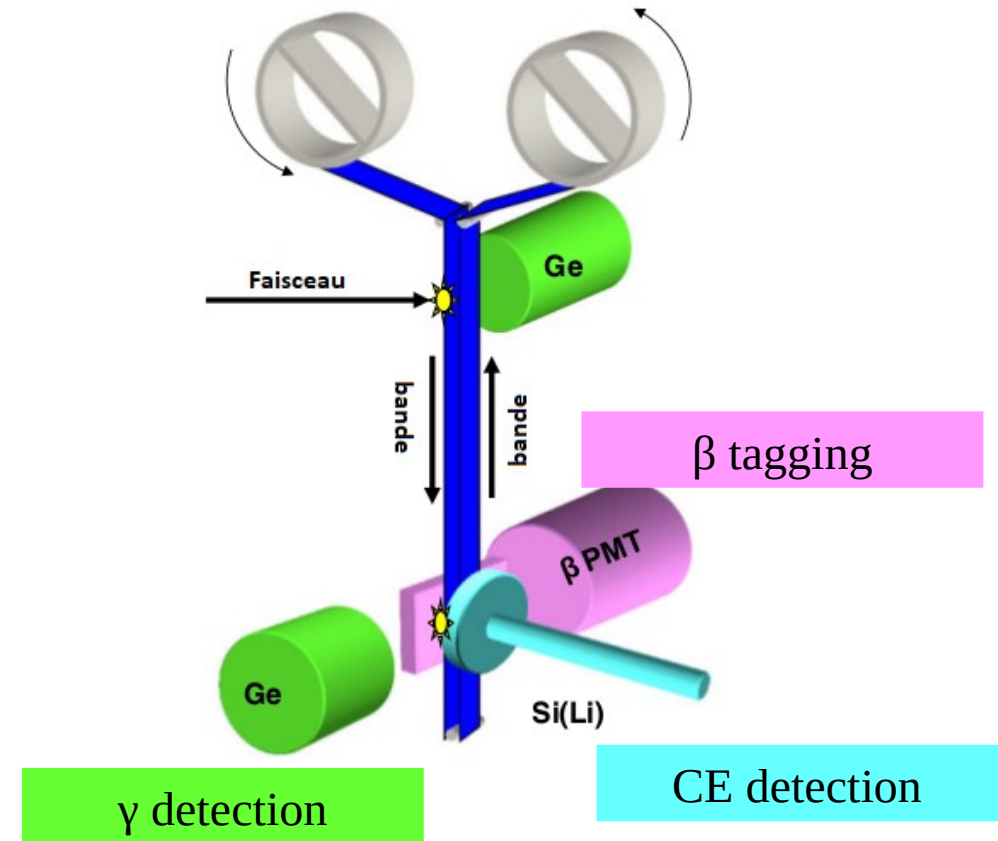


Short lifetimes  
unaccessible

Very close geometry  
at the detection point



Important  $\gamma$  background  
in CE spectra



# Conversion electrons spectroscopy at ALTO pre-2022

Roughly 1s to bring the source in front of the detectors

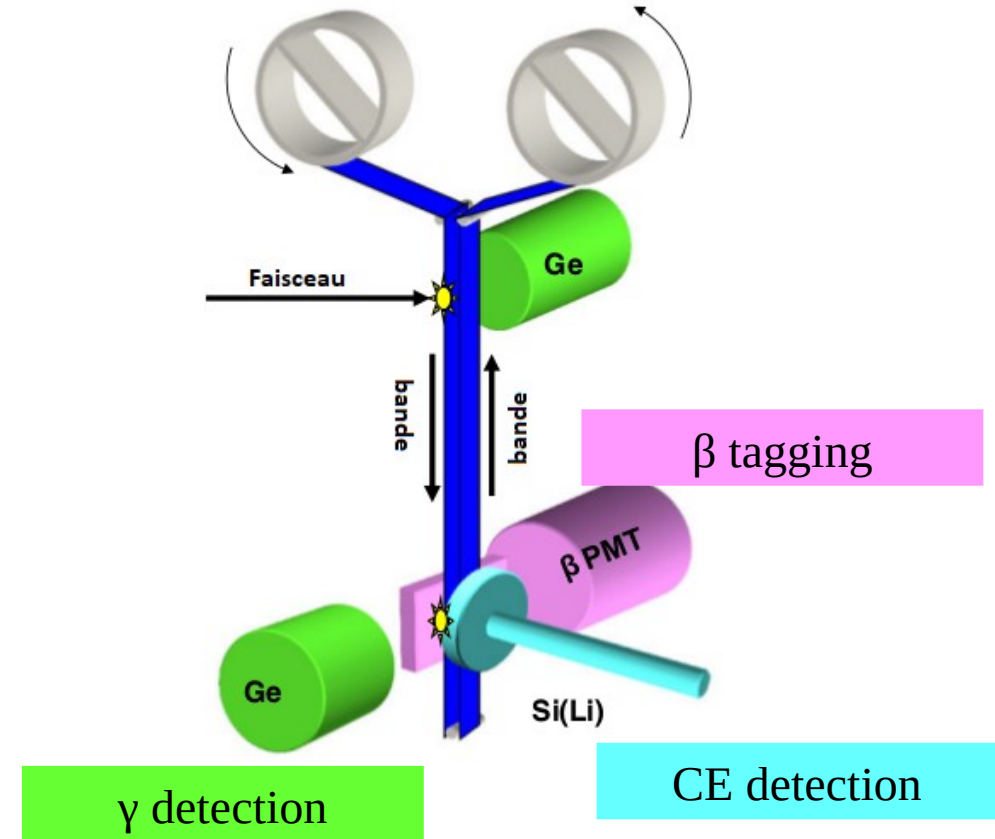
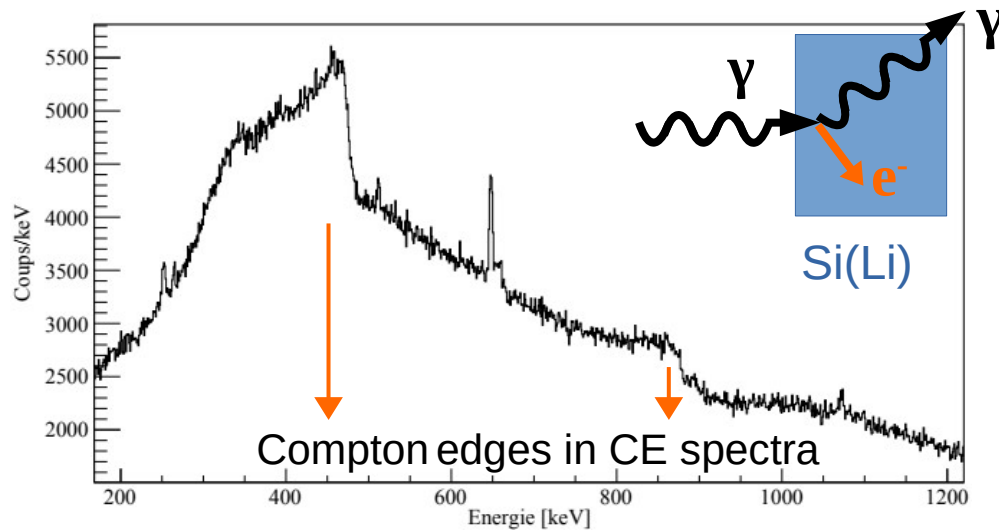


Short lifetimes  
unaccessible

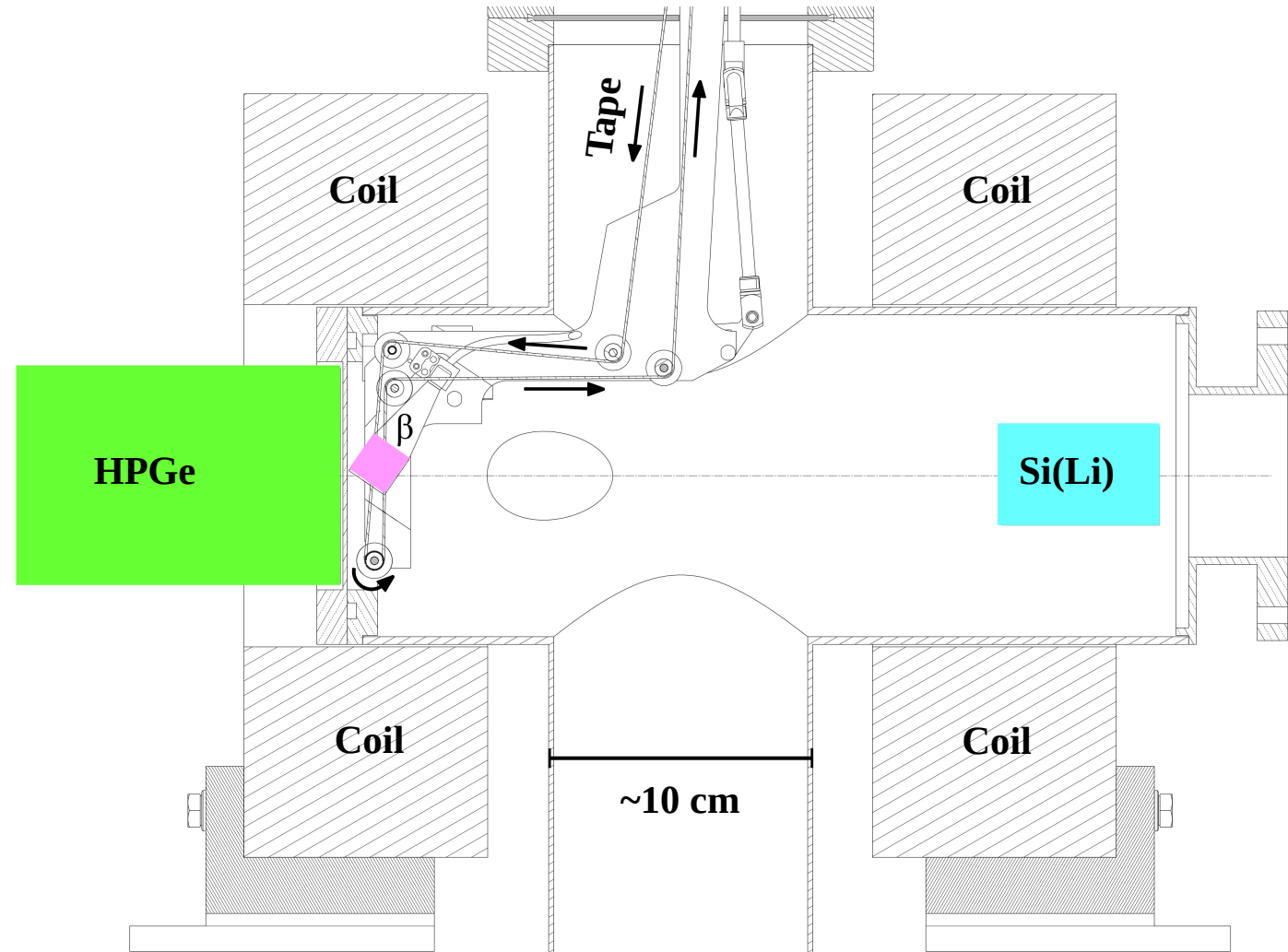
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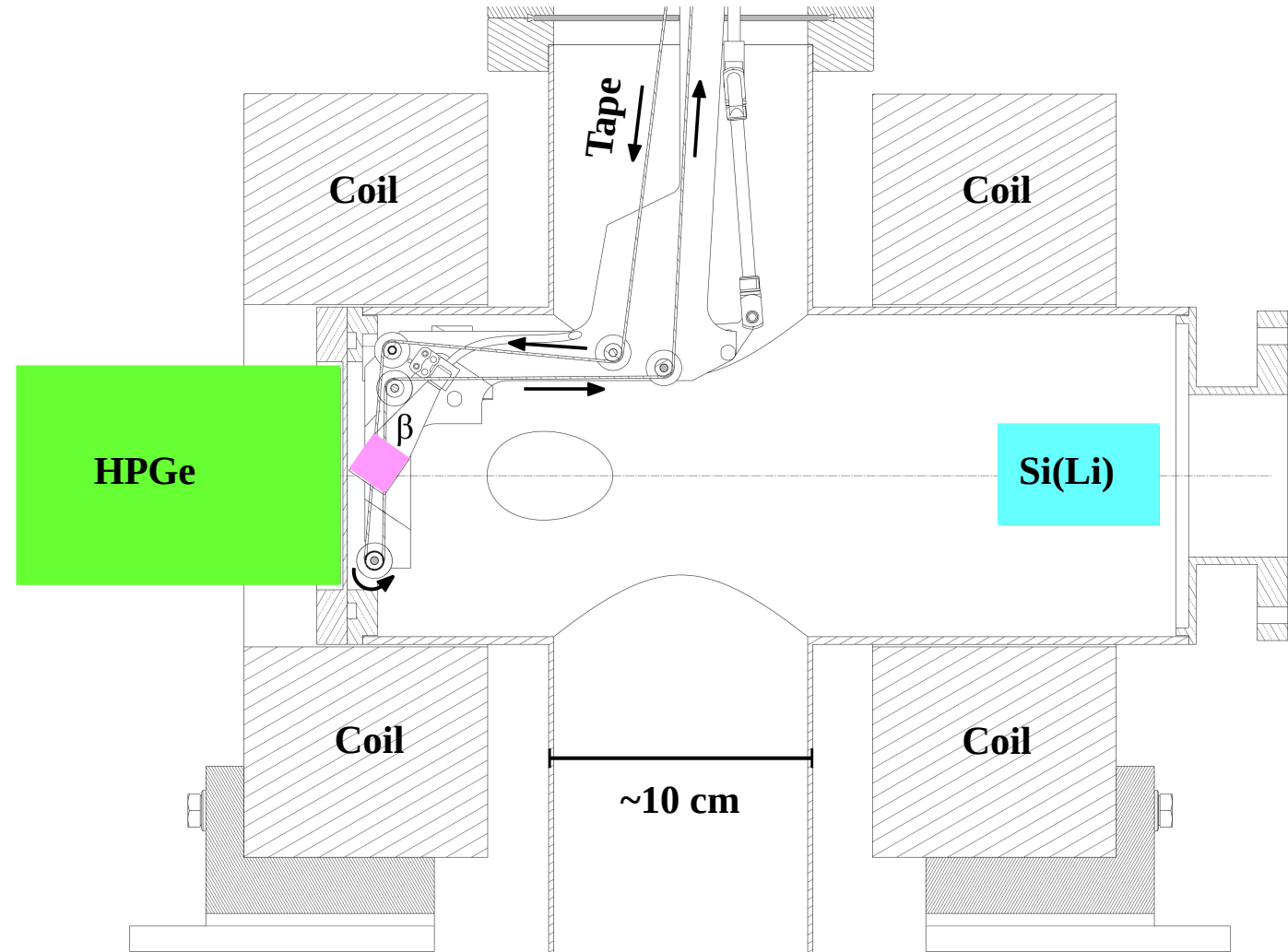
# COnversion electrons Chasing at Orsay



# COnversion electrons Chasing at Orsay

Magnetic transporter (Helmholtz configuration)

- Beam collected on tape
- Plastic scintillator for  $\beta$ -tagging
- Conversion electrons guided inside the chamber to compensate the loss of solid angle
- Tape unwinded to remove the source



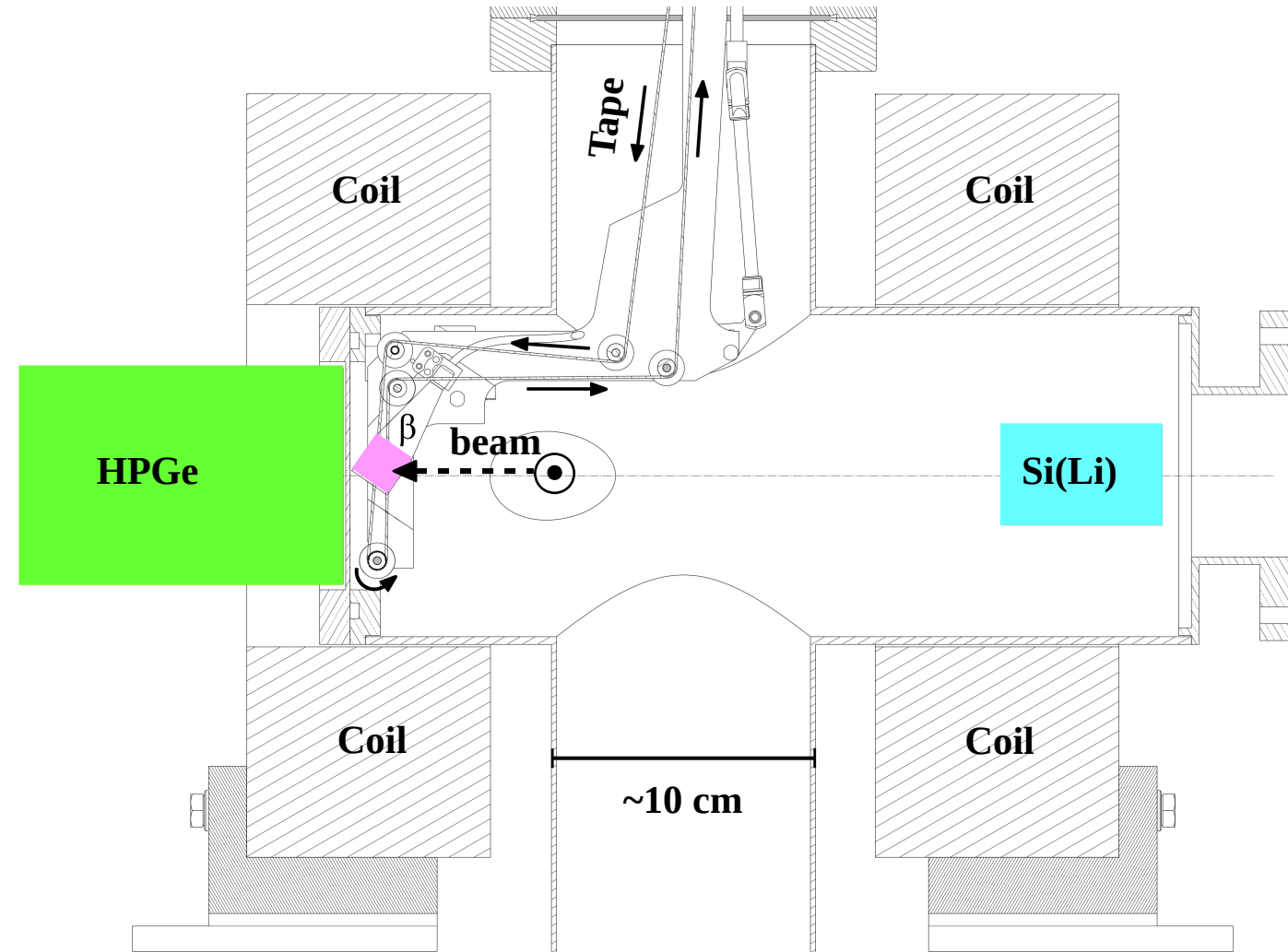


# Conversion electrons Chasing at Orsay



Magnetic transporter (Helmholtz configuration)

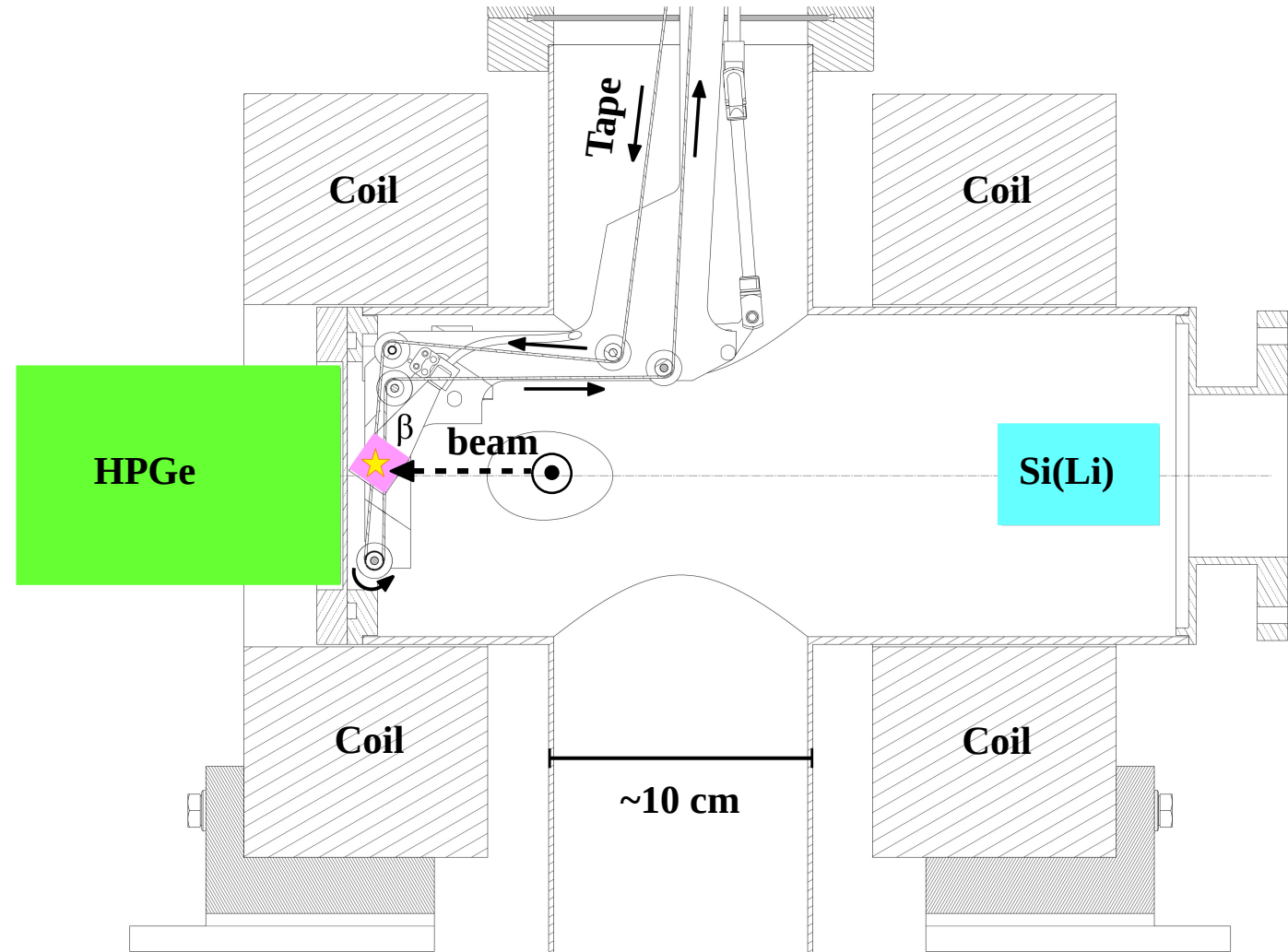
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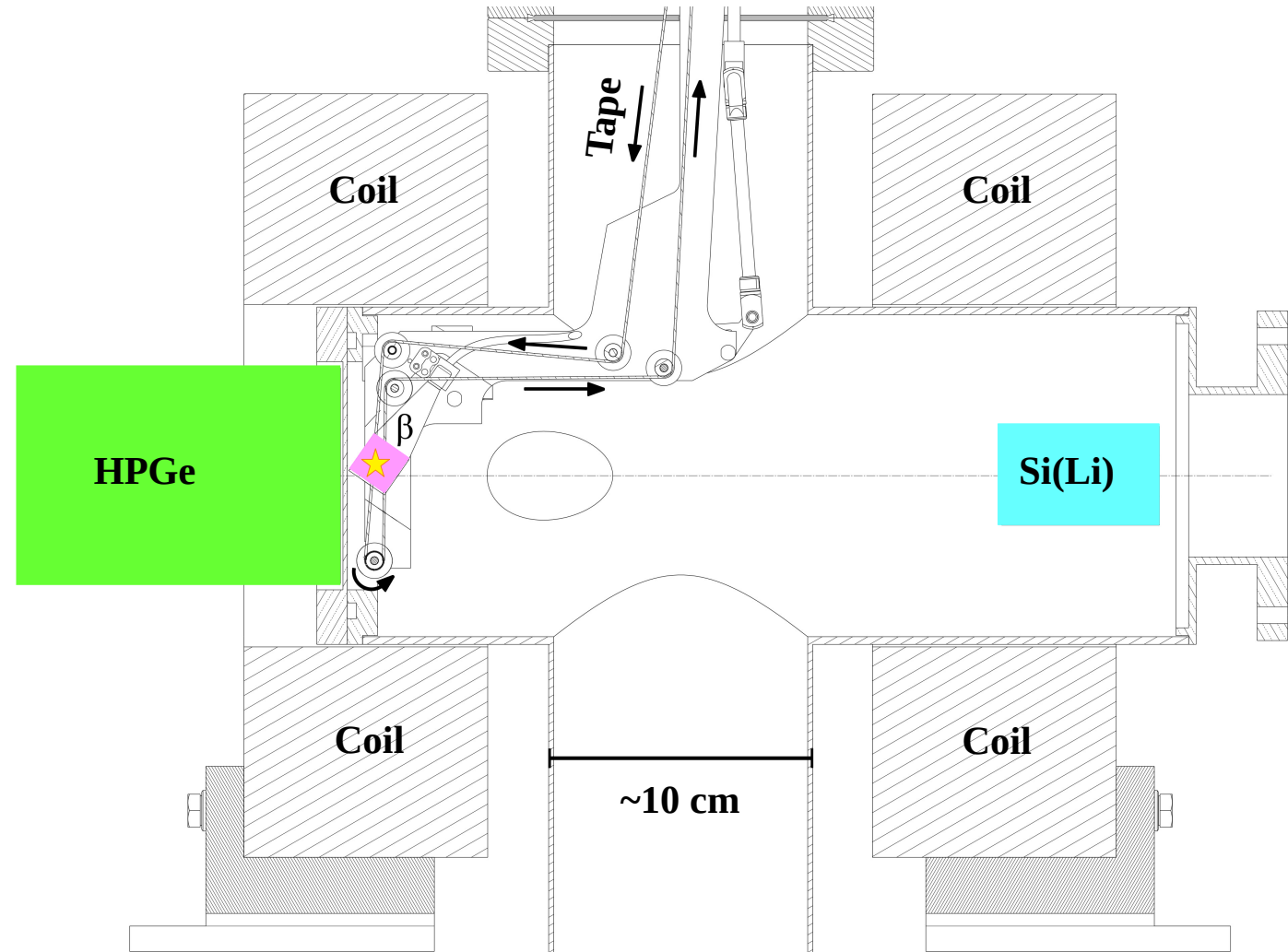
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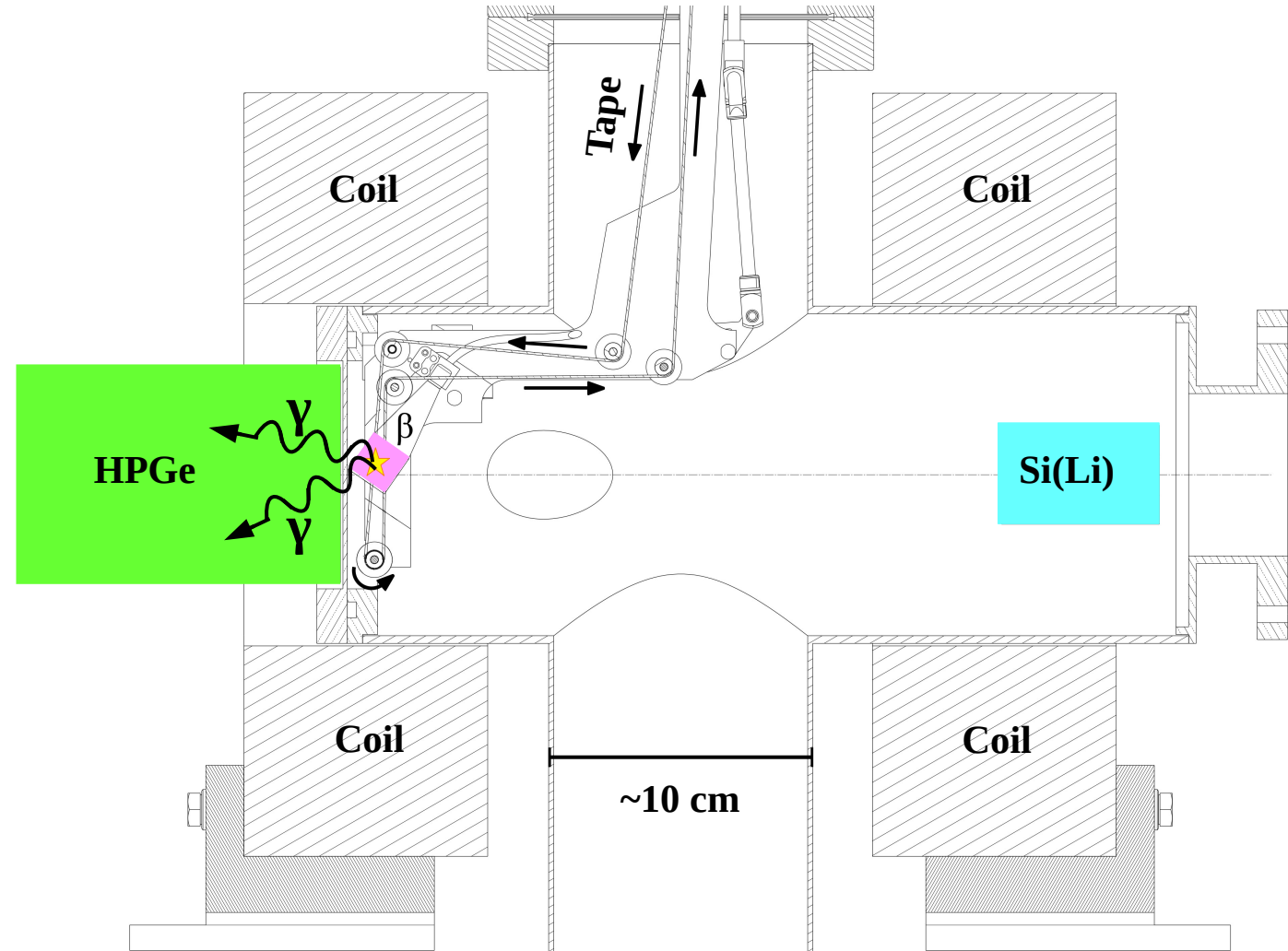
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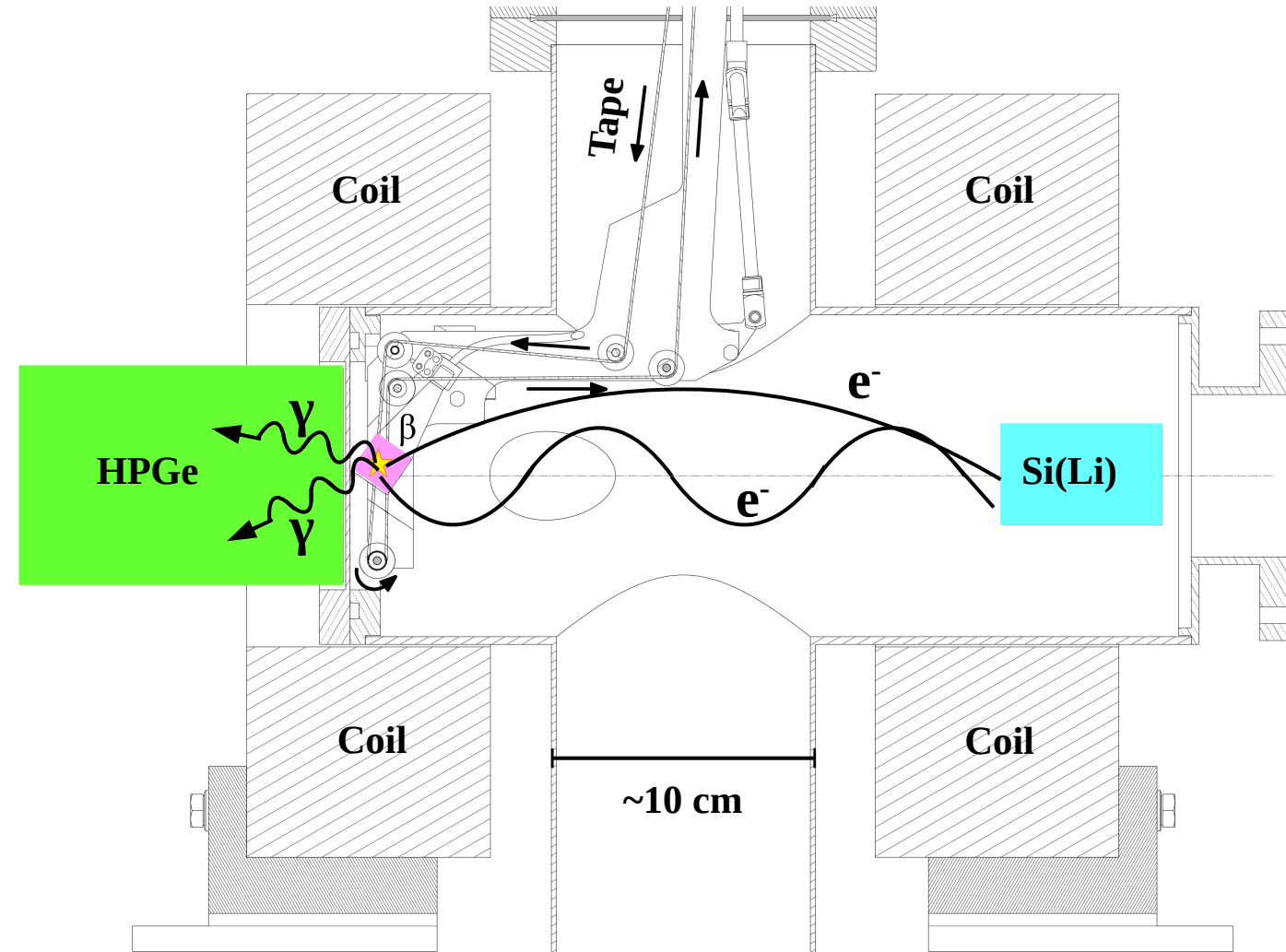


# Conversion electrons Chasing at Orsay

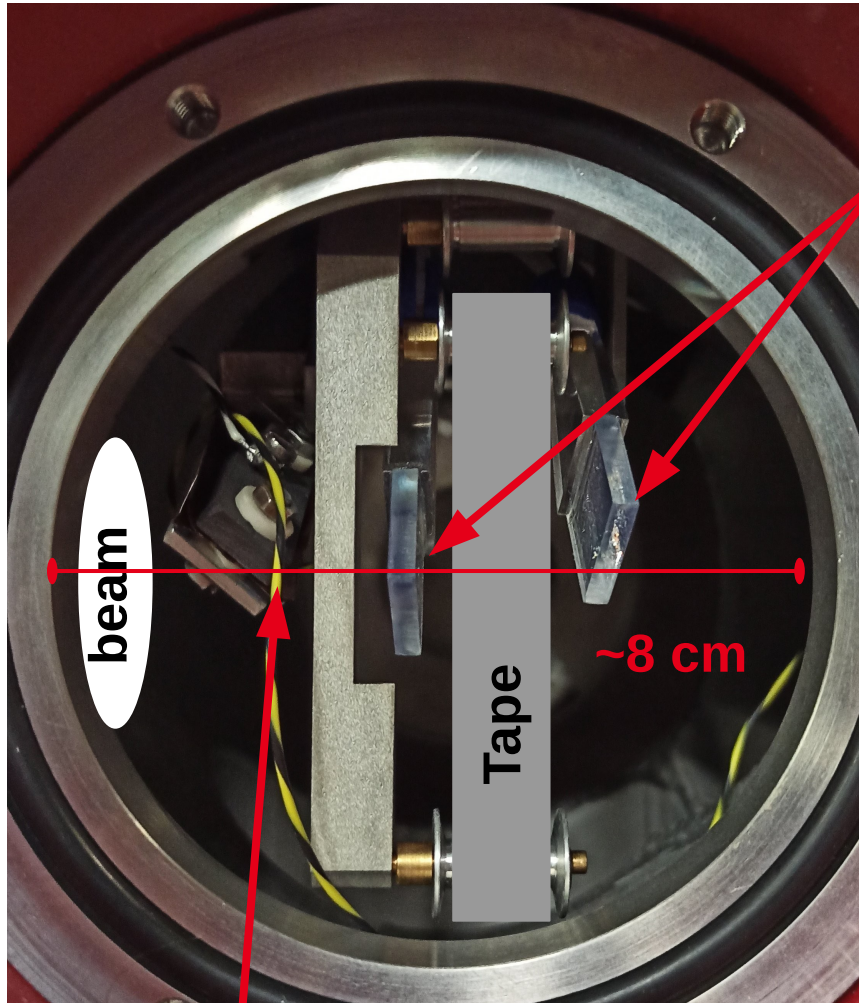


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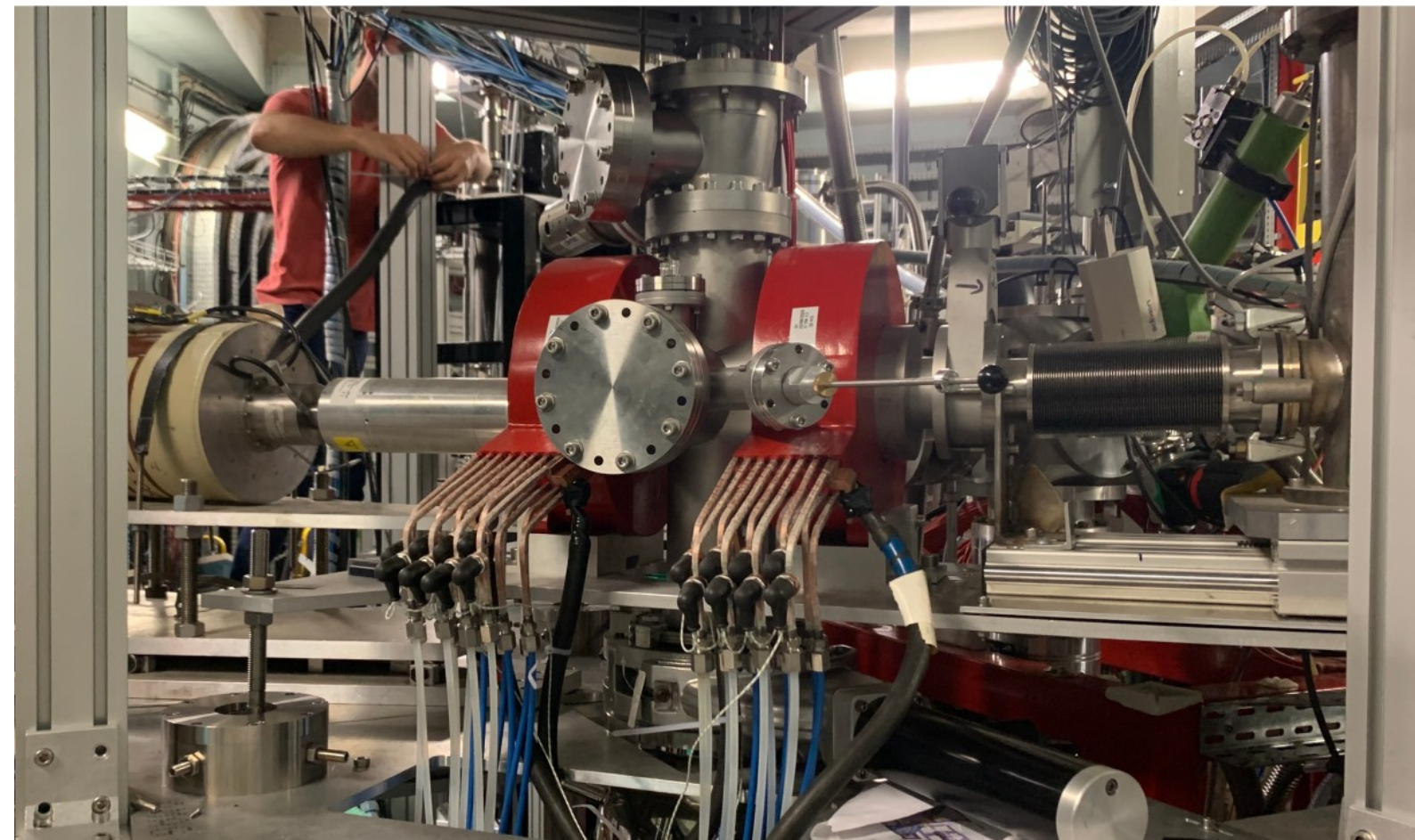


# COnversion electrons Chasing at Orsay

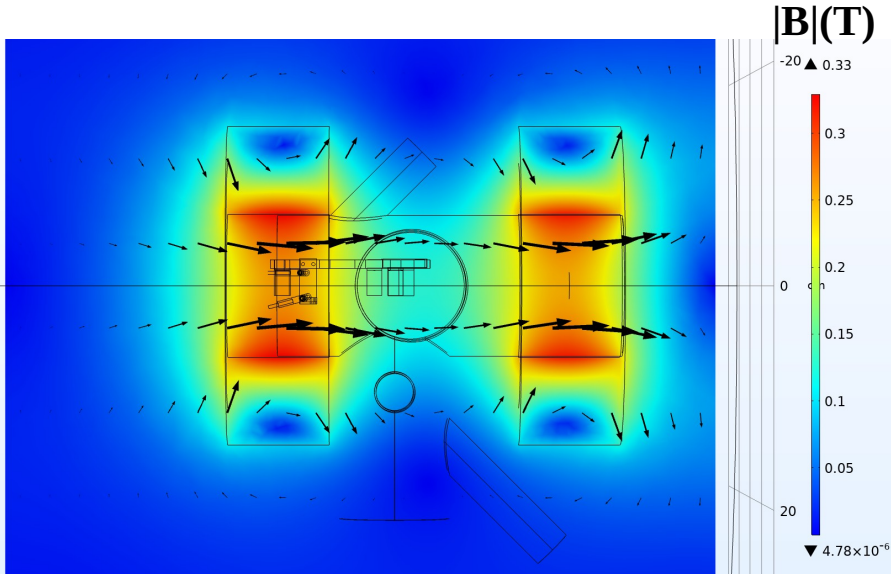


Plastic scintillator

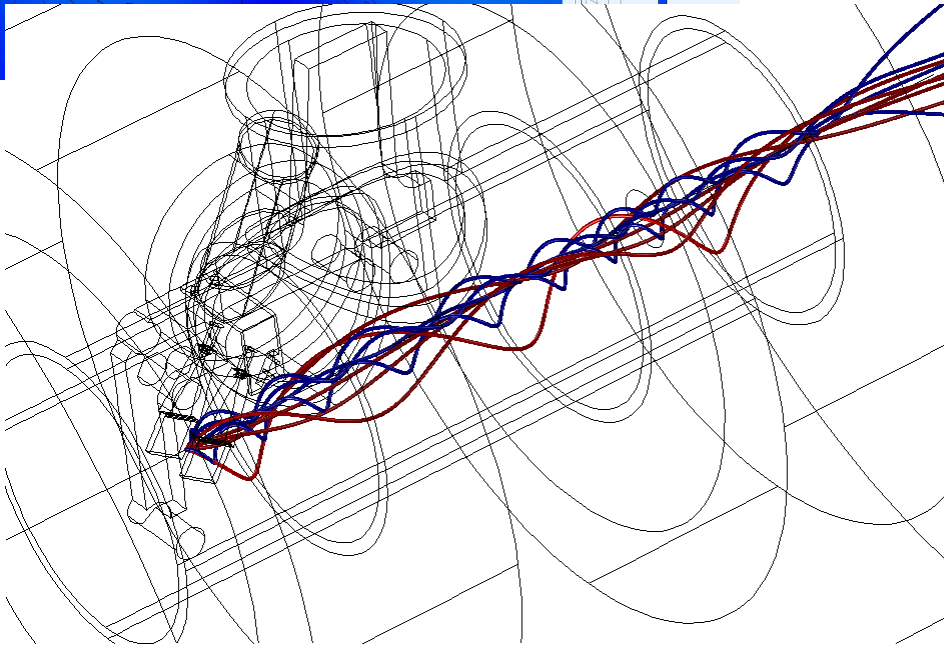
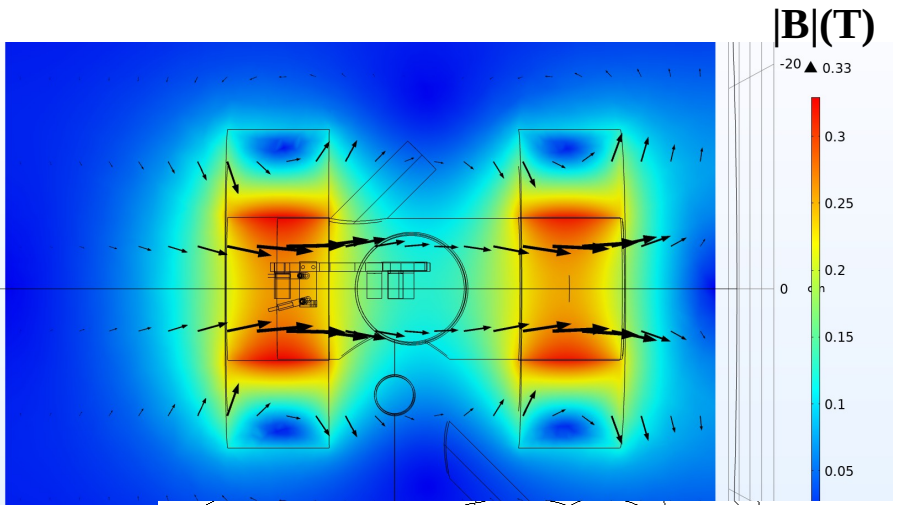
Faraday cup



# CO nversion electrons Chasing at Orsay

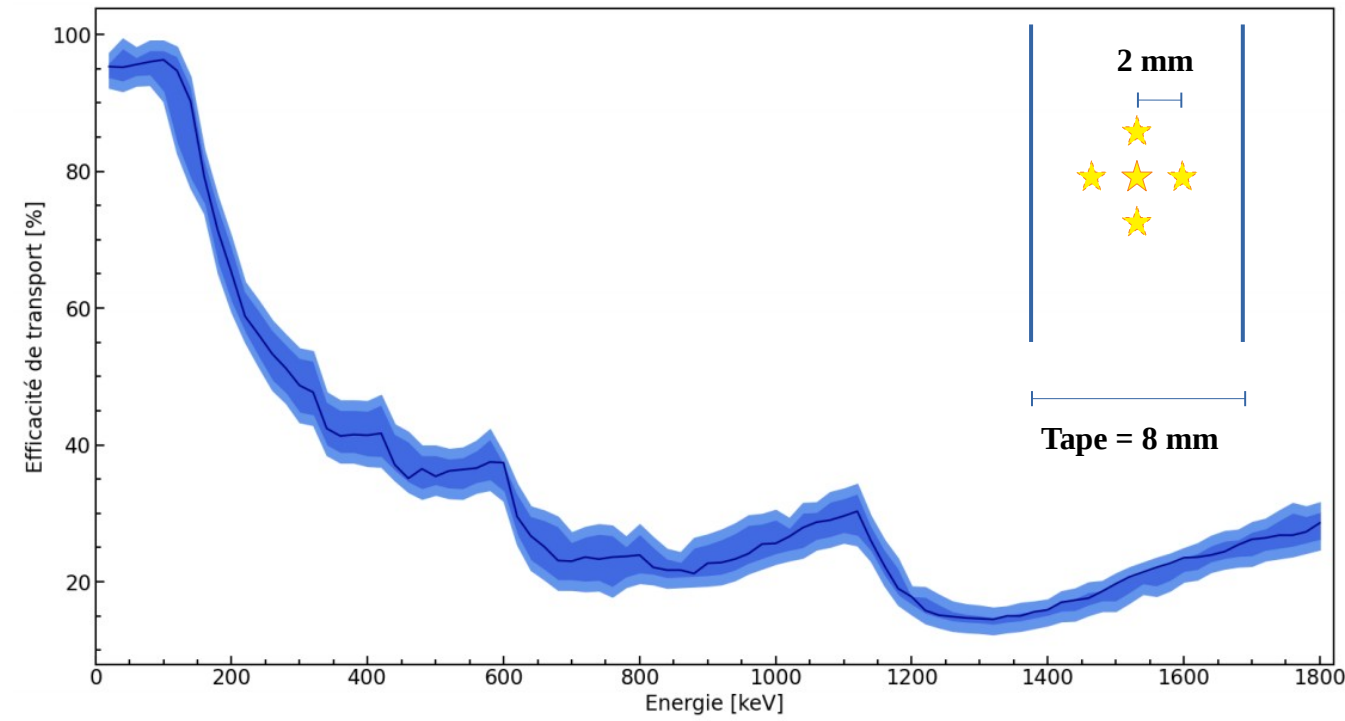
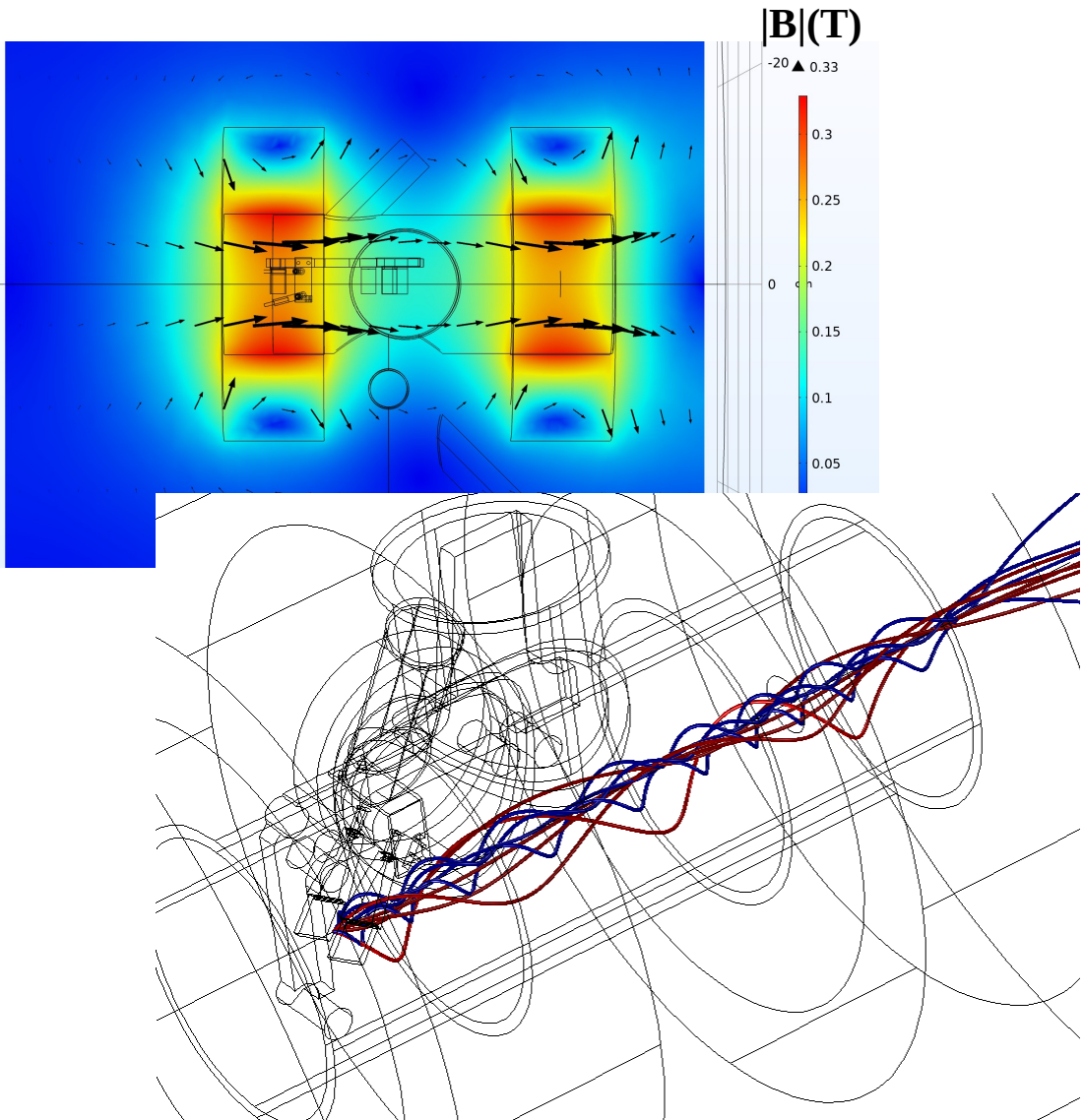


# COnversion electrons Chasing at Orsay

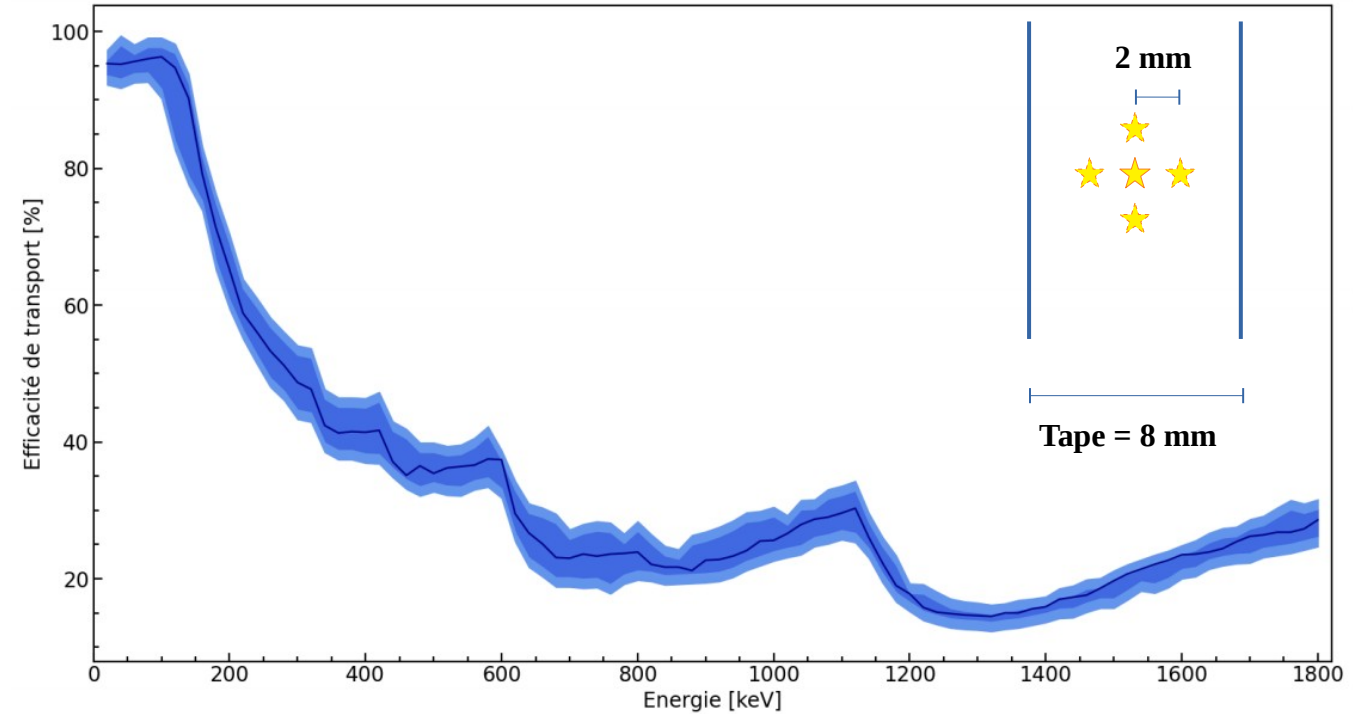
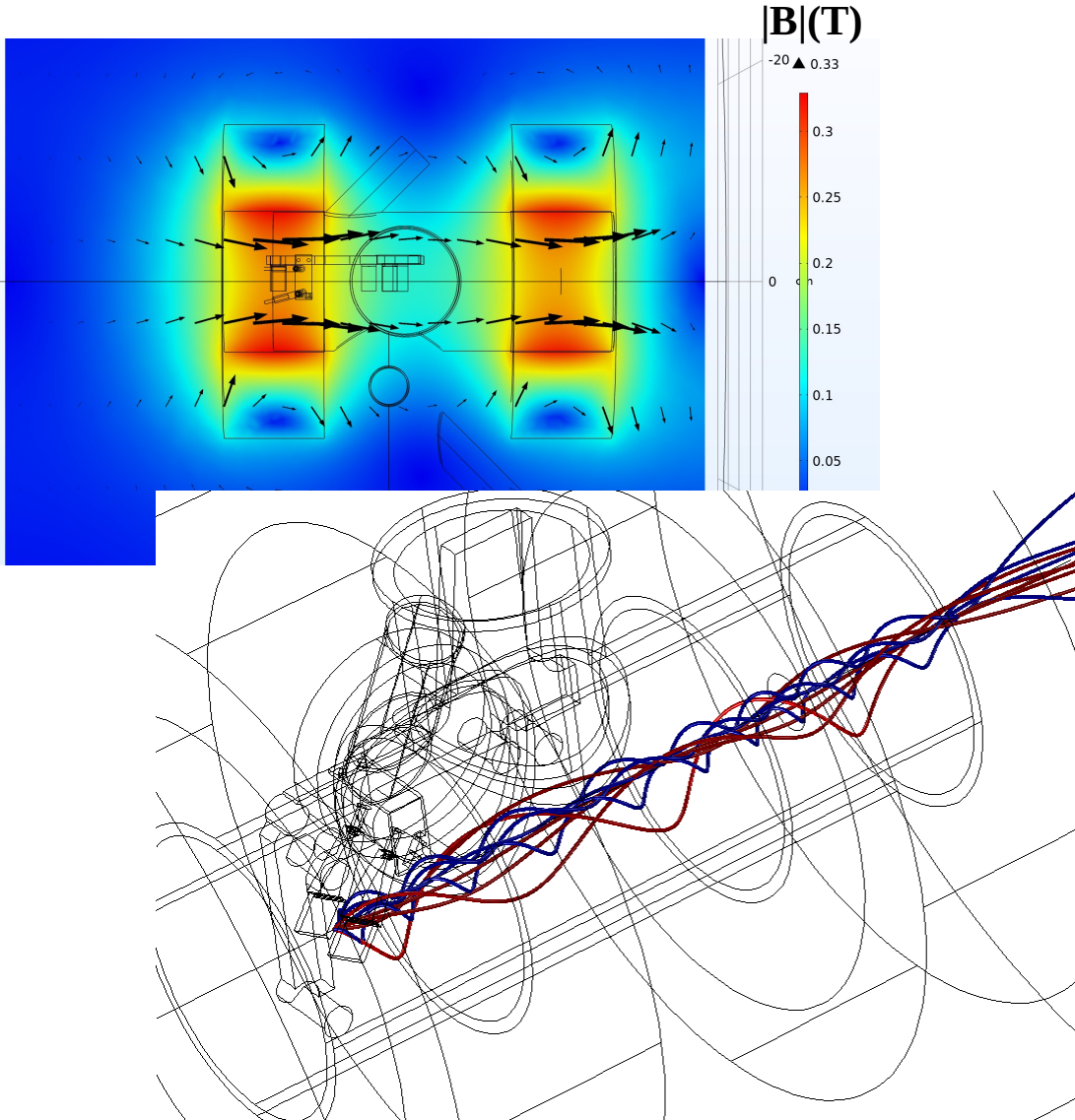




# COnversion electrons Chasing at Orsay



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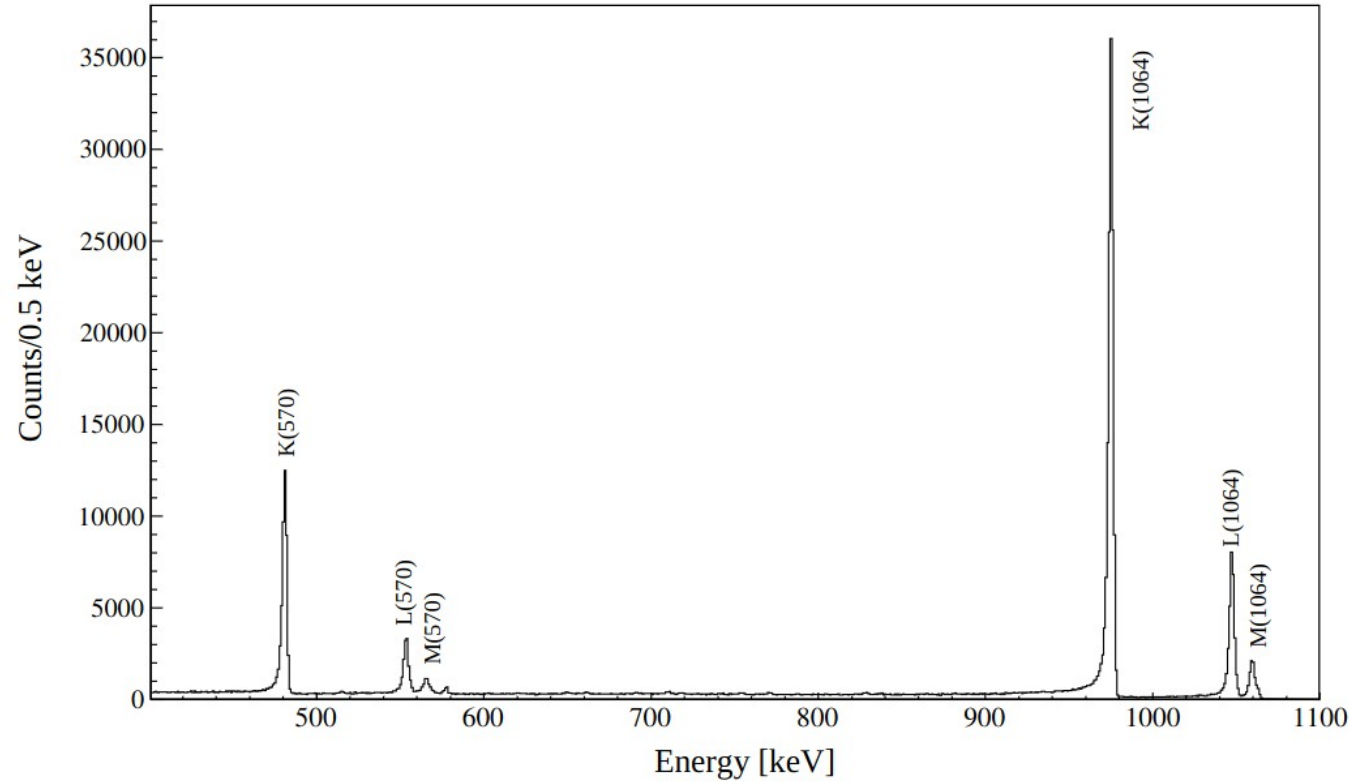
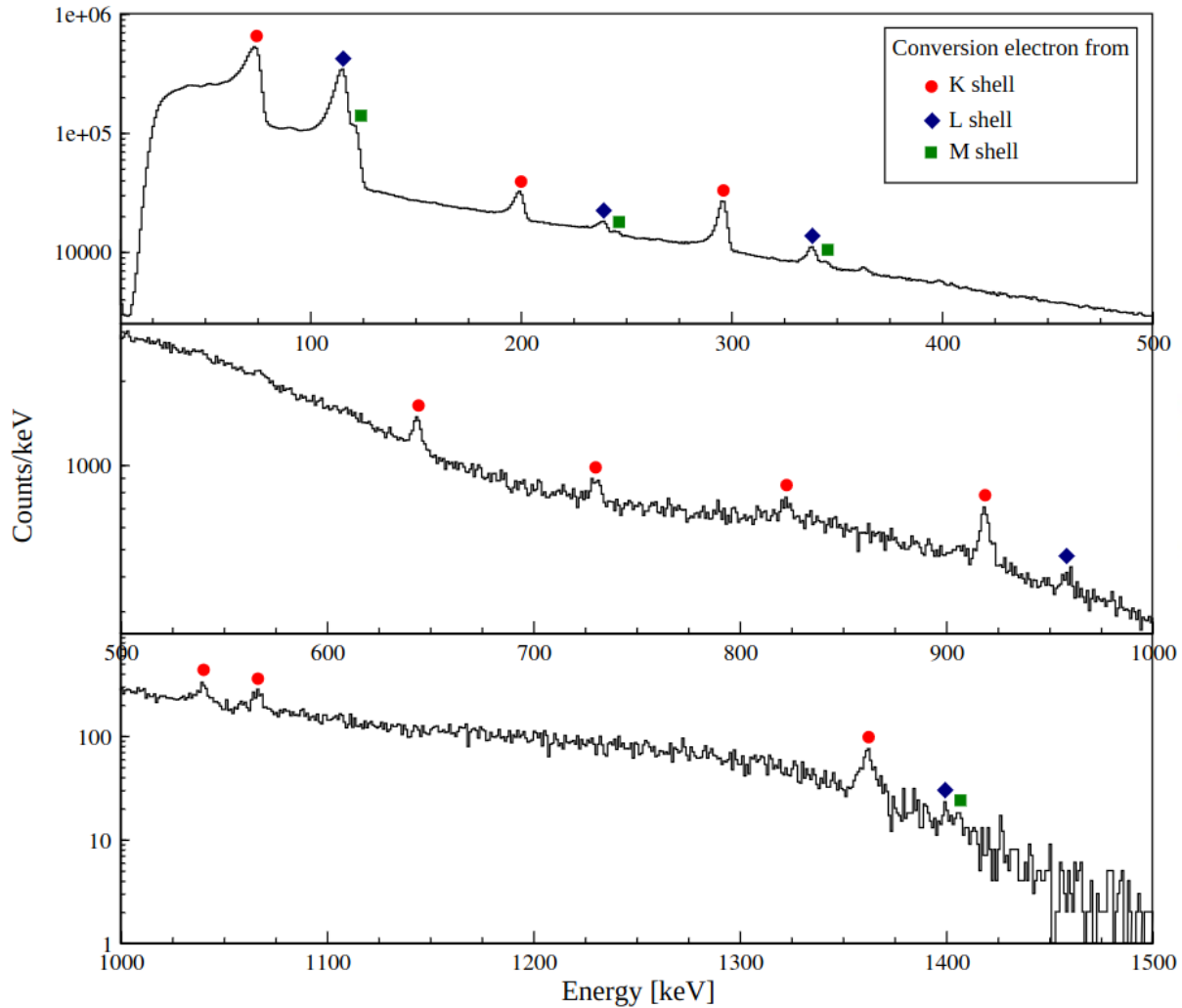


Electrons spiraling in the magnetic field

Collection point = detection point

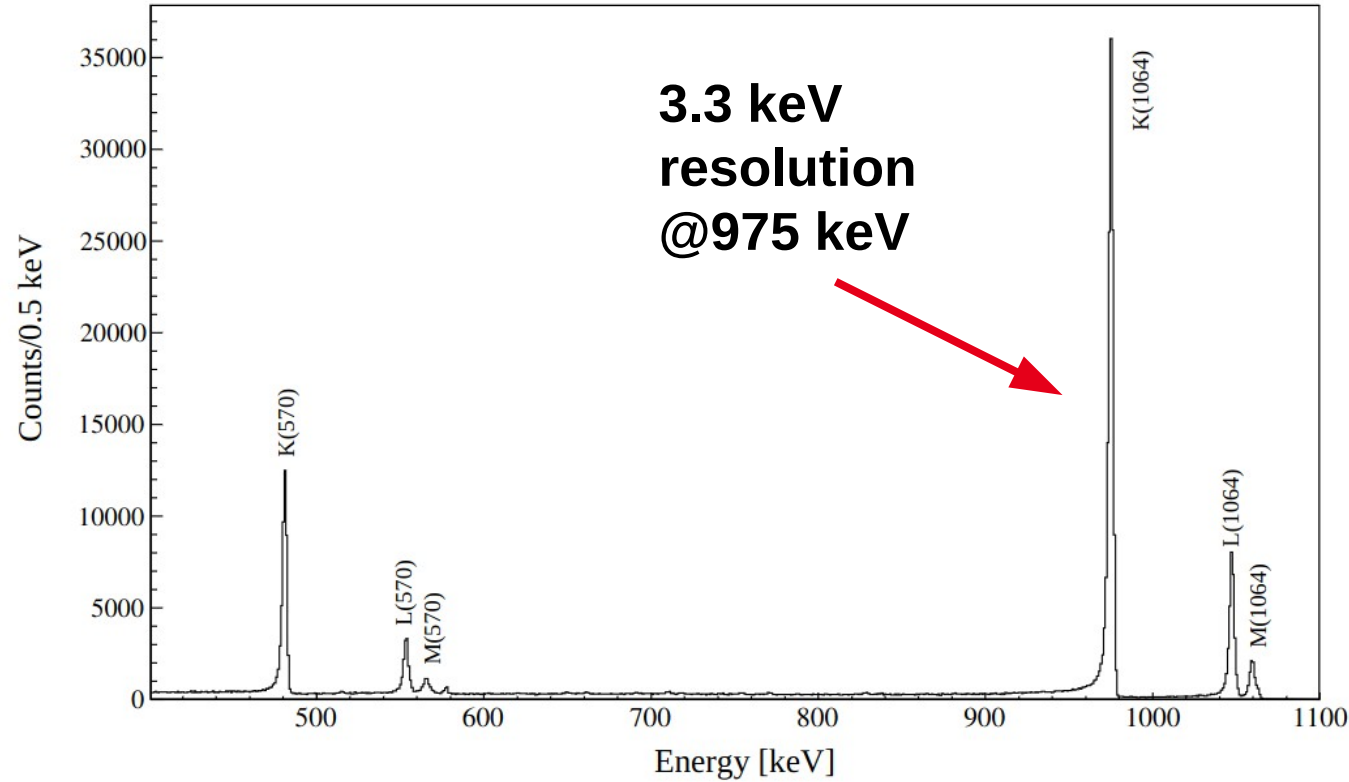
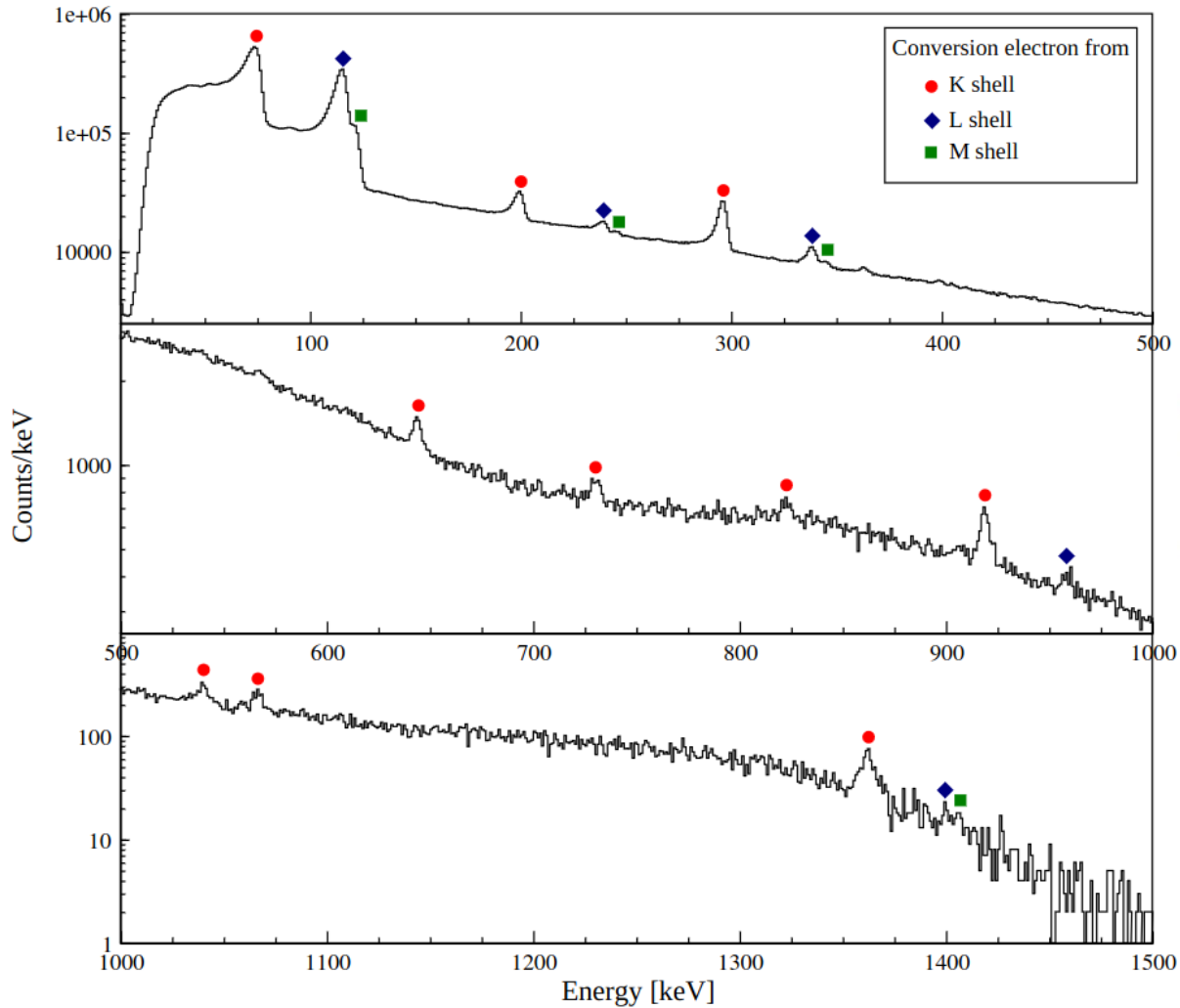
Solid angle covered by Si(Li) reduced by  $\sim 3000$

# Off-line commissioning



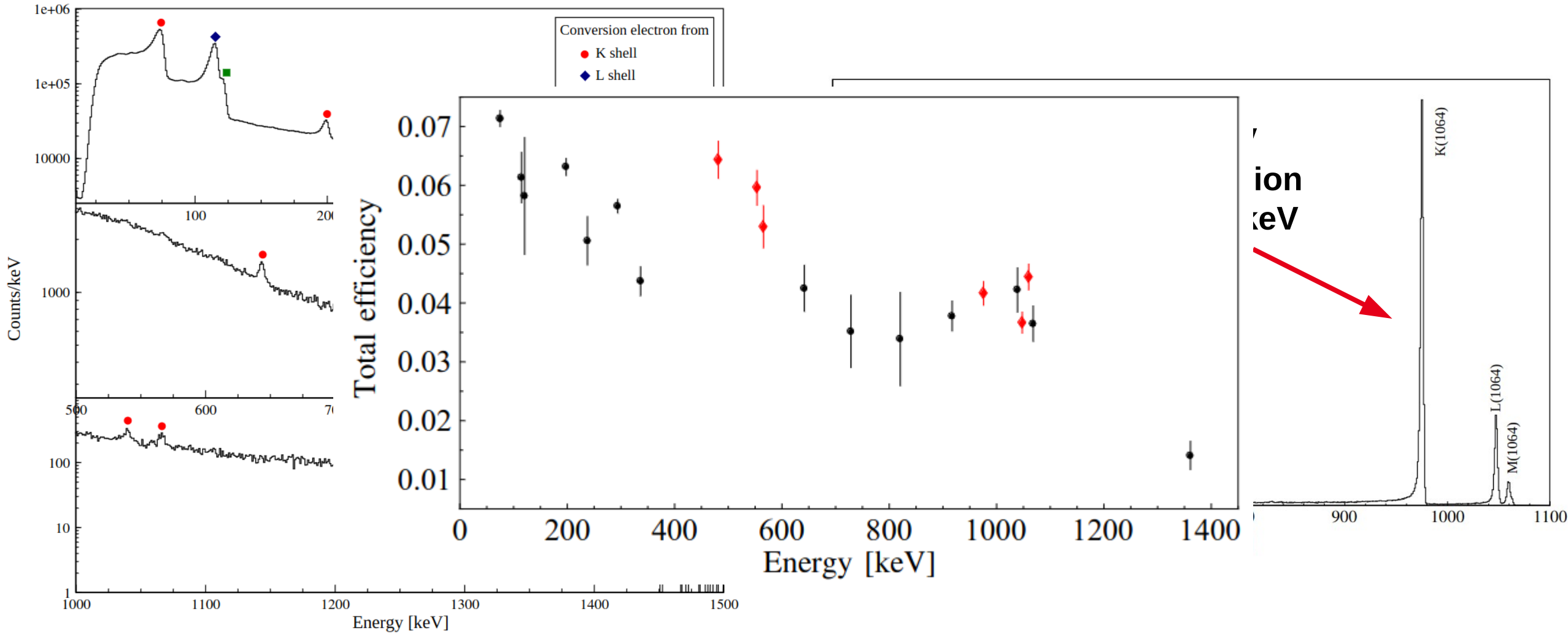
Spectra obtained with COeCO and standard sources of  $^{152}\text{Eu}$  and  $^{207}\text{Bi}$

# Off-line commissioning



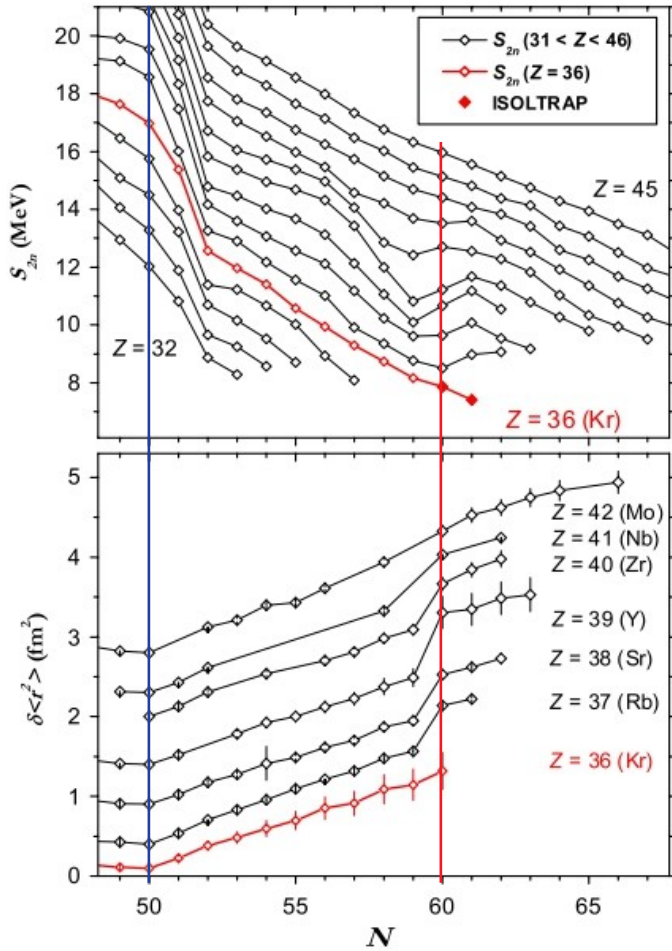
Spectra obtained with COeCO and standard sources of  $^{152}\text{Eu}$  and  $^{207}\text{Bi}$

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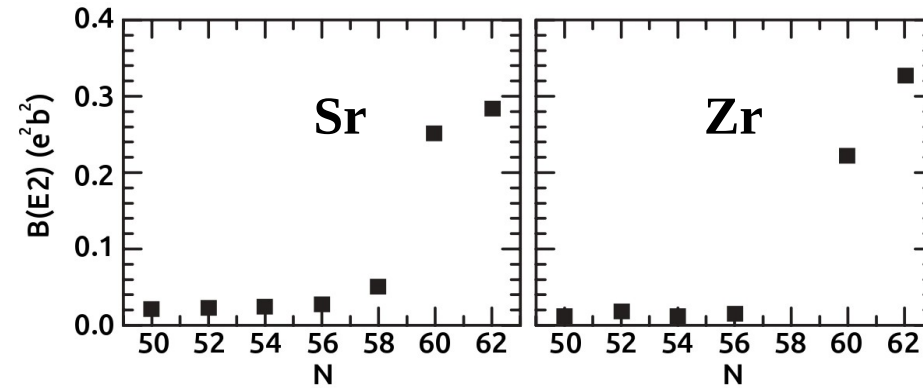


Spectra obtained with COeCO and standard sources of  $^{152}\text{Eu}$  and  $^{207}\text{Bi}$

# Physics case : shape transition around N=60



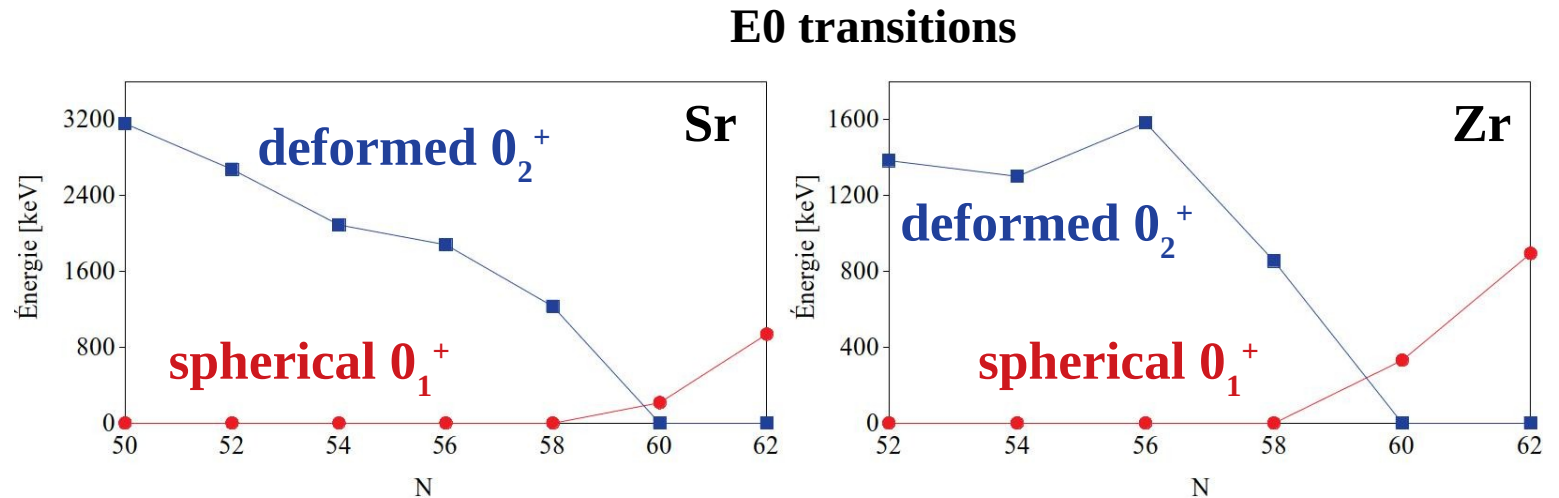
Masses



Reduced transition probabilities

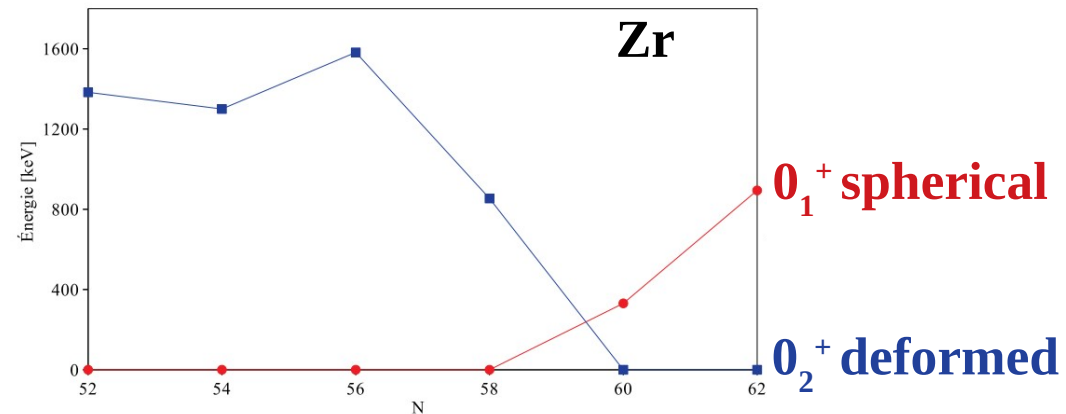
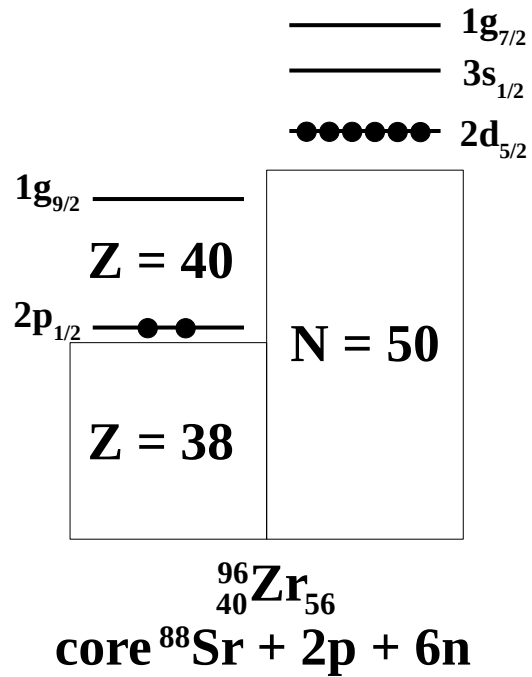
From H. Mei *et al.* Phys. Rev. C 85 034321, 2012

Radius

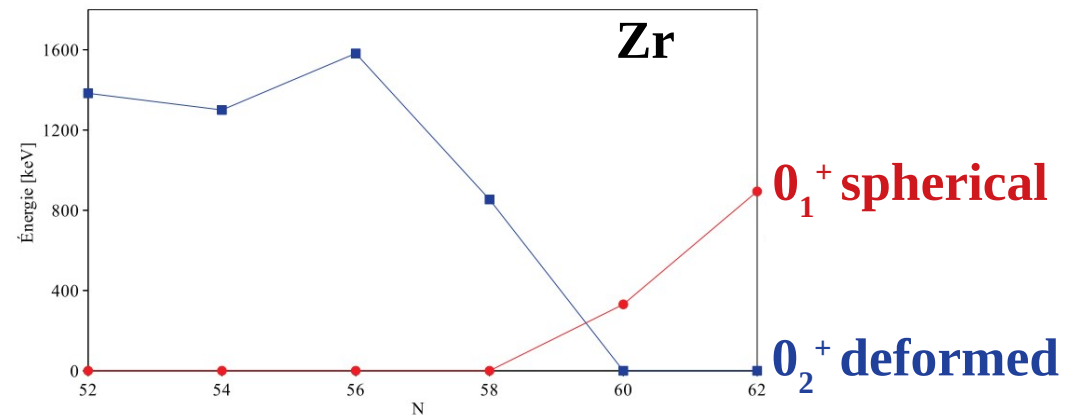
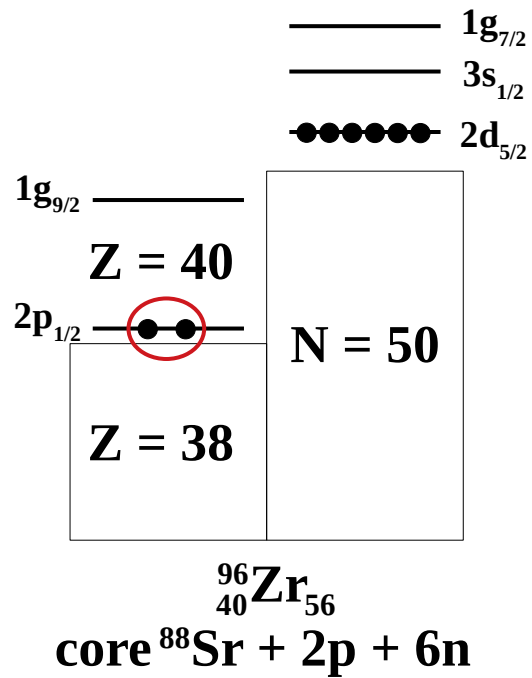


S. Naimi *et al.* Phys. Rev. Lett. 105 032502, 2010

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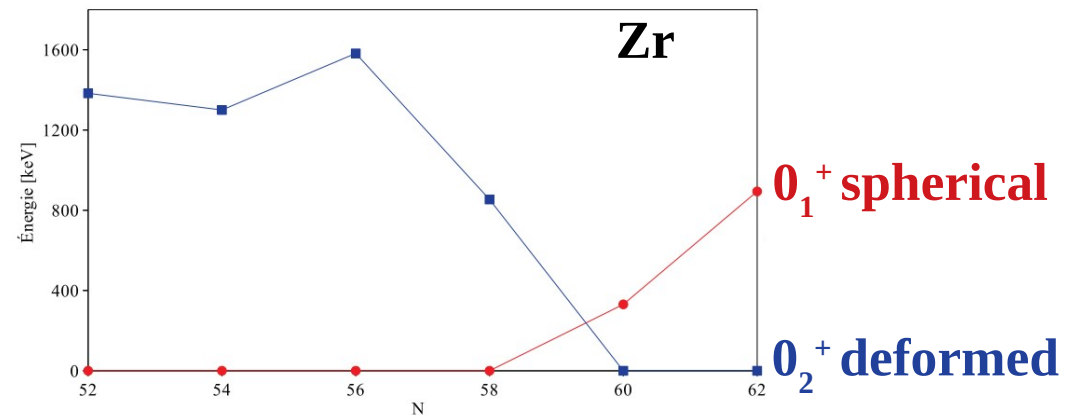
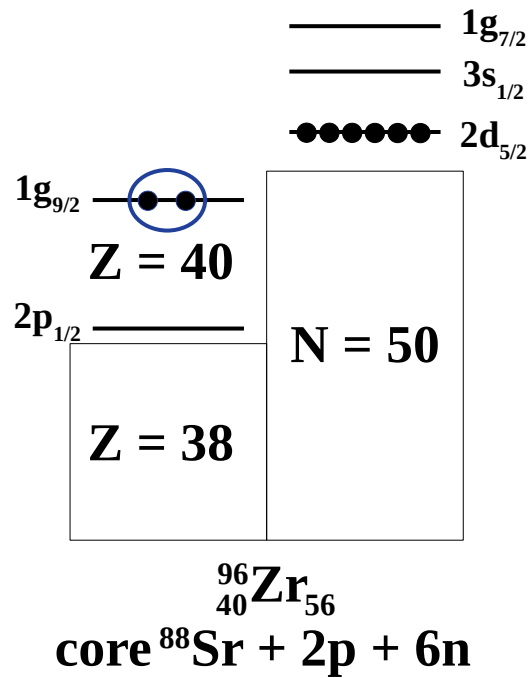


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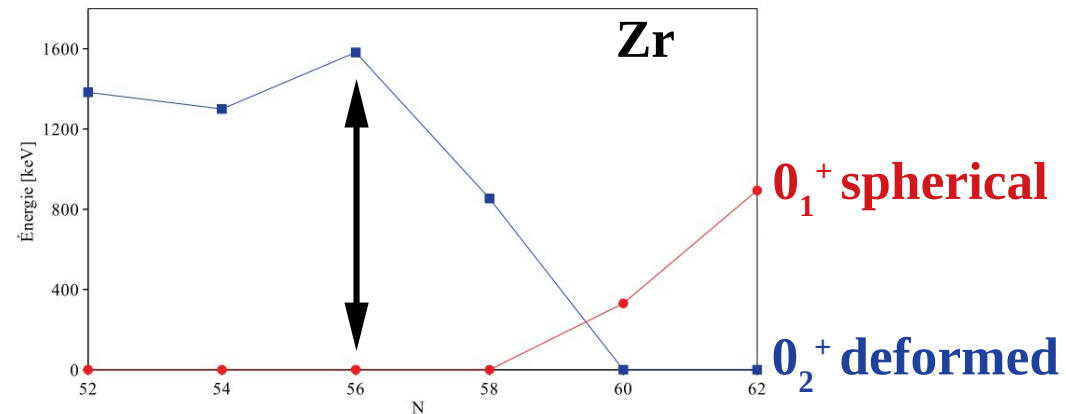
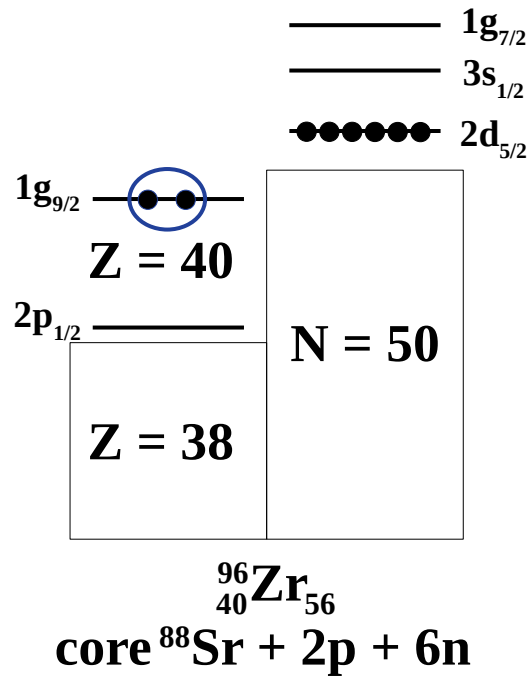




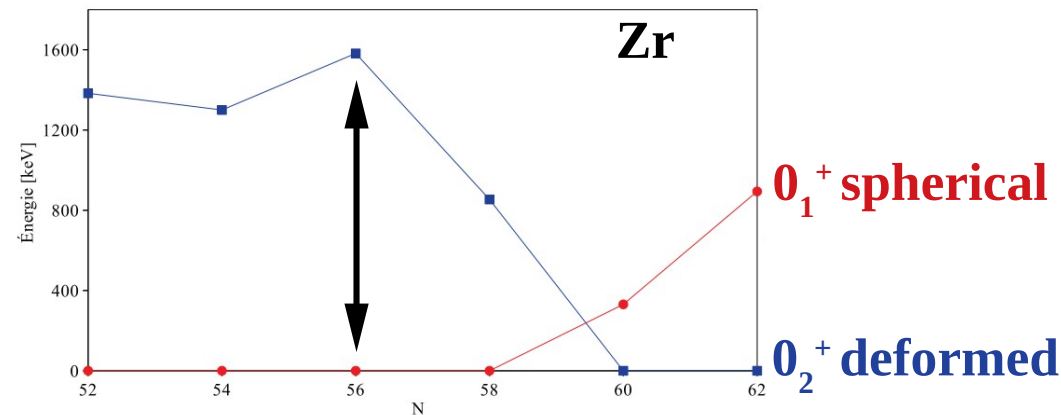
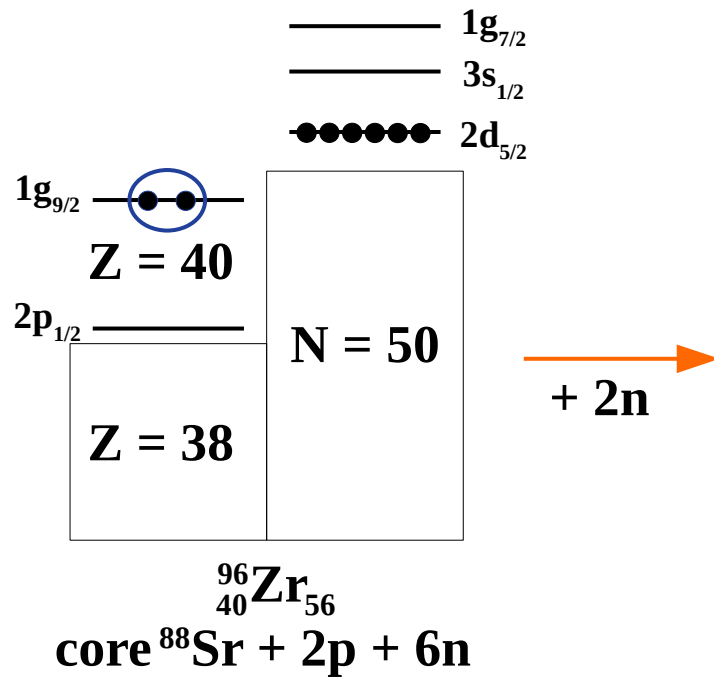
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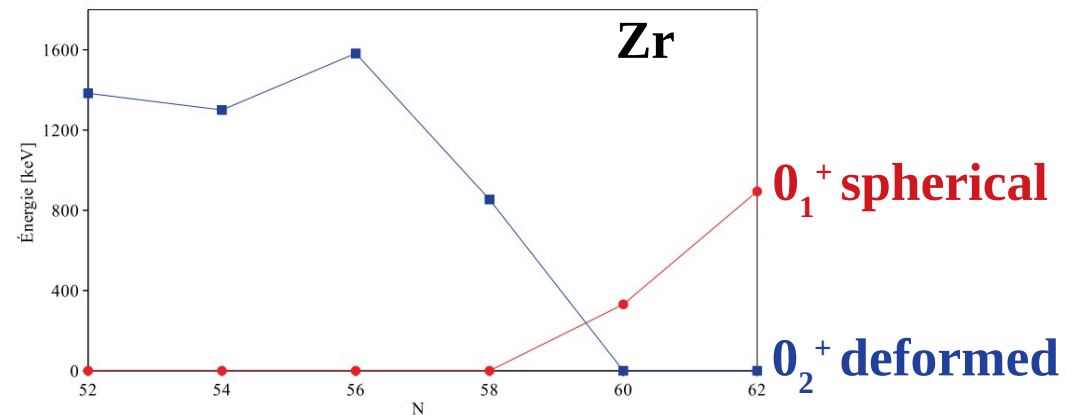
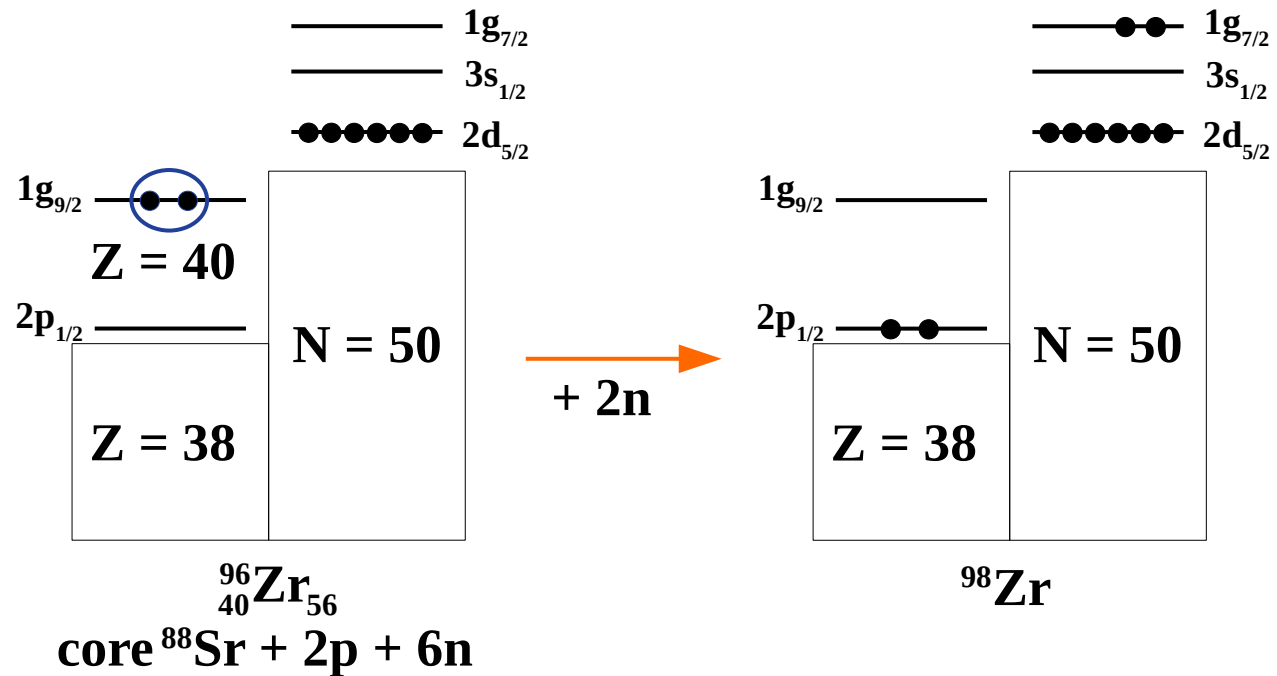
# Physics case : shape transition around N=60



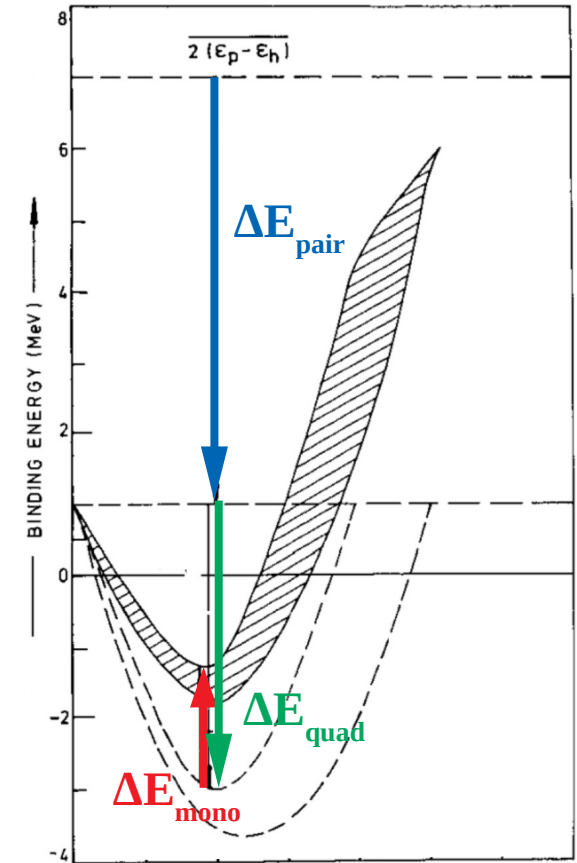
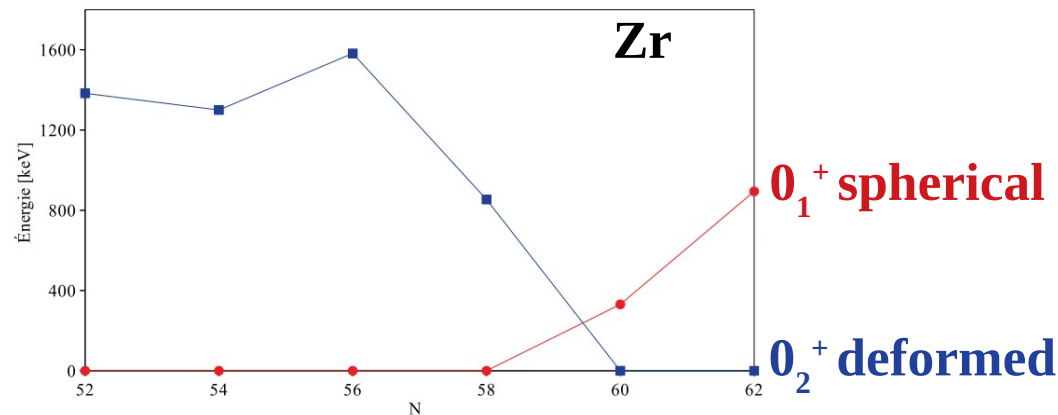
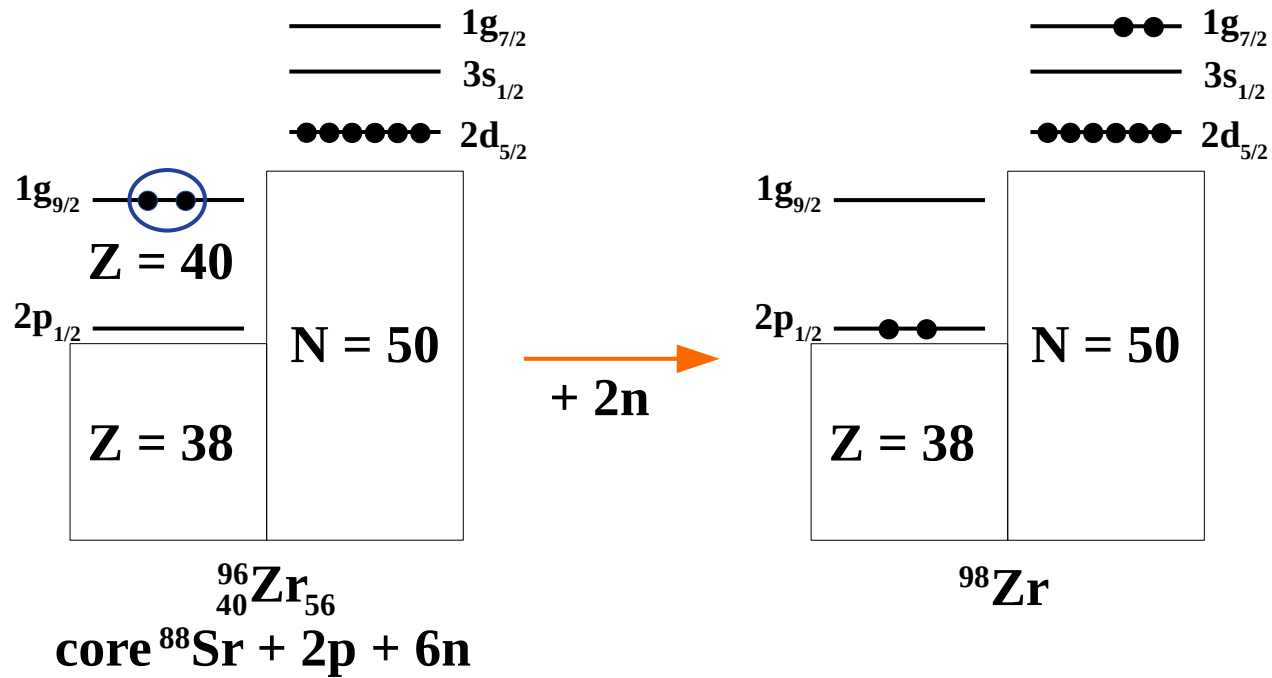
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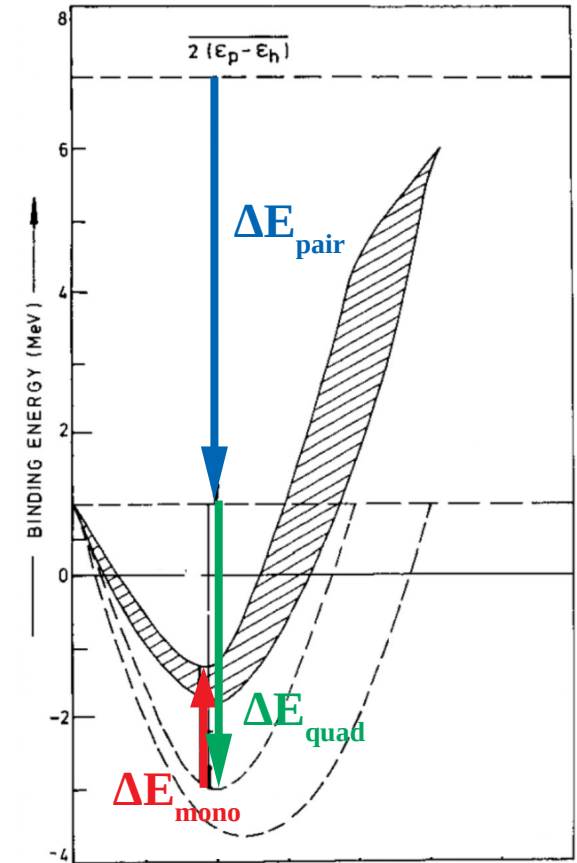
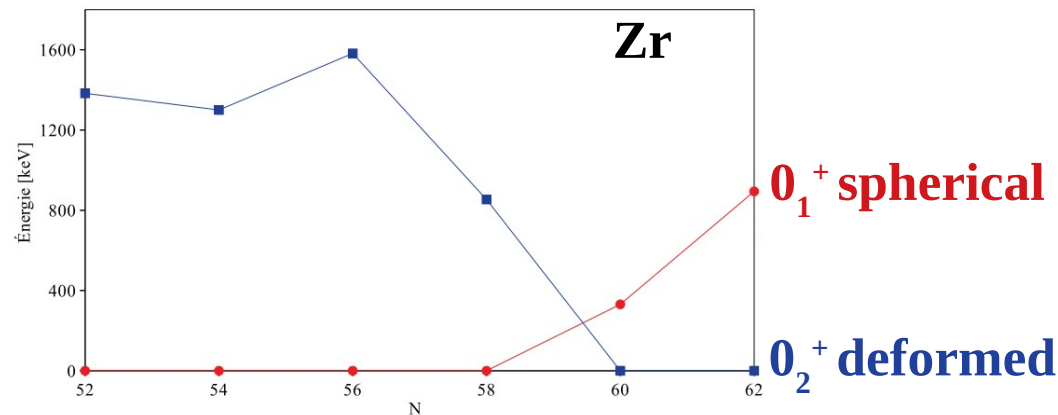
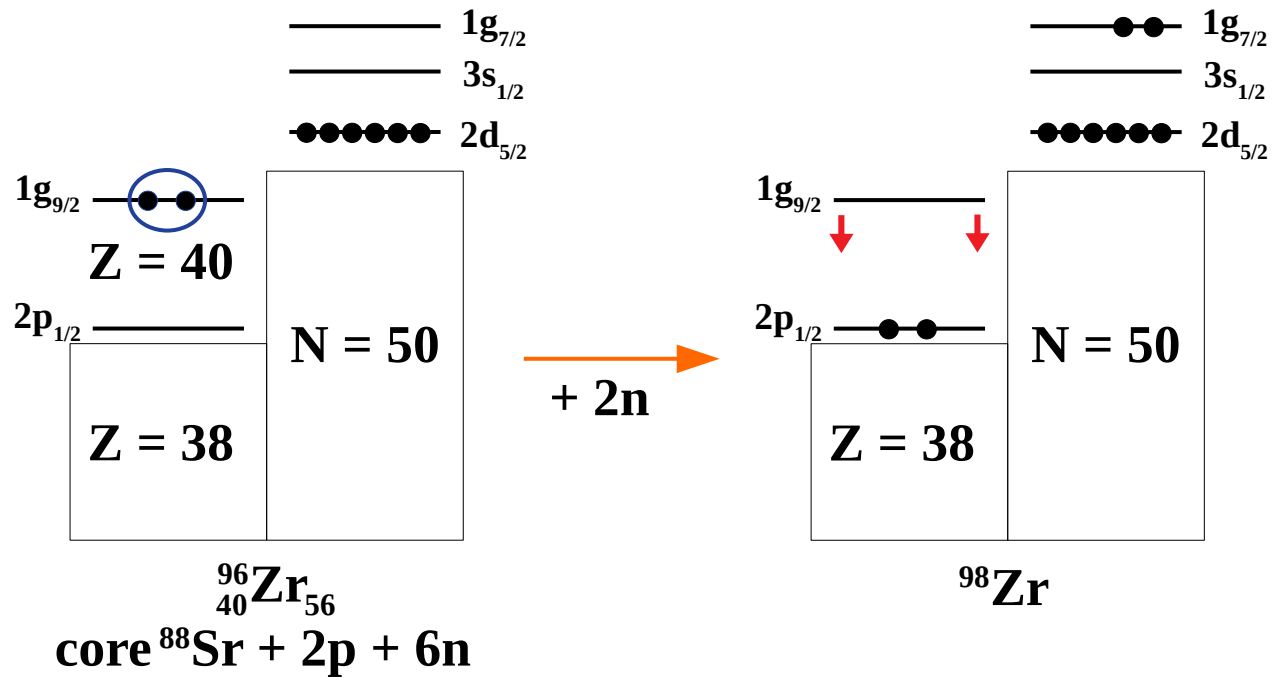


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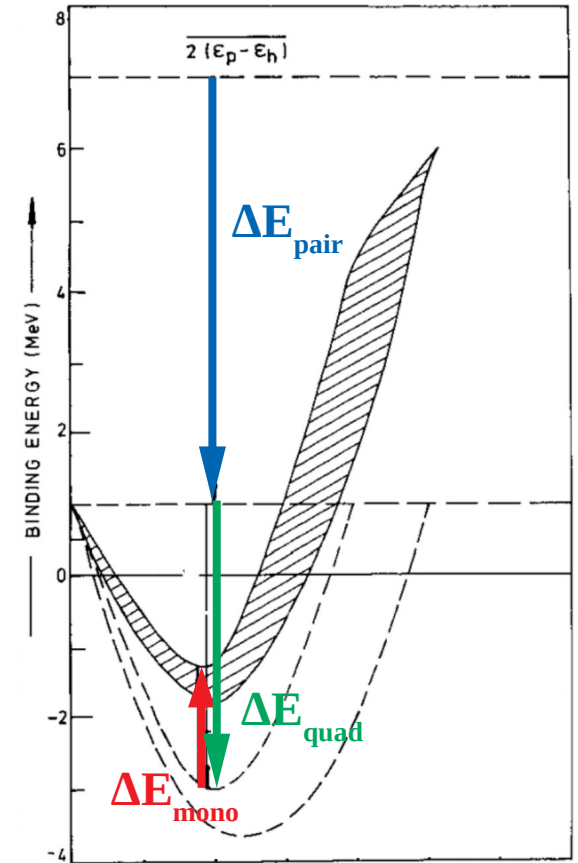
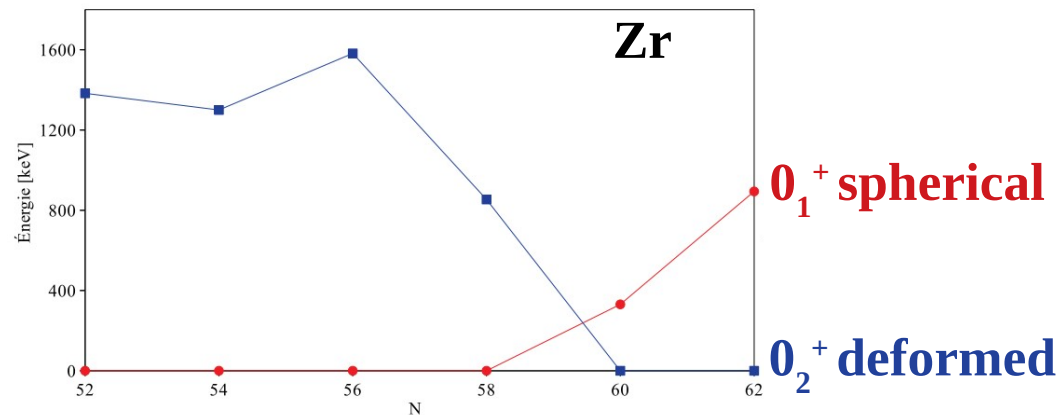
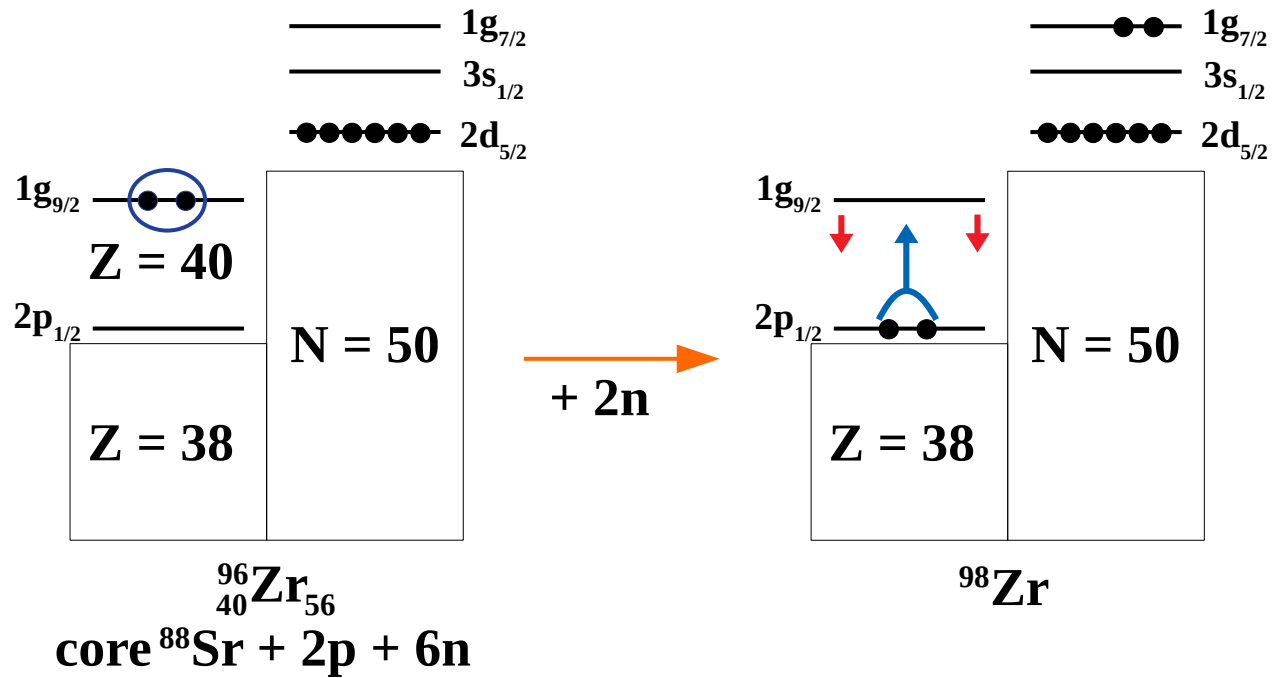
P. Federman and S. Pittel,  
Phys. Rev. C 20, 820, 1979

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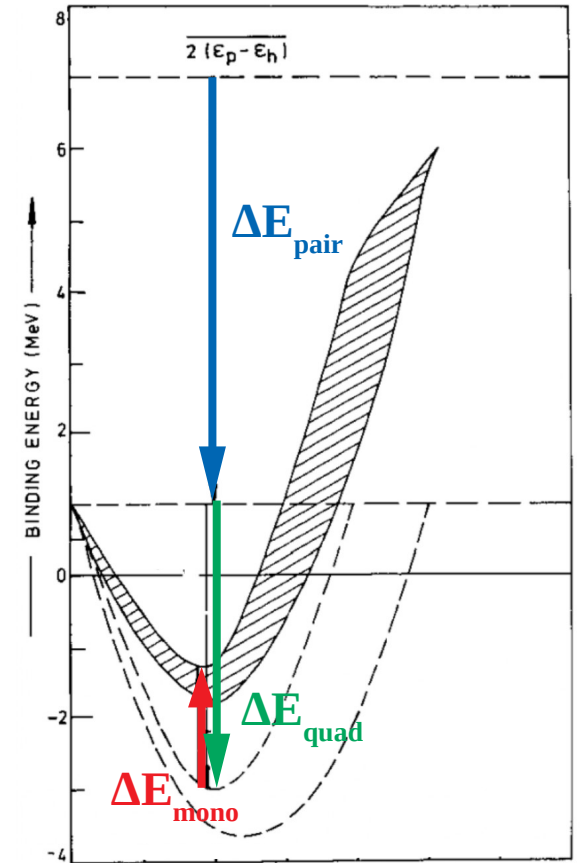
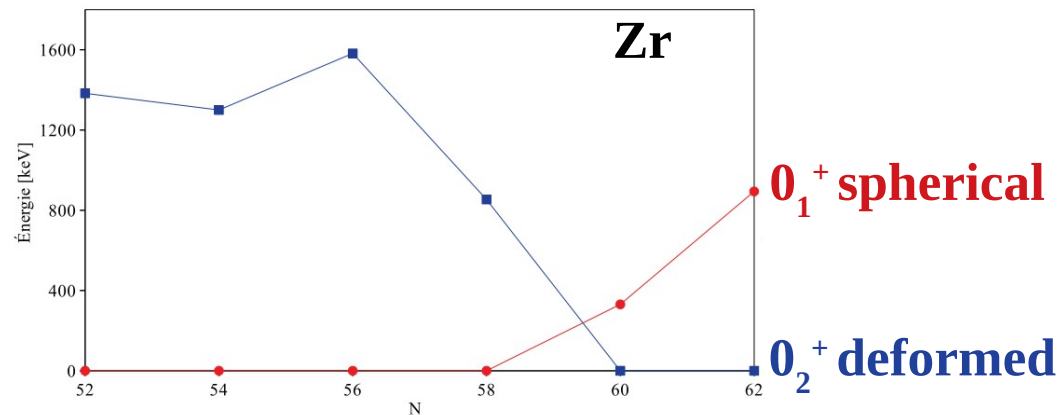
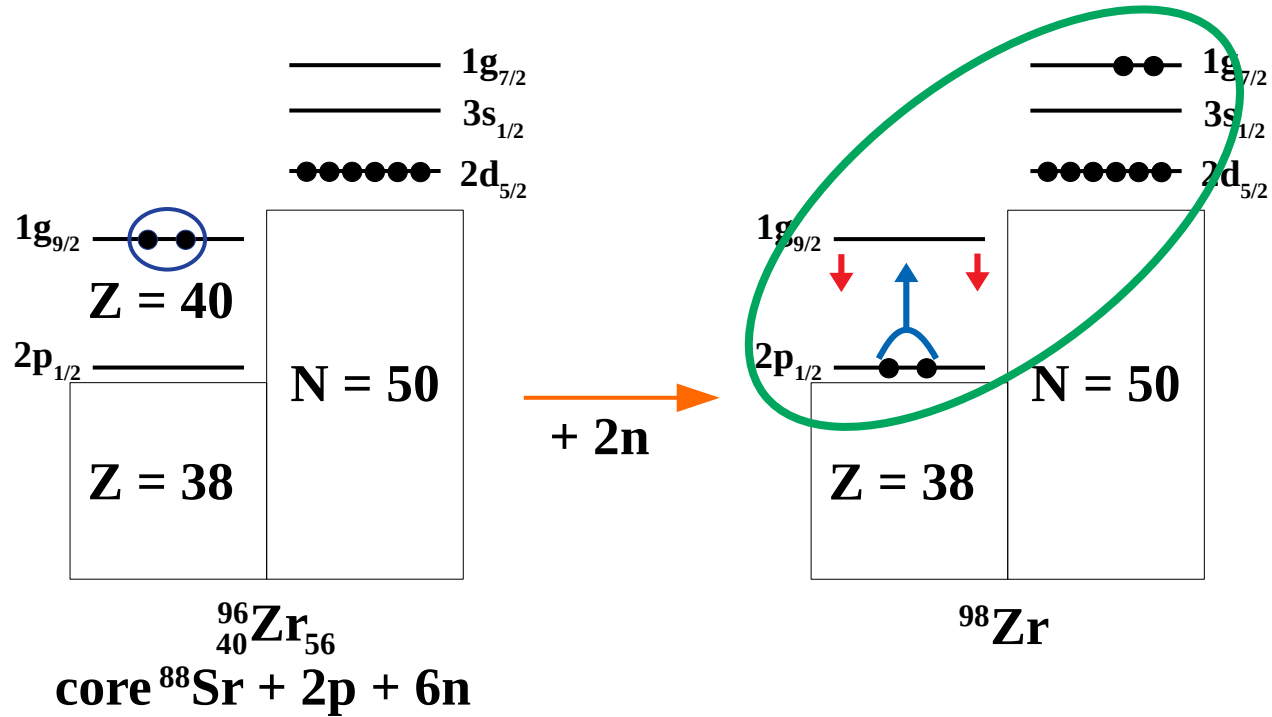
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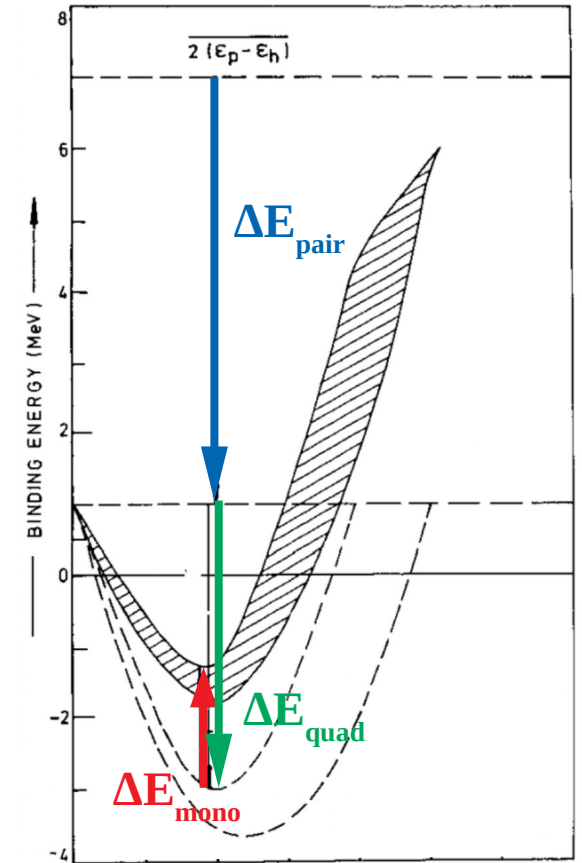
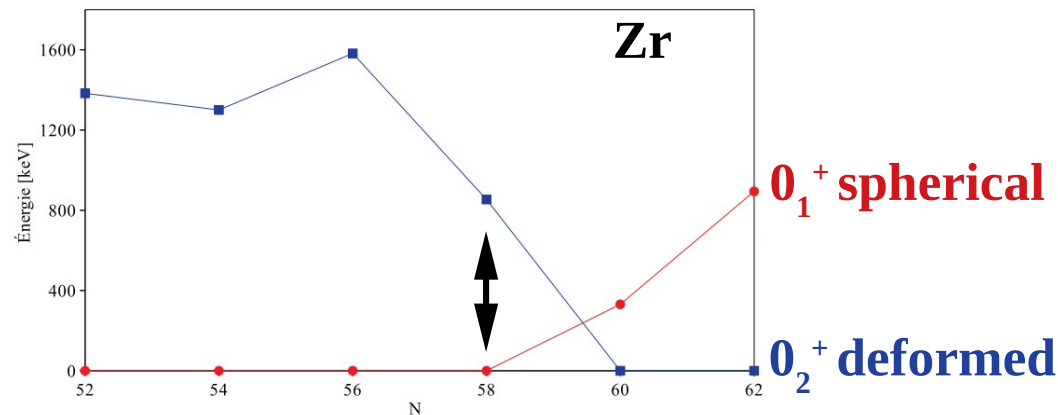
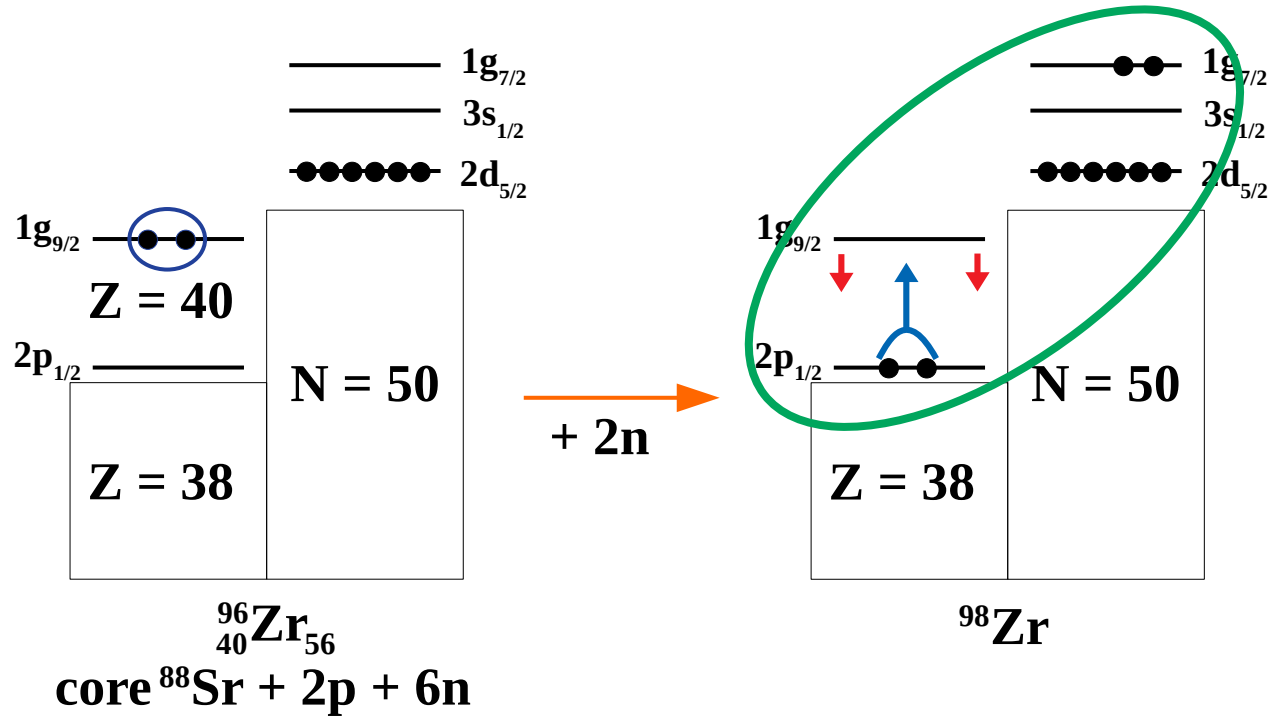
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P. Federman and S. Pittel,  
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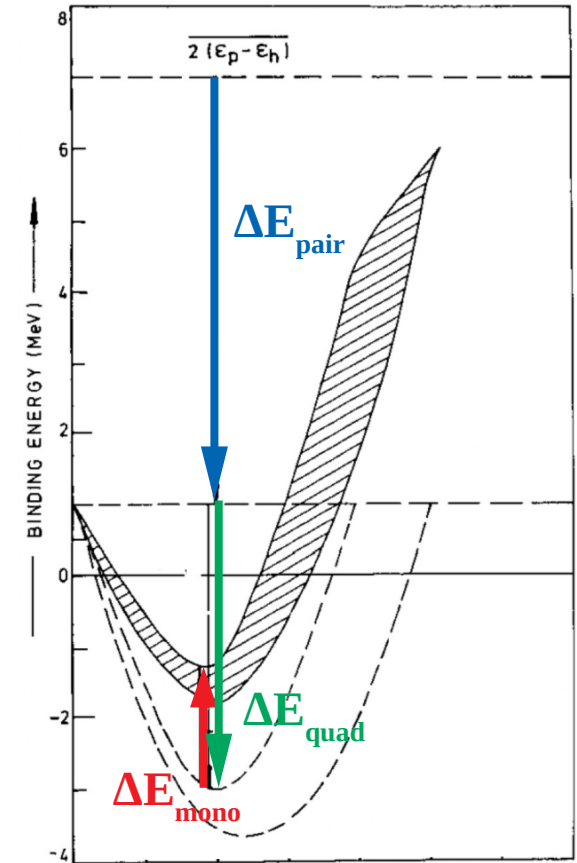
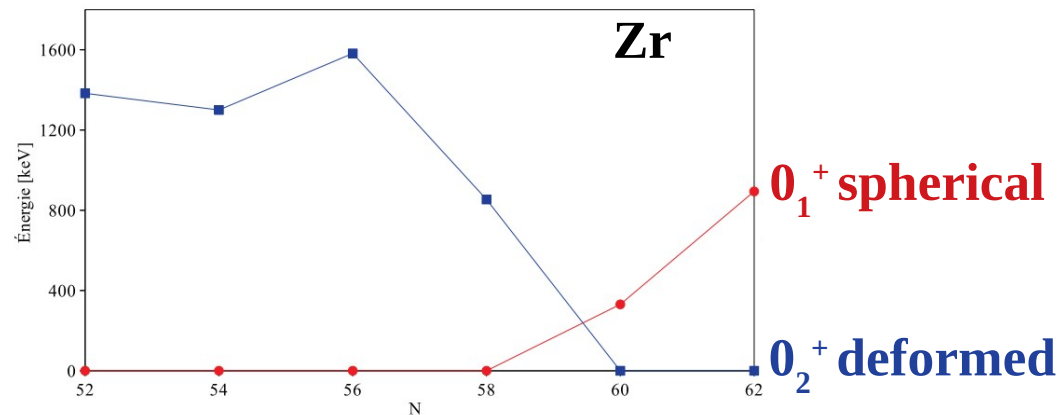
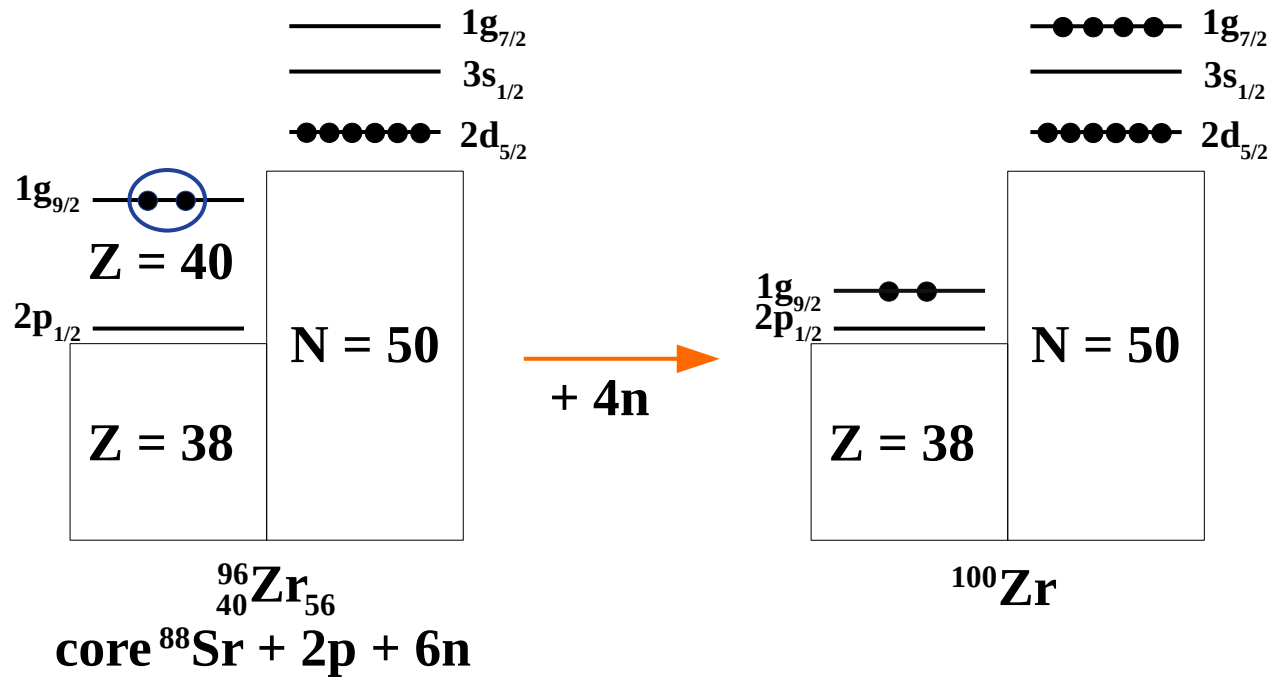


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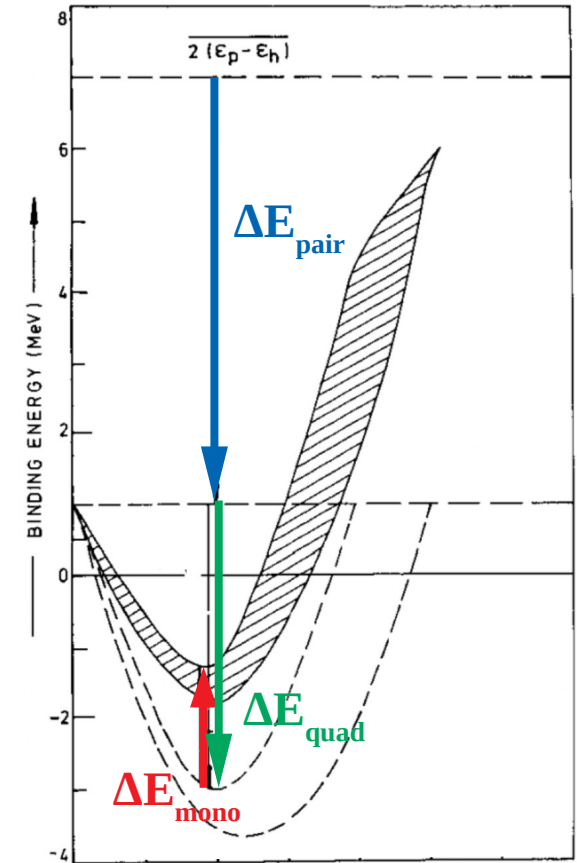
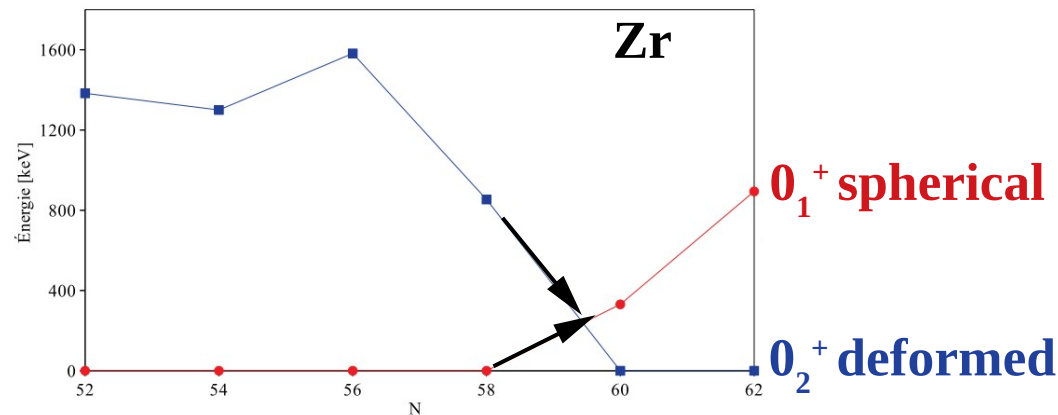
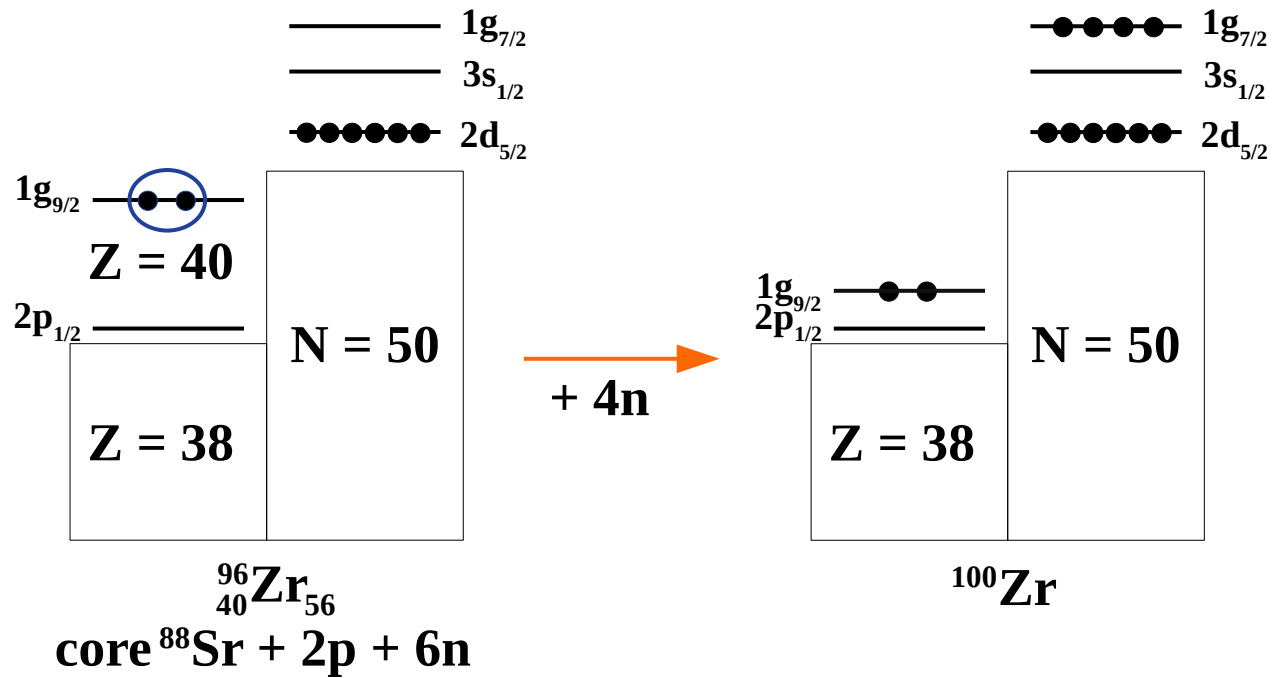
P. Federman and S. Pittel,  
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P. Federman and S. Pittel,  
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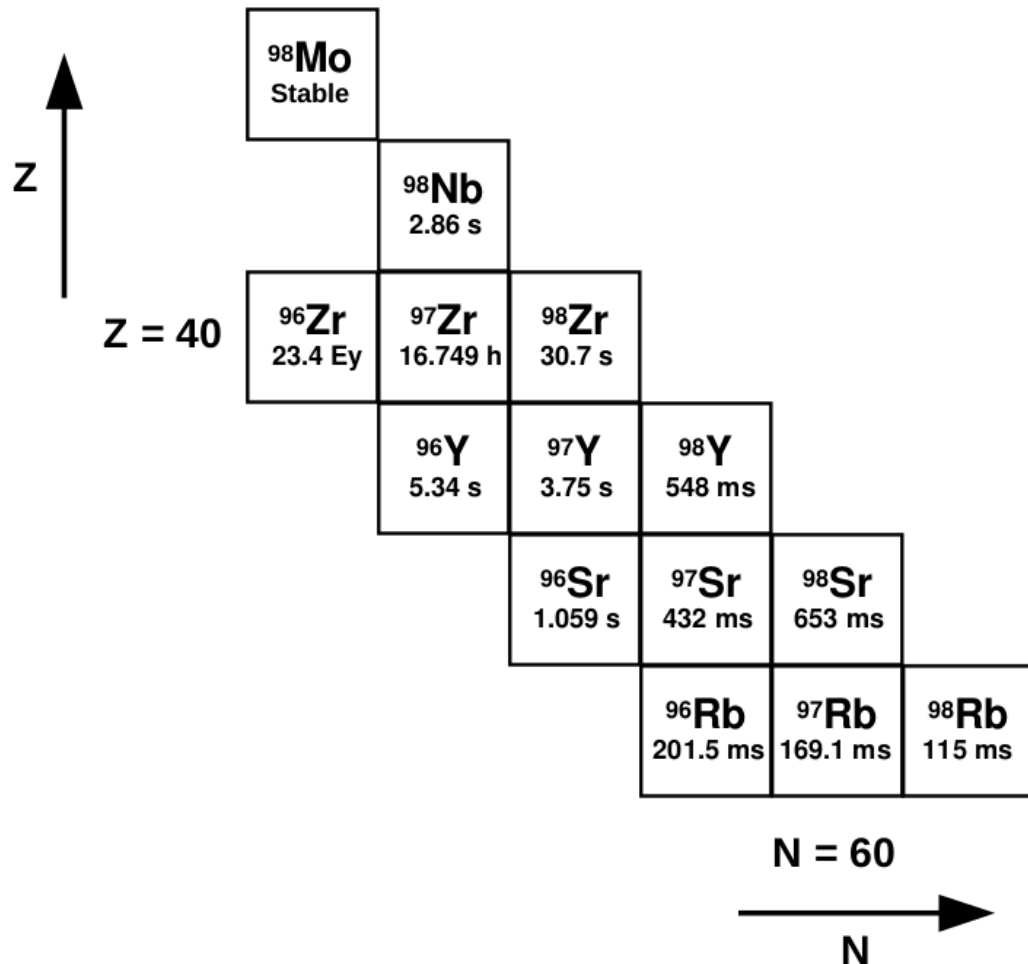
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P. Federman and S. Pittel,  
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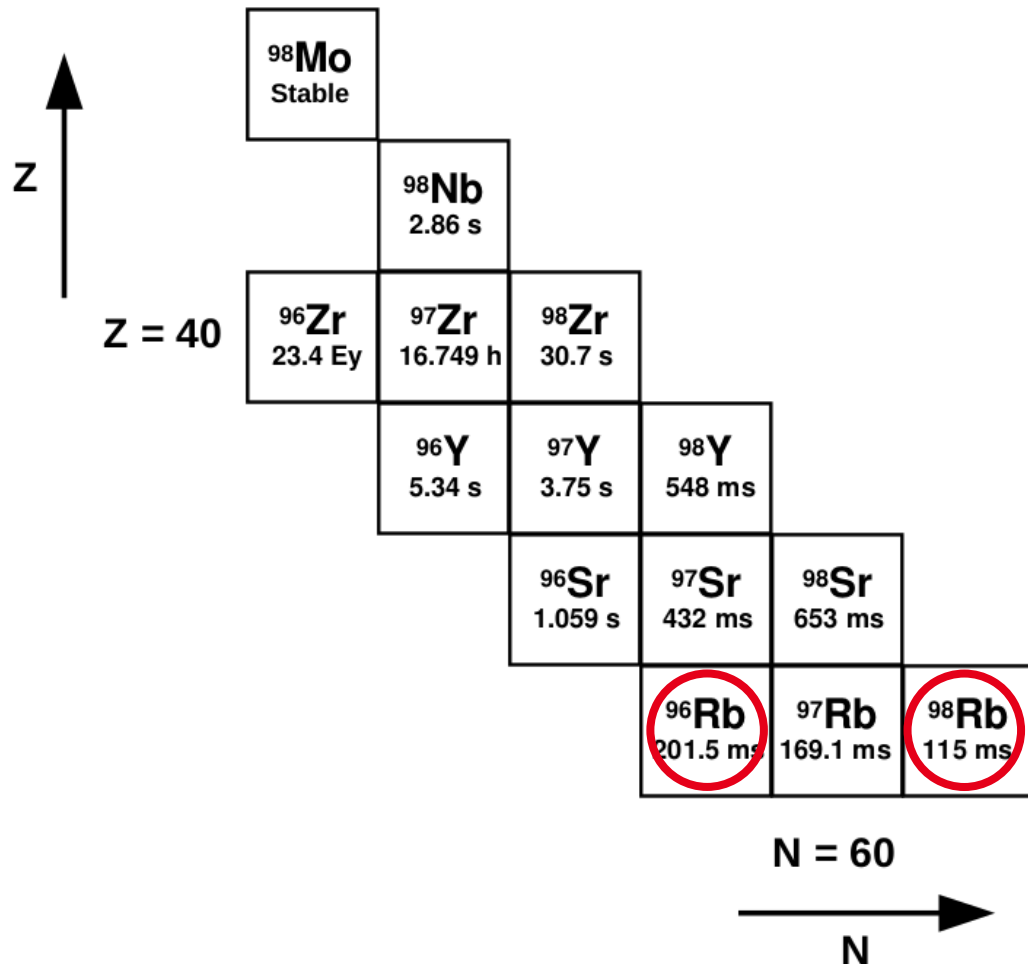
# First experiment with COeCO (2022)

- $^{96-100}\text{Rb}$  beams (surface ionisation)



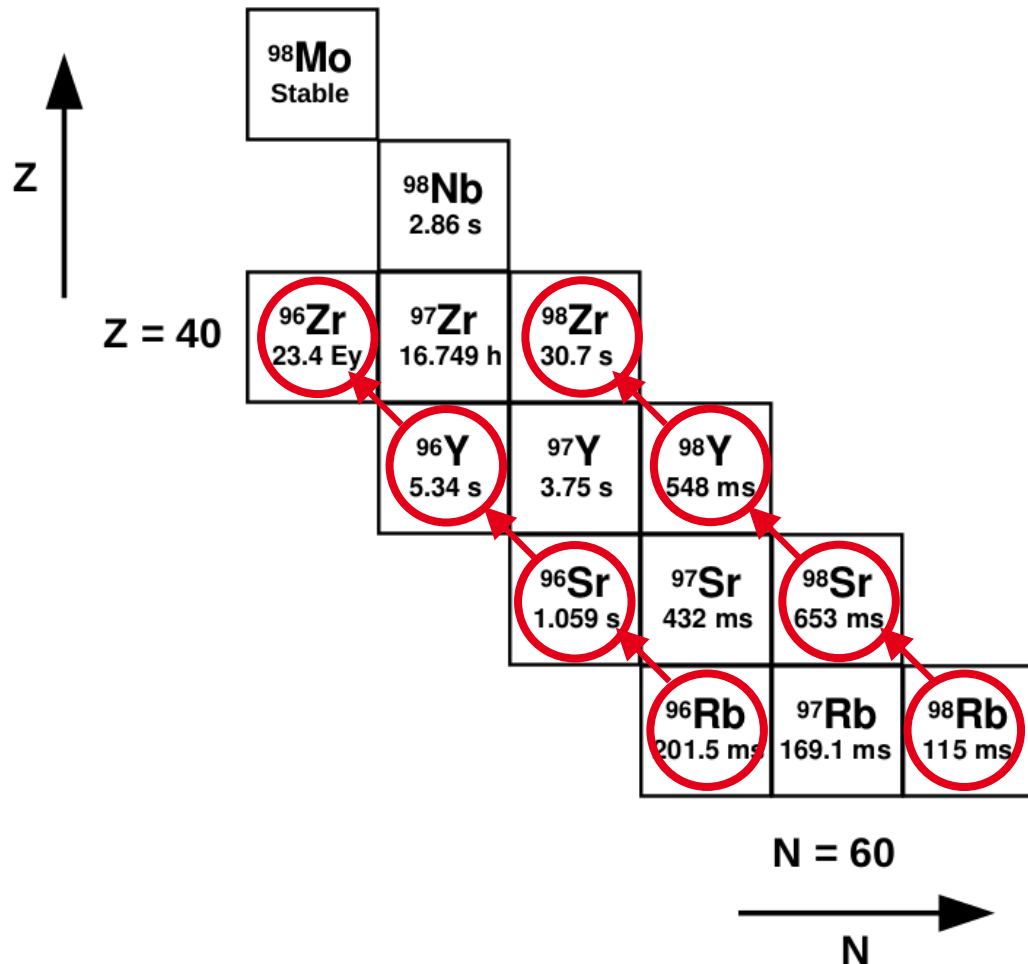
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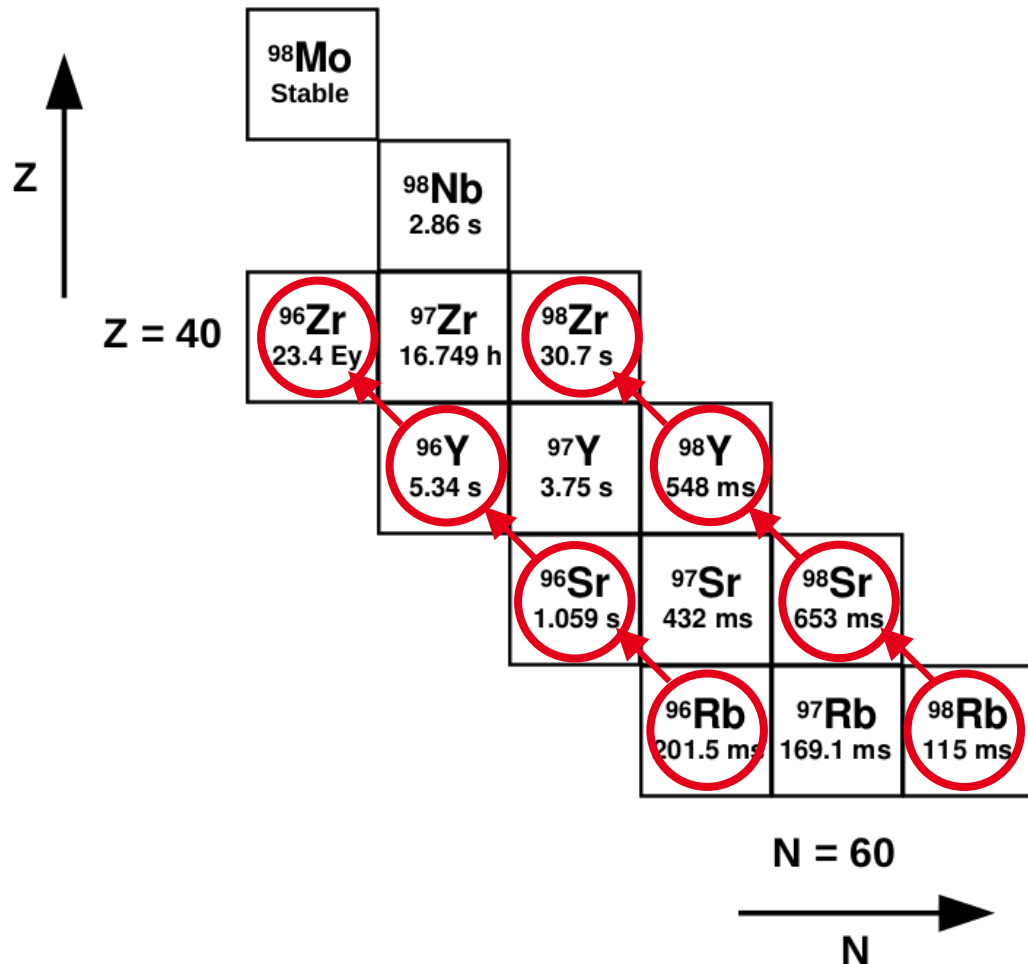
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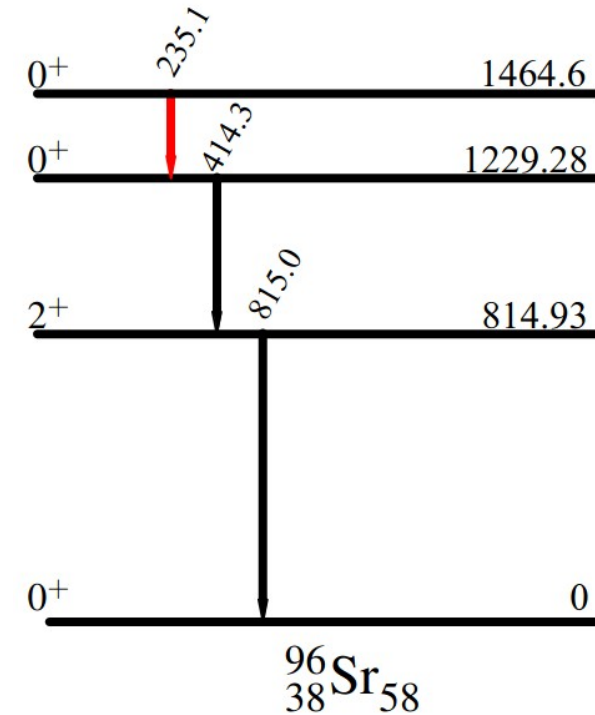
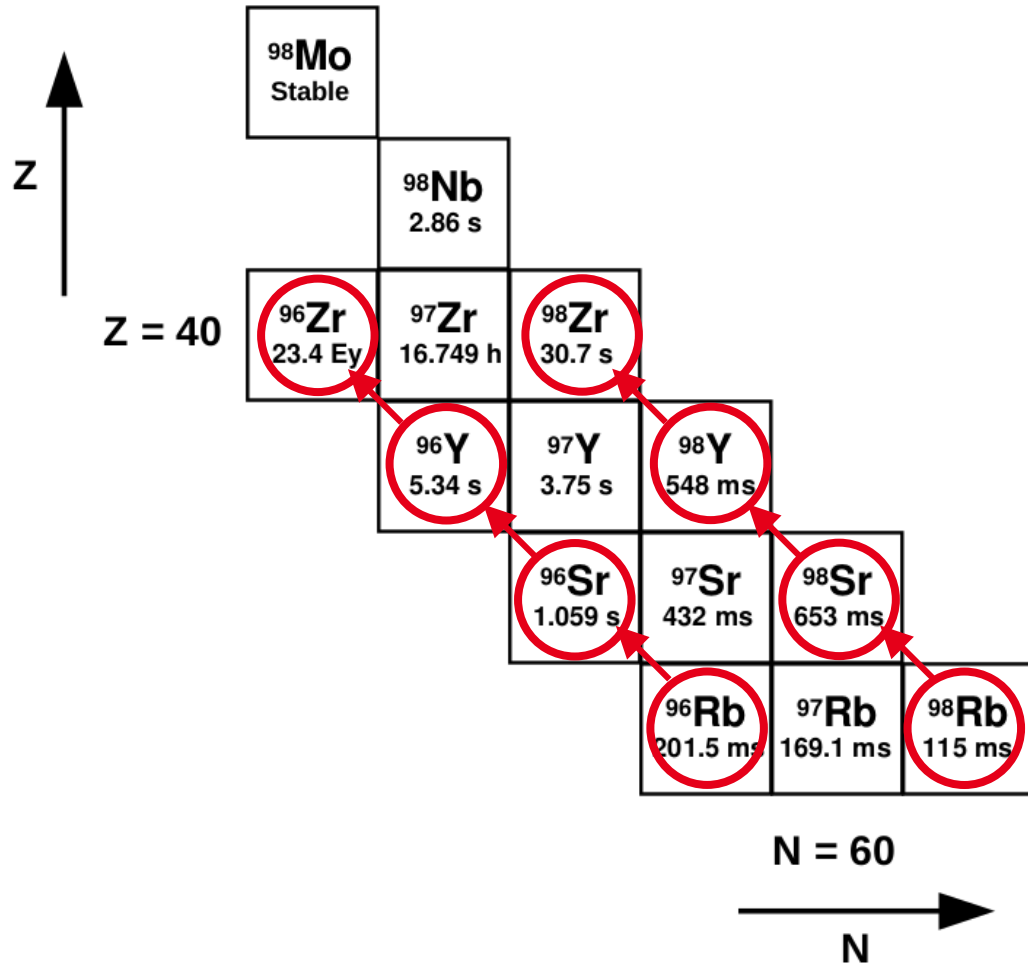
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- Very intense E0 transition in  $^{98}\text{Zr}$

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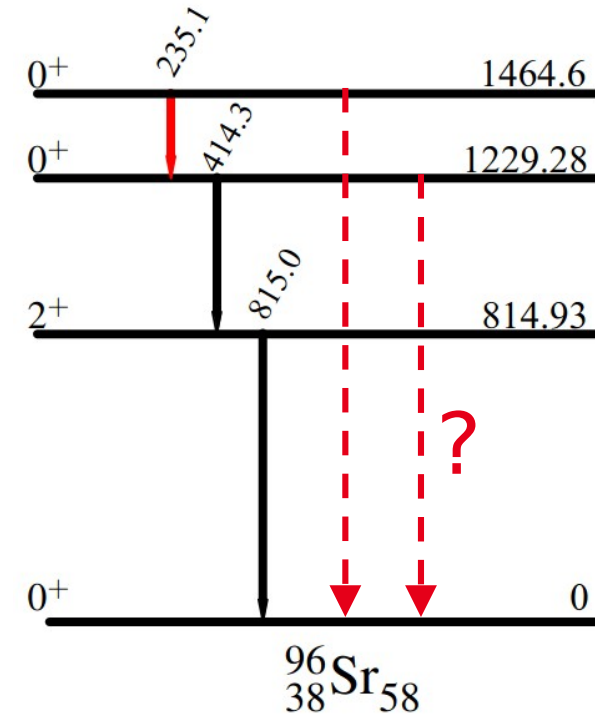
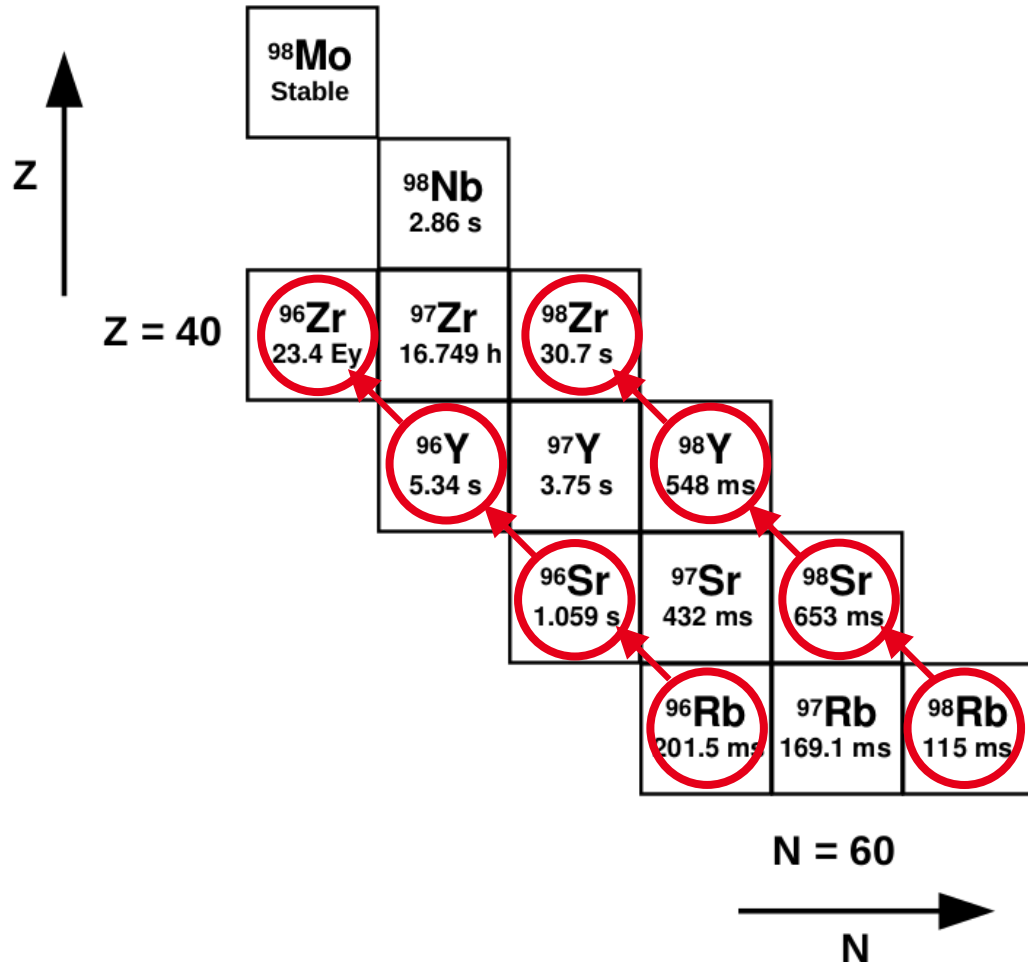


- Very intense E0 transition in  $^{98}\text{Zr}$



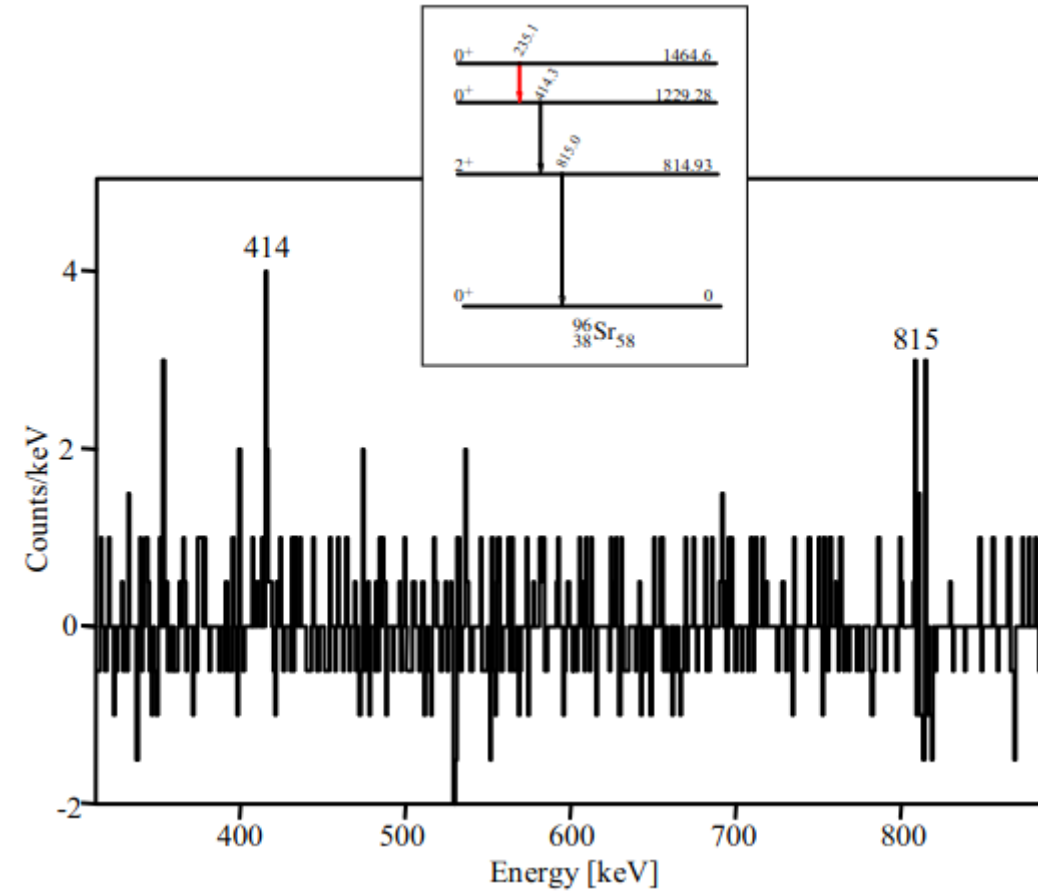
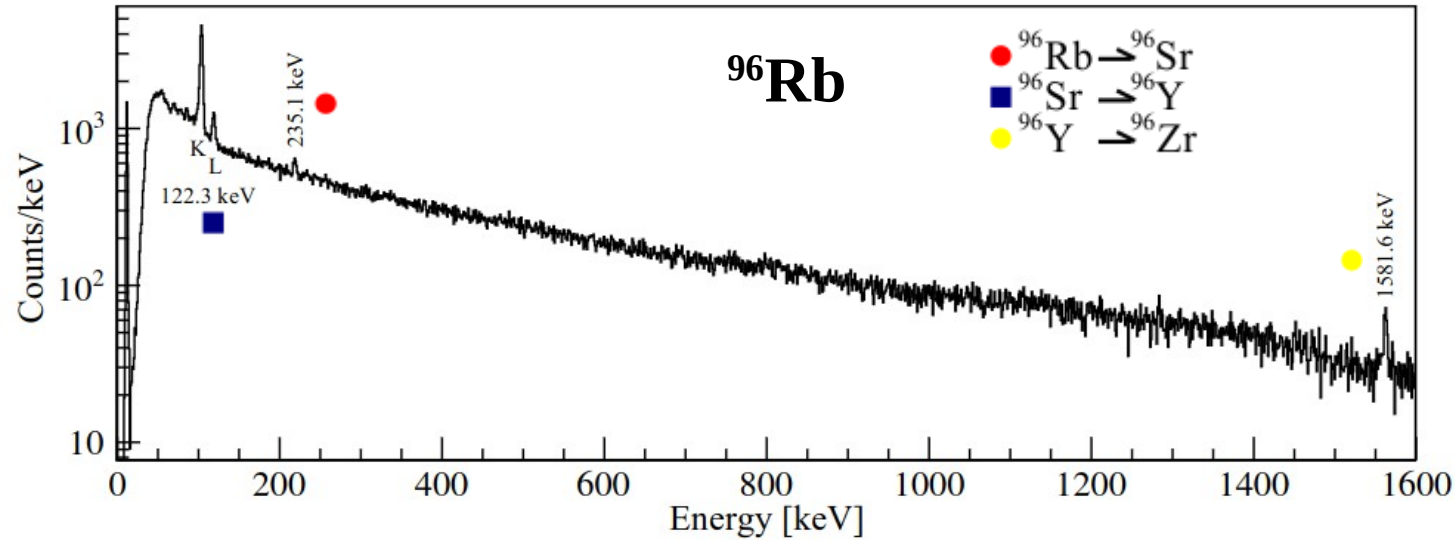
# First experiment with COeCO (2022)

- $^{96-100}\text{Rb}$  beams (surface ionisation)



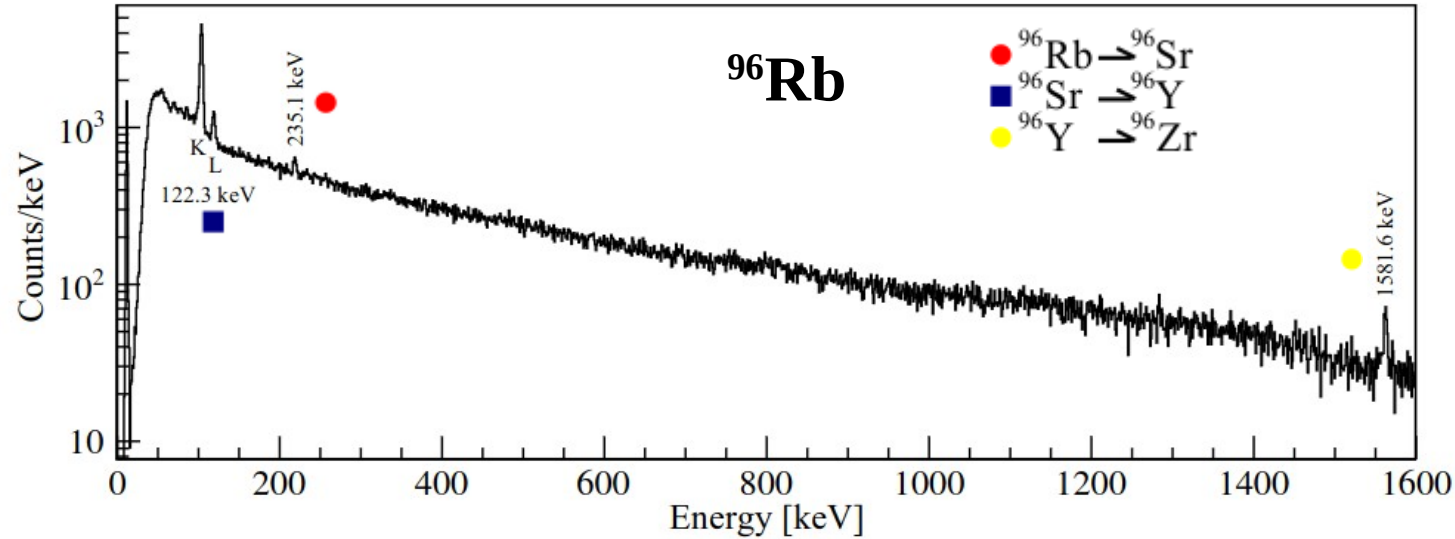
- Very intense E0 transition in  $^{98}\text{Zr}$
- Yet unobserved E0 transitions to the ground state in  $^{96}\text{Sr}$

$^{96}\text{Rb}$ ,  $T_{1/2} = 201.5 \text{ ms}$ ,  $\Phi = 8.10^4 \text{ pps}$

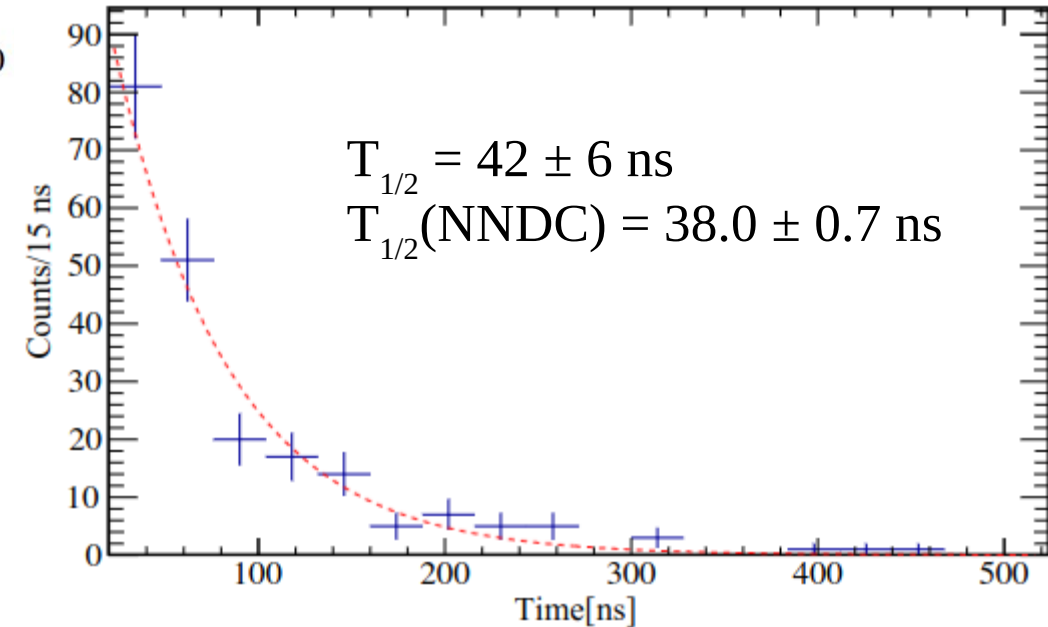


- No trace of any E0 transition to the ground state
- $\gamma$  spectrum gated on E0 transition in  $^{96}\text{Sr}$  validates its placement in the level-scheme
- Measurement of the half-life of the E0 transition in  $^{96}\text{Zr}$

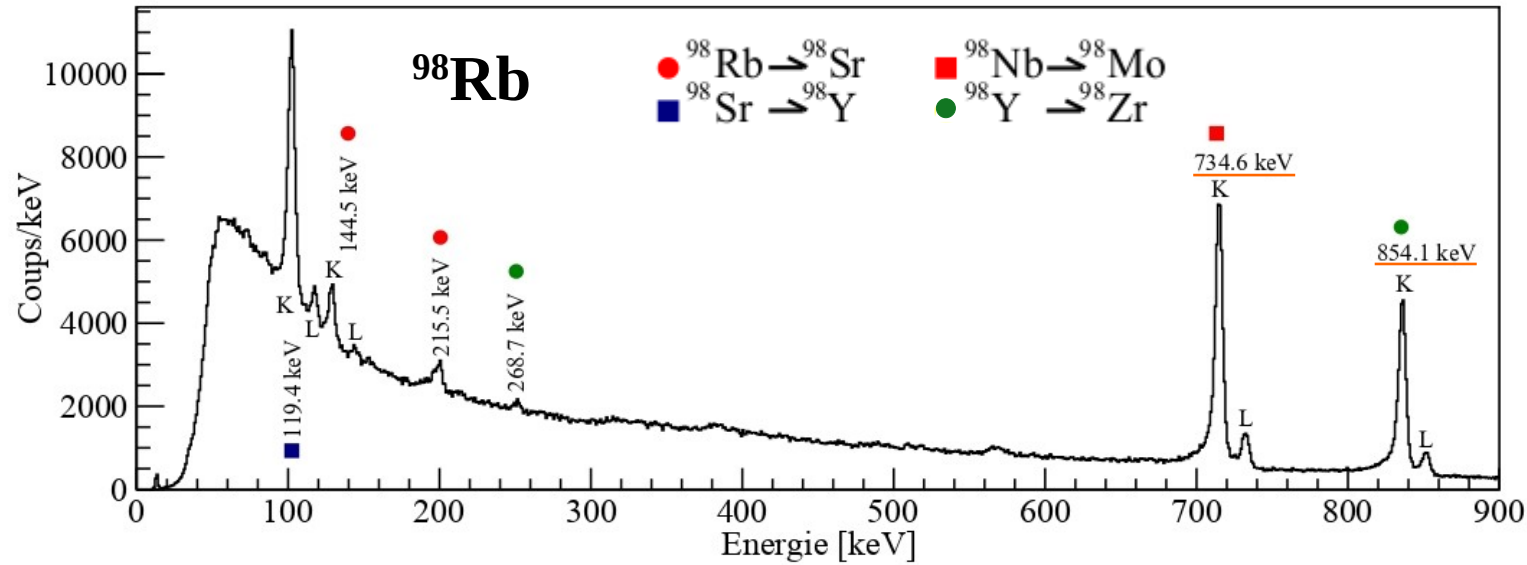
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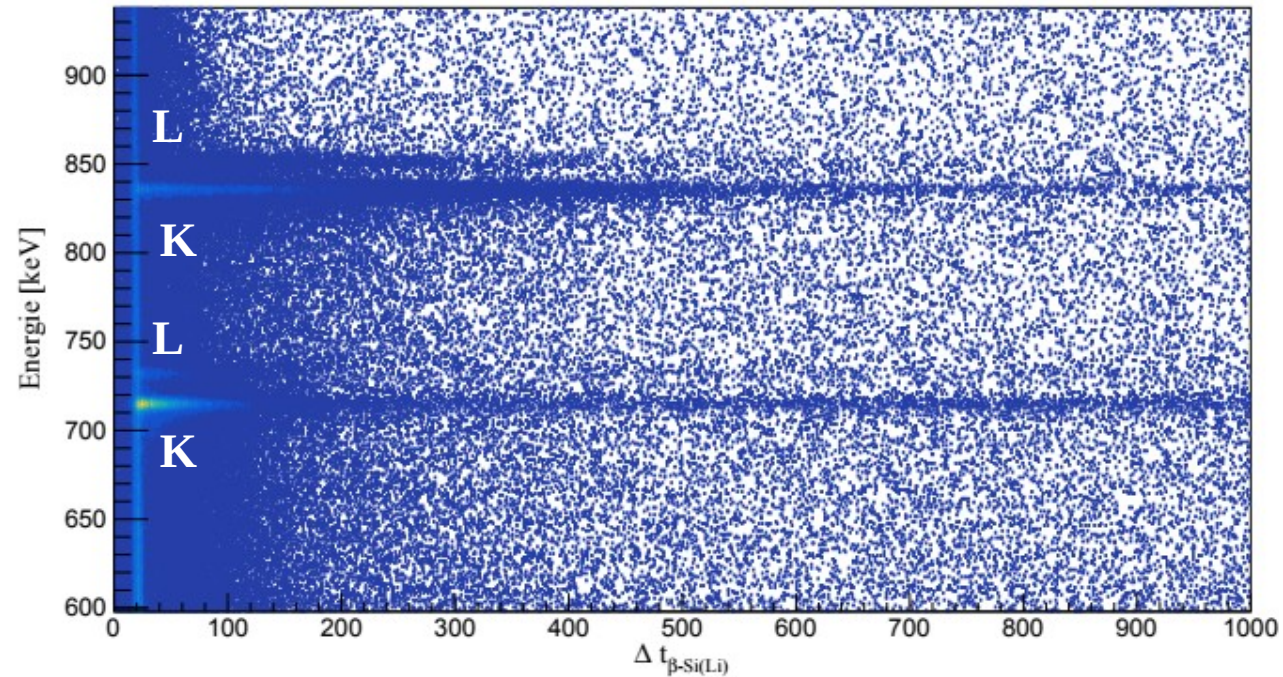


$^{98}\text{Rb}$ ,  $T_{1/2} = 96/115 \text{ ms}$ ,  $\Phi = 4 \cdot 10^3 \text{ pps}$



- Measurement done with fixed tape :  
high activity of the daughter nuclei

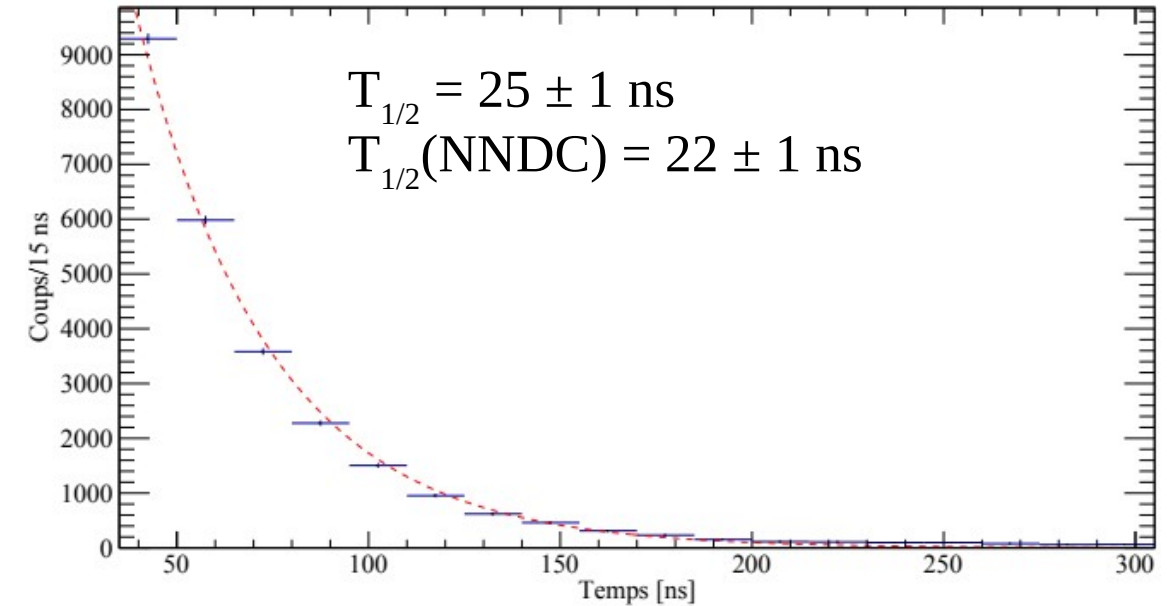
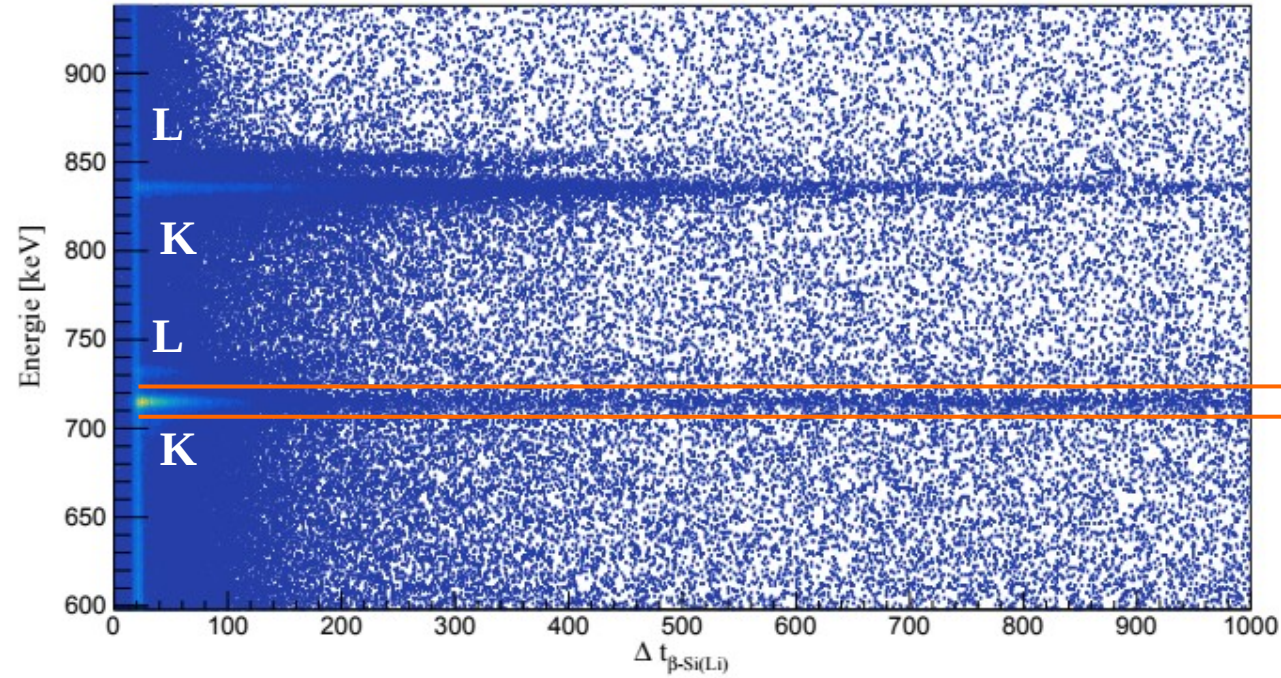
$^{98}\text{Rb}$ ,  $T_{1/2} = 96/115 \text{ ms}$ ,  $\Phi = 4 \cdot 10^3 \text{ pps}$



- Time difference between an event in the plastic scintillator ( $\beta$ ) and an event in the Si(Li) (CE)

- Compute strength of the transition,  $\rho^2 = \frac{\ln(2)}{T_{1/2} \Omega_K}$

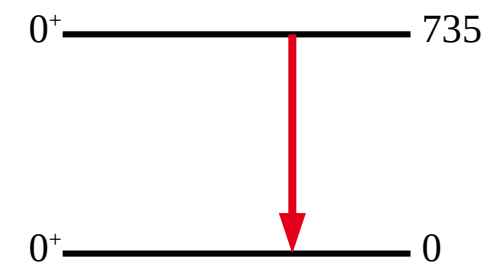
$^{98}\text{Rb}$ ,  $T_{1/2} = 96/115 \text{ ms}$ ,  $\Phi = 4 \cdot 10^3 \text{ pps}$



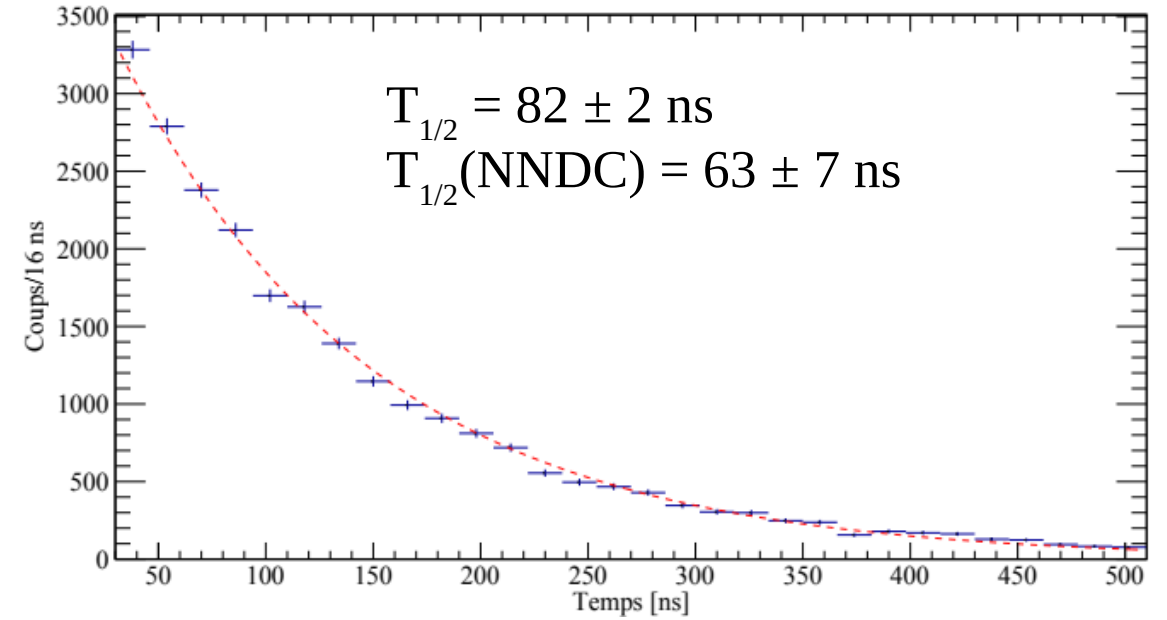
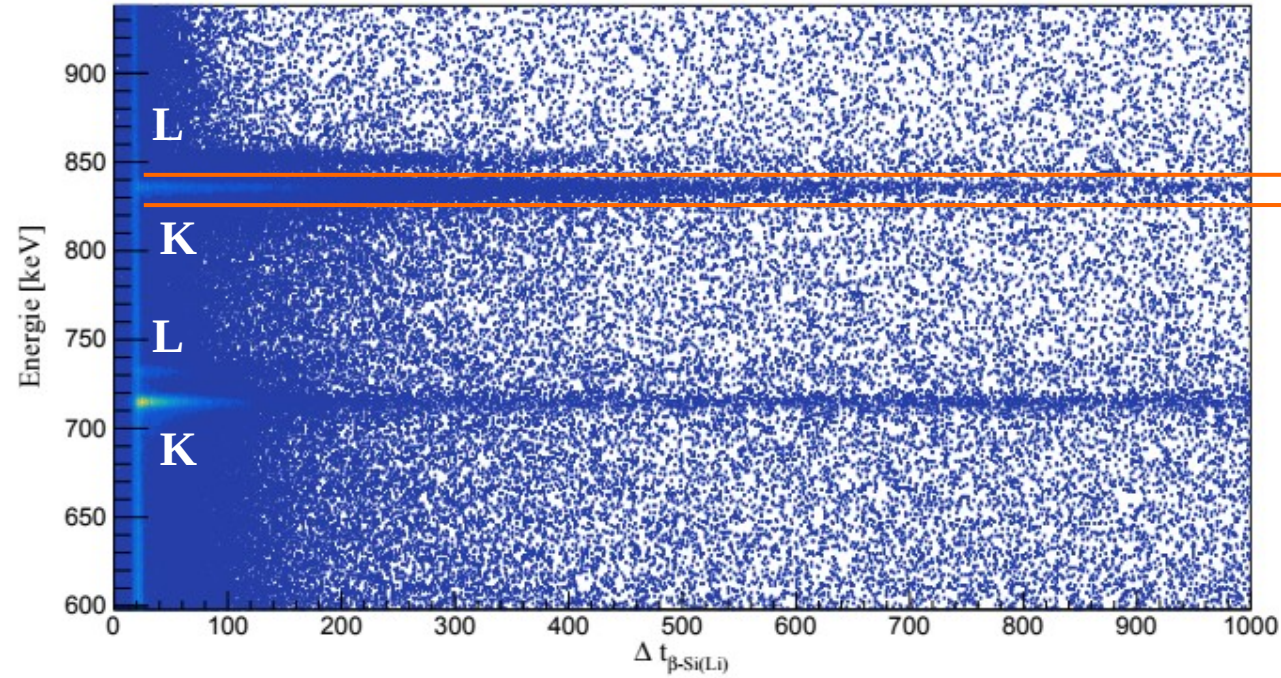
- Time difference between an event in the plastic scintillator ( $\beta$ ) and an event in the Si(Li) (CE)

- Compute strength of the transition,  $\rho^2 = \frac{\ln(2)}{T_{1/2} \Omega_K}$

- Time behaviour of the E0 transition at 735keV in  $^{98}\text{Mo}$

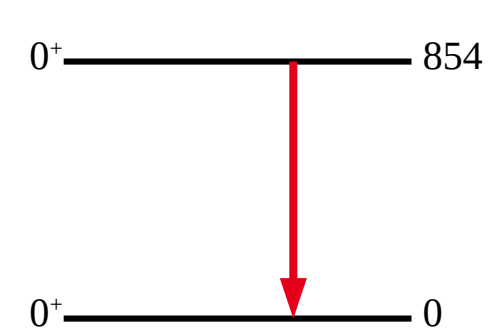


# $^{98}\text{Rb}$ , $T_{1/2} = 96/115 \text{ ms}$ , $\Phi = 4 \cdot 10^3 \text{ pps}$



- Time difference between an event in the plastic scintillator ( $\beta$ ) and an event in the Si(Li) (CE)

- Compute strength of the transition,  $\rho^2 = \frac{\ln(2)}{T_{1/2} \Omega_K}$



- Time behaviour of the E0 transition at 854keV in  $^{98}\text{Zr}$

$$\rho^2 = 9,6 \cdot 10^{-3}$$

# Two-states mixing model

States resulting from the mixing of two deformed states 1 and 2 with mixing angle  $\theta$  :

$$\begin{cases} |0_i^+\rangle = \cos\theta |0_1^+\rangle + \sin\theta |0_2^+\rangle \\ |0_f^+\rangle = -\sin\theta |0_1^+\rangle + \cos\theta |0_2^+\rangle \end{cases}$$

Transition strength given by :

$$\rho^2(E0) = \left| \frac{\langle \Phi_f | \hat{T}(E0) | \Phi_i \rangle}{eR^2} \right|^2$$

If the surface of both states shape can be described by a sum of spherical harmonics :

$$\rho^2(E0) = \frac{Z^2}{R_0^2} \cos^2\theta \sin^2\theta \left[ \Delta \langle r^2 \rangle \right]^2$$

Mixing amplitude can be measured via reduced transition probabilities :

$$\cos^2(\theta) = 0.90(5)$$

Garrett *et al.*, An experimental view on shape coexistence in nuclei, 10.1016/j.pnpnp.2021.10393

$$\delta \langle r \rangle^2 = 0.29 \pm 0.02 \text{ fm}^2$$



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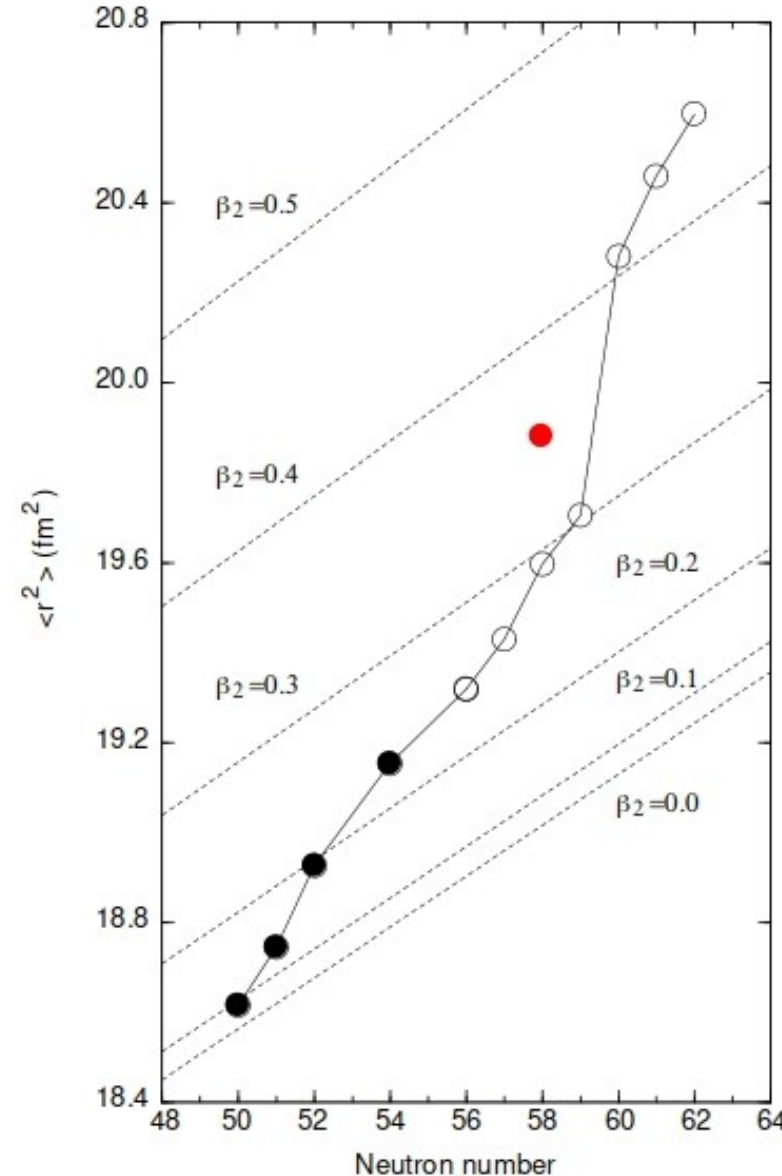


Figure from Campbell et al., PRL 89(8), 2002,  
10.1103/PhysRevLett.89.082501

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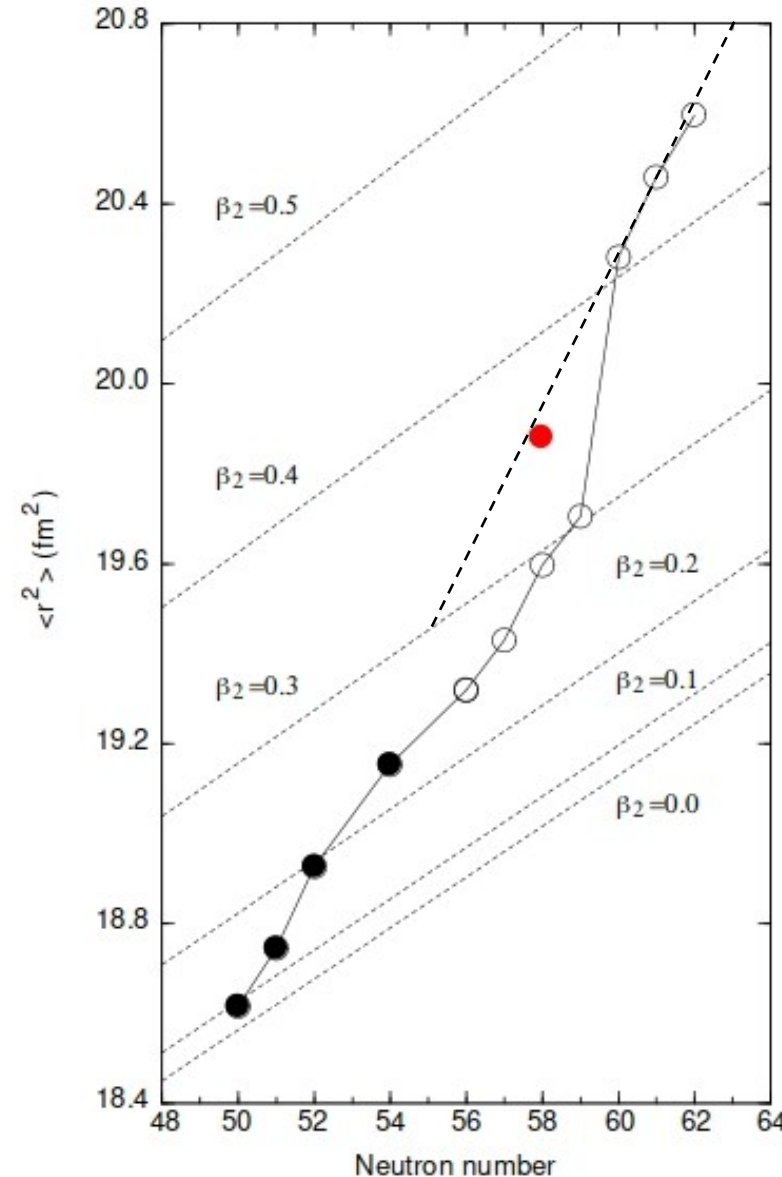
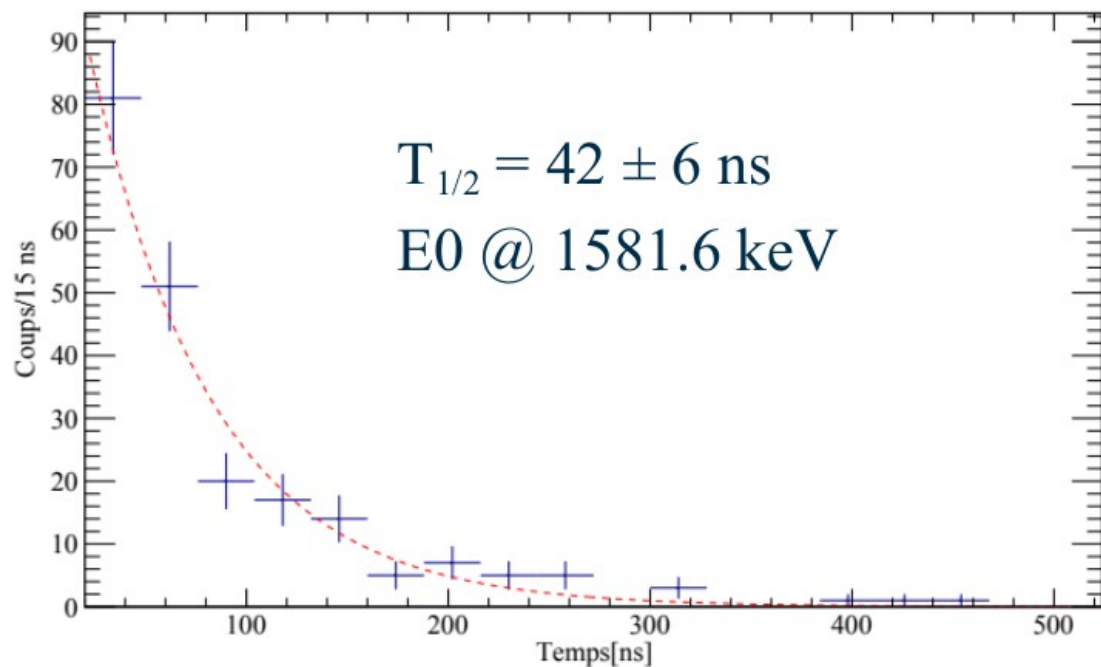
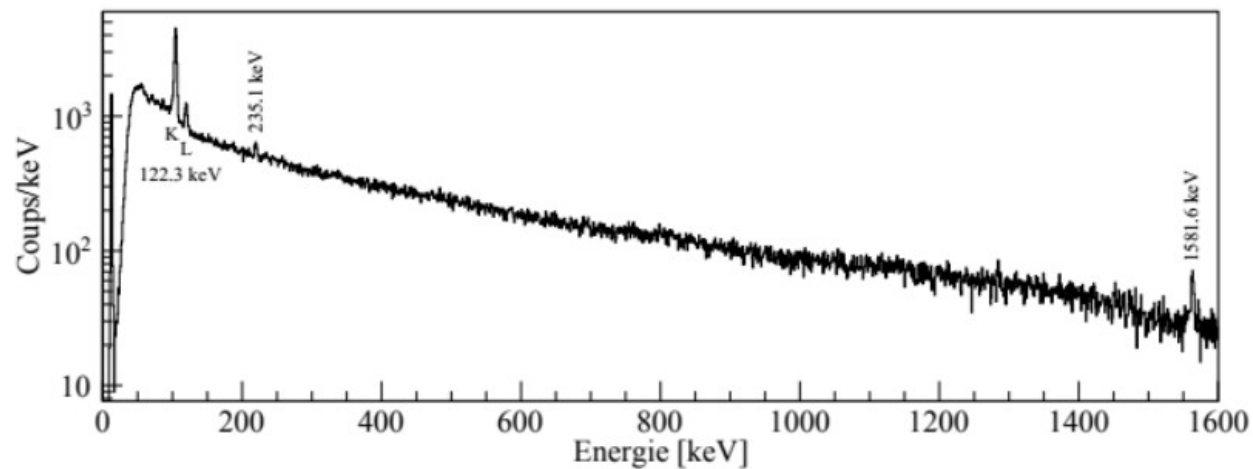
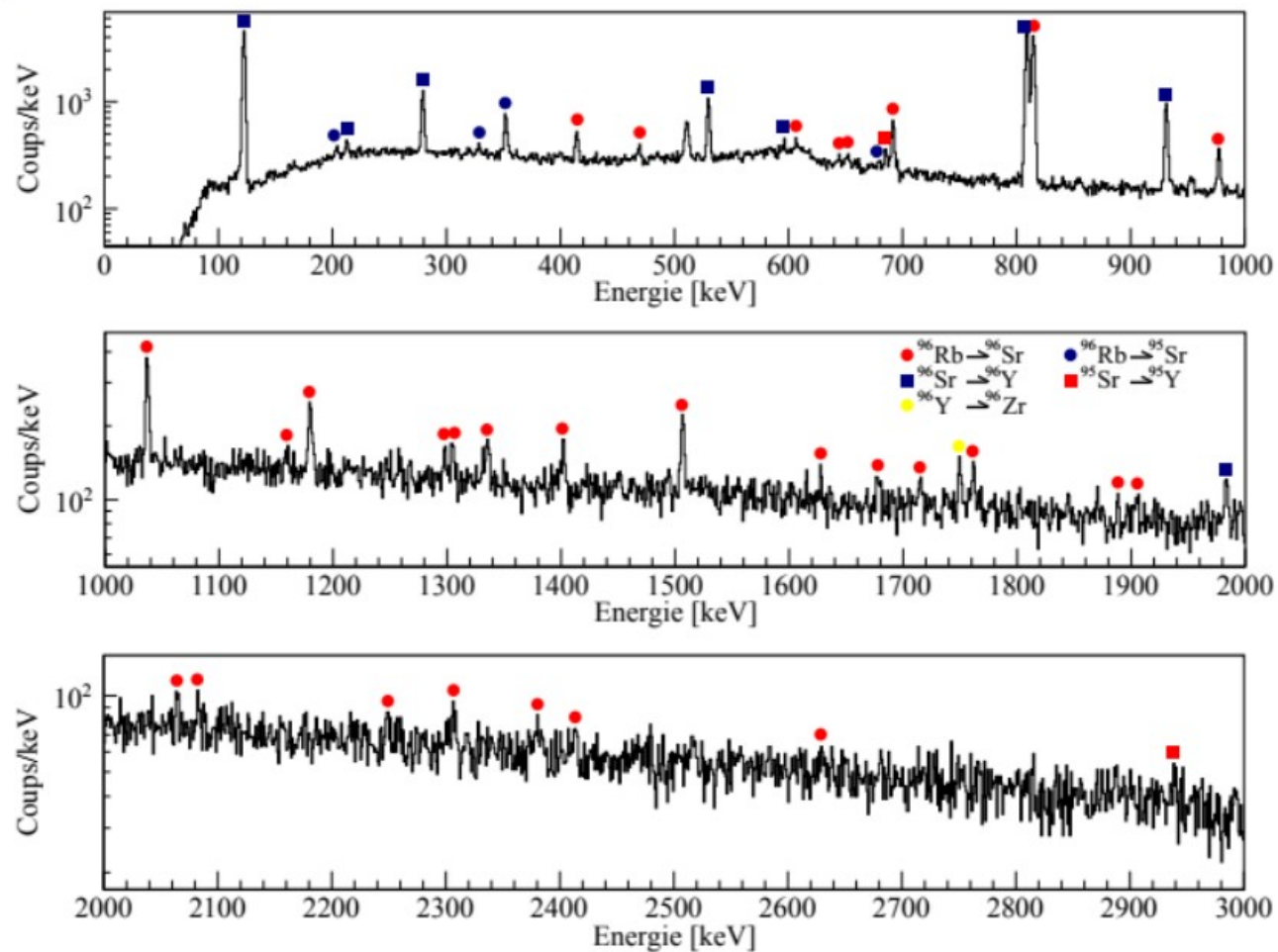


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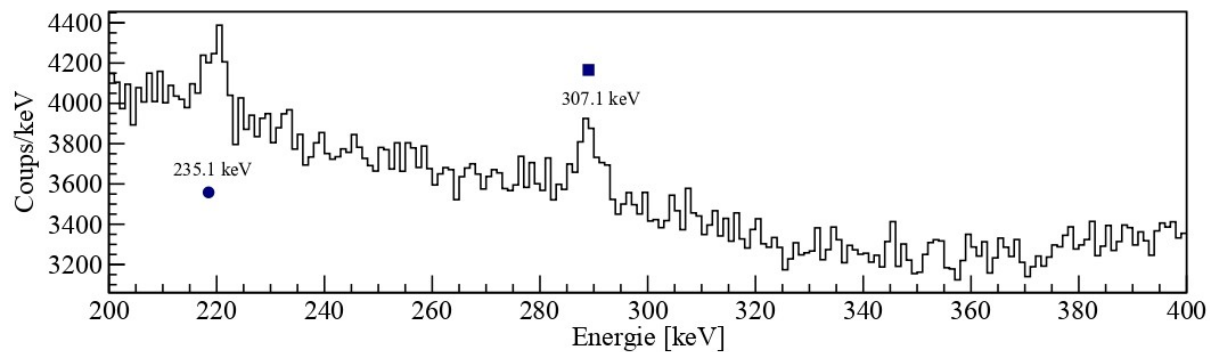
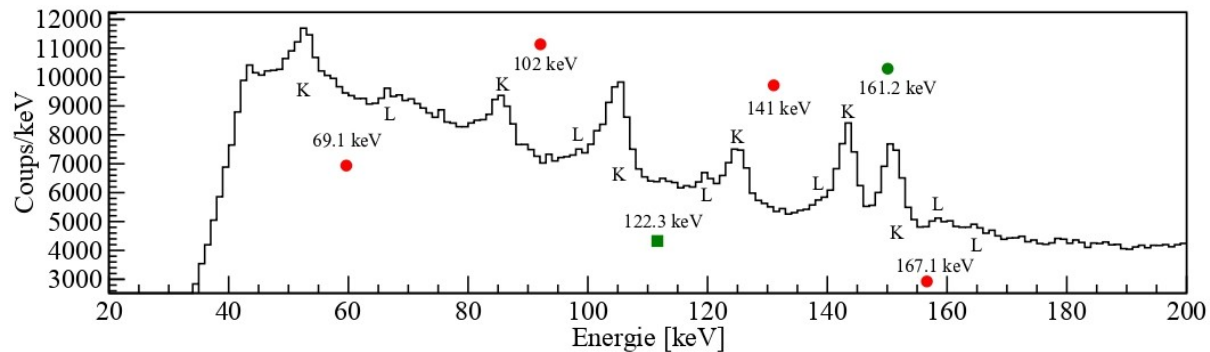
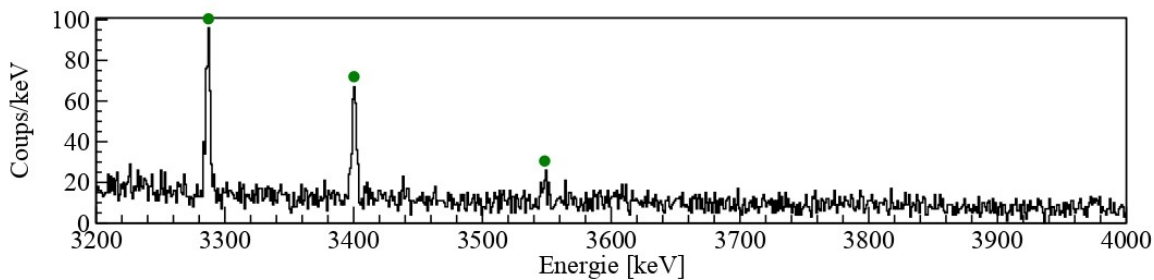
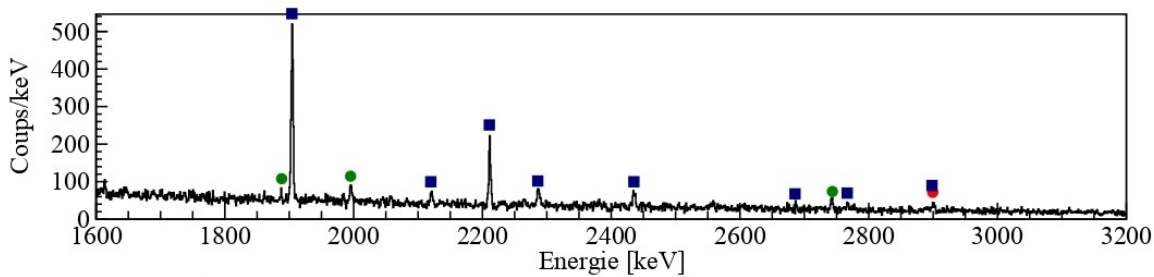
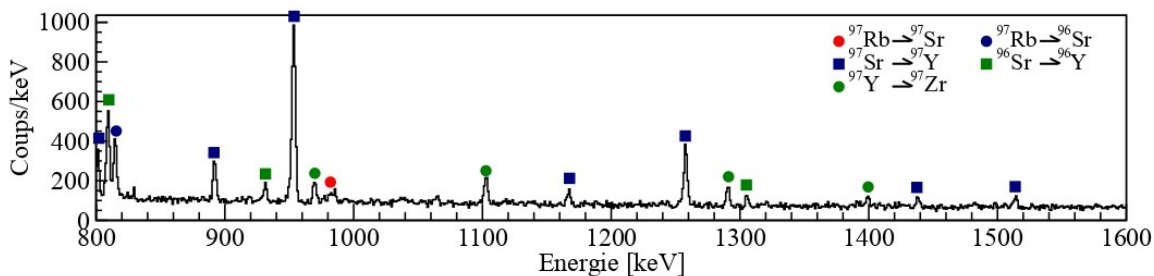
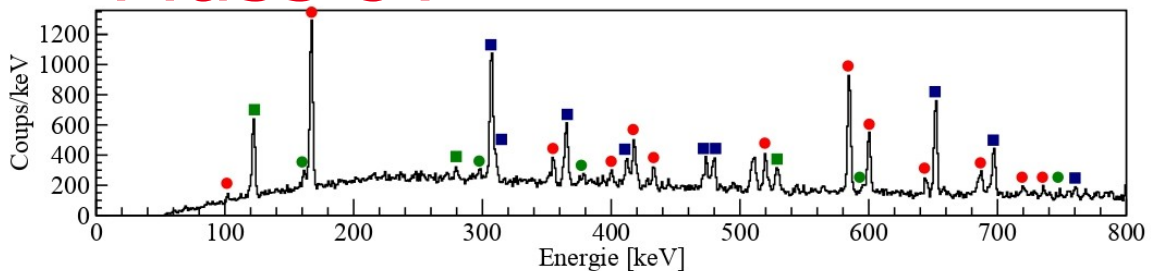
# Conclusions

- Construction and commissioning of a new decay station dedicated to conversion electrons
  - half-life of first excited  $0^+$  state in  $^{98}\text{Zr}$  measured to be  $T_{1/2} = 82 \pm 2$  ns
  - new values of  $\rho^2$  and  $\delta\langle r^2 \rangle$  measured with COeCO add to our understanding of shape transition in the  $A \sim 100$  region
- Research program on shape coexistence using  $\beta$ -decay and conversion electrons spectroscopy at ALTO
  - continue studies in the  $A \sim 100$  region
  - investigate  $N = 50$  region
  - possibility to move COeCO to DESIR to explore the region around  $^{100}\text{Sn}$

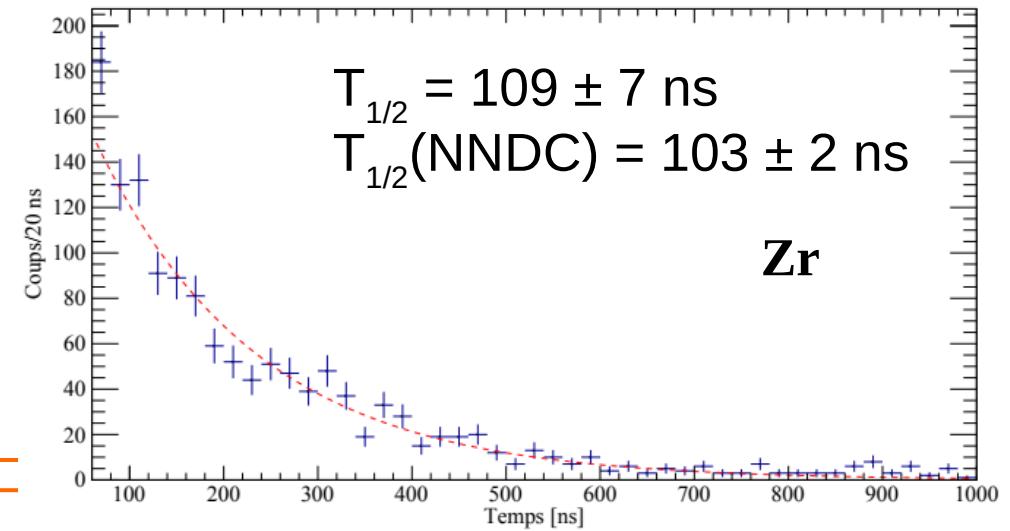
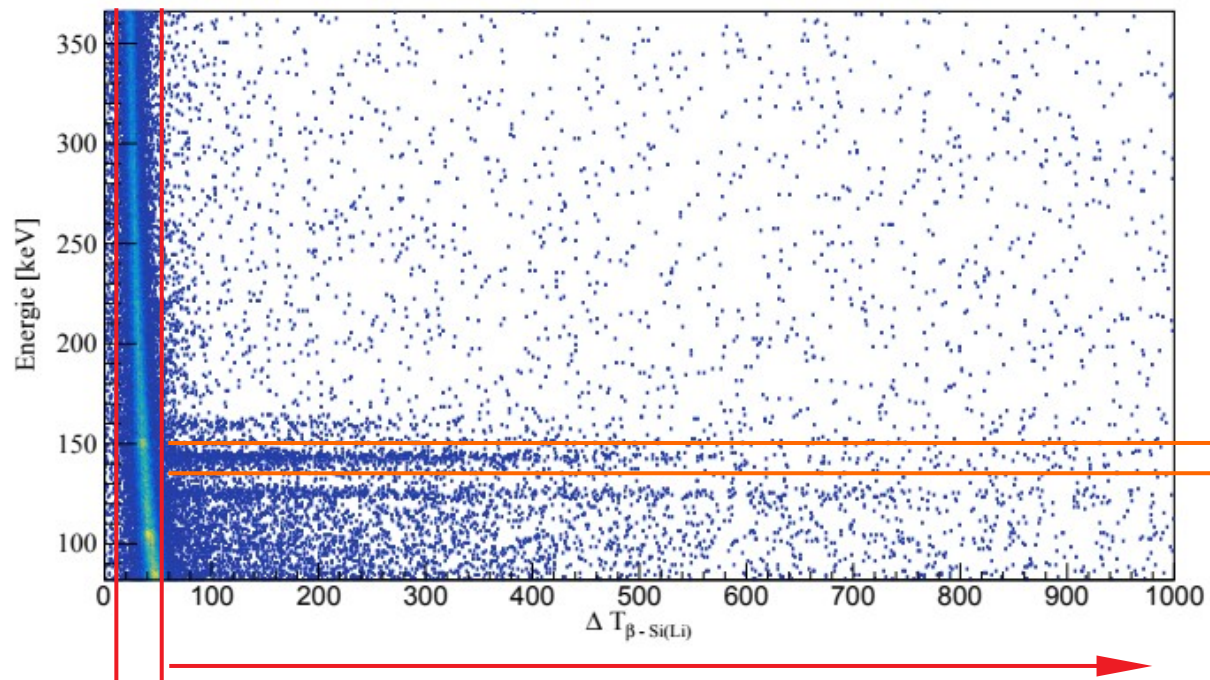
# Mass 96



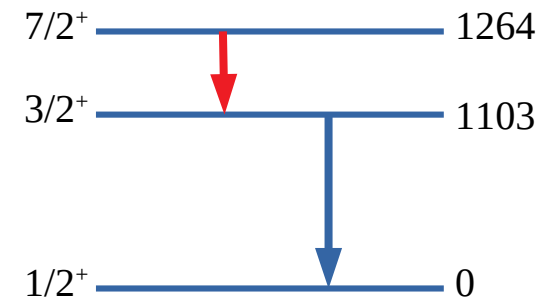
# Mass 97



# Mass 97



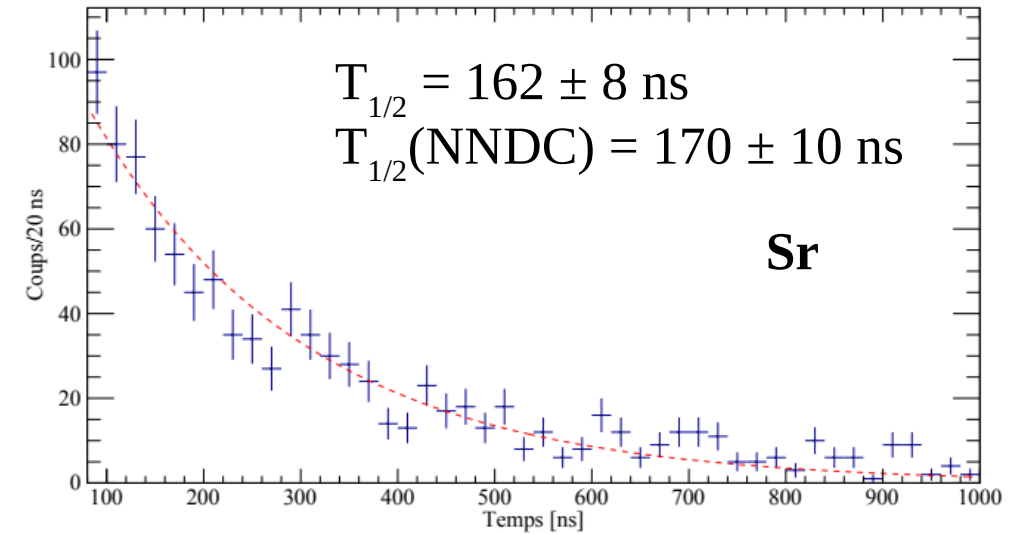
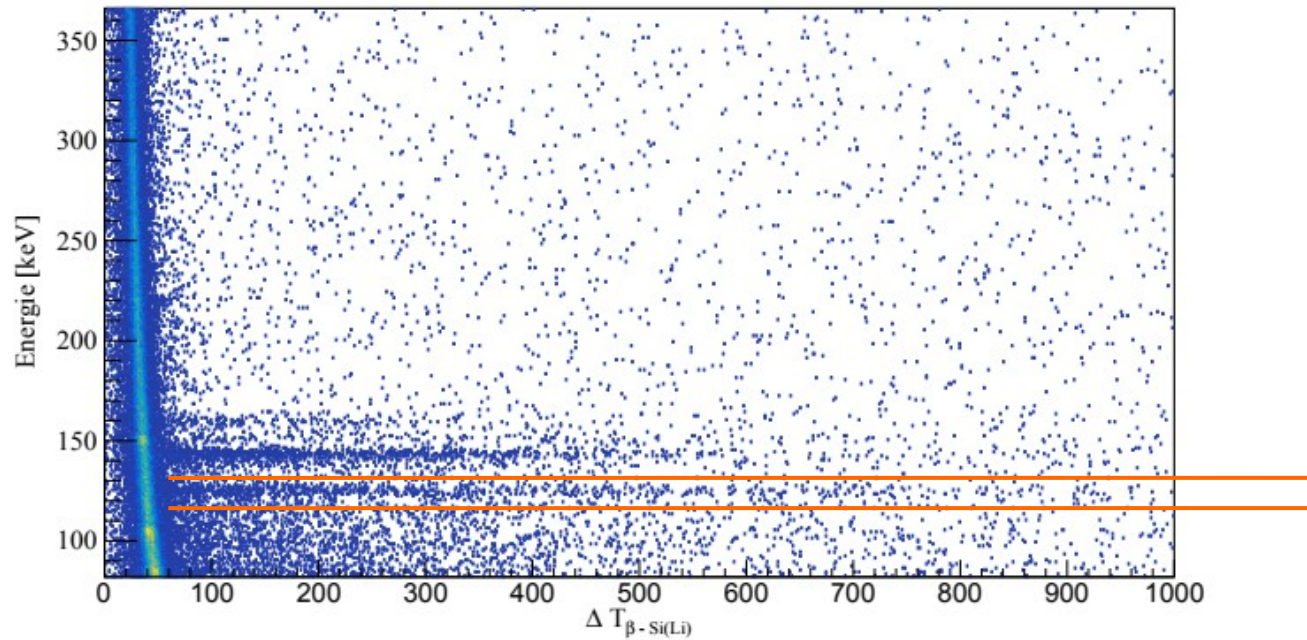
Time behaviour of the 161 keV transition in  $^{97}\text{Zr}$



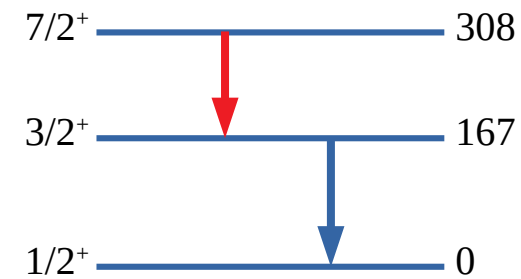
Detection of the  $\beta$ -electron in the scintillator

$\beta$ -delayed conversion electrons

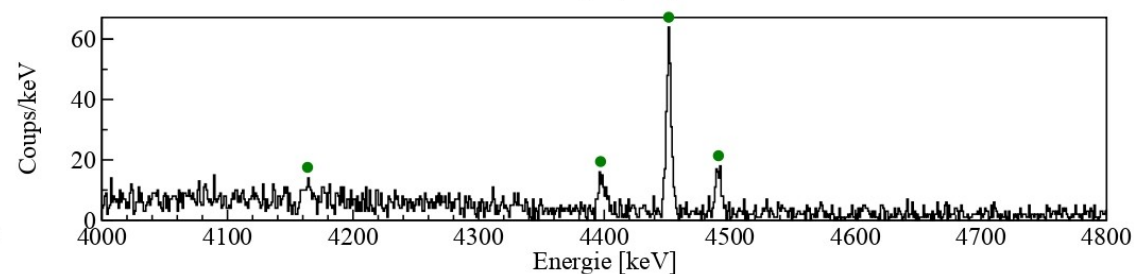
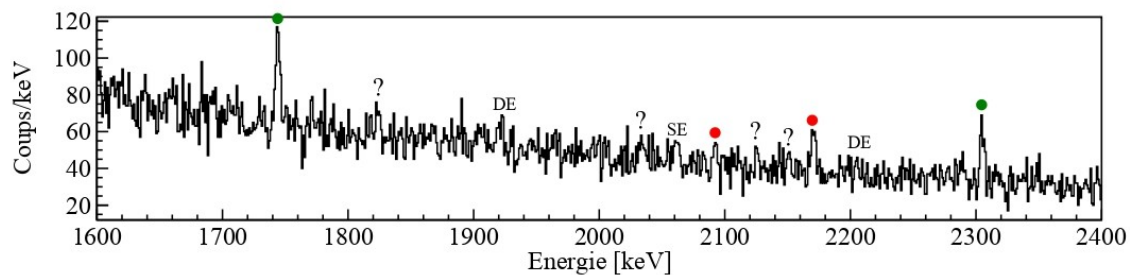
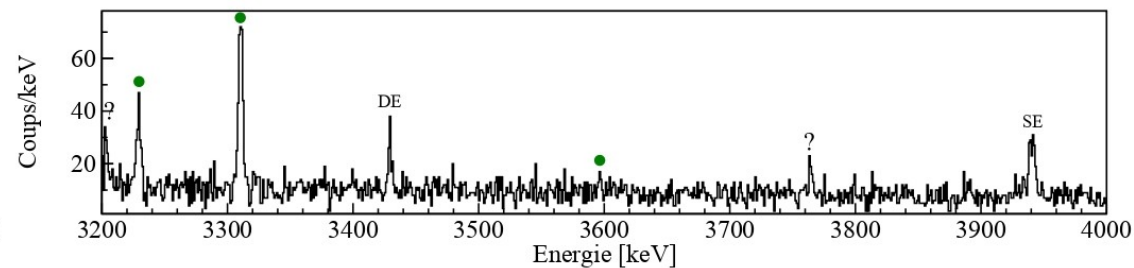
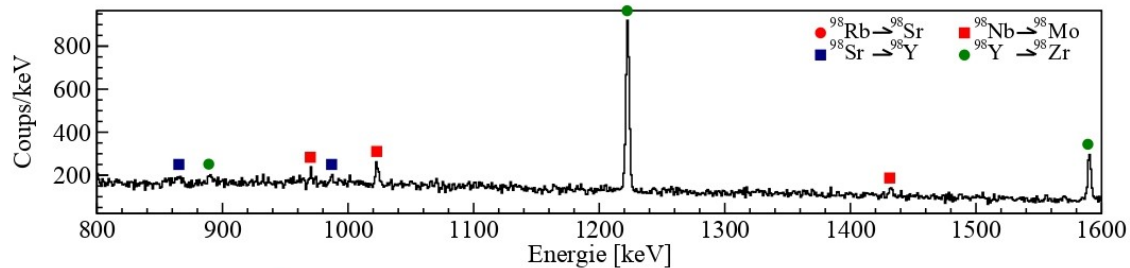
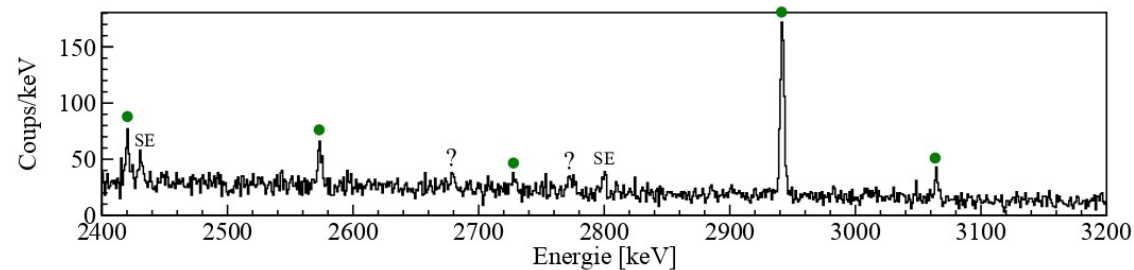
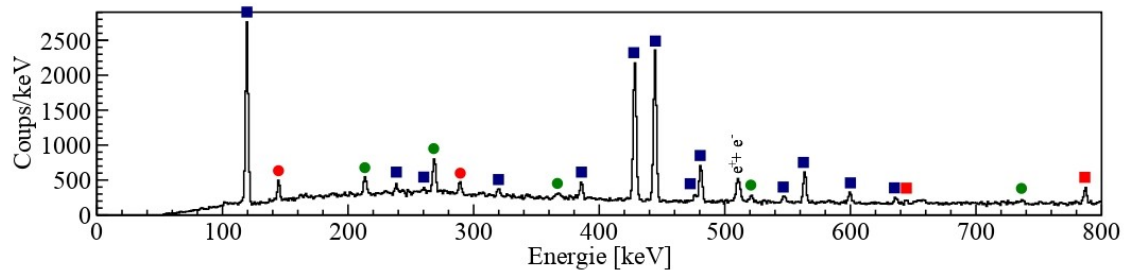
# Mass 97



Time behaviour of the 141 keV transition in  $^{97}\text{Sr}$

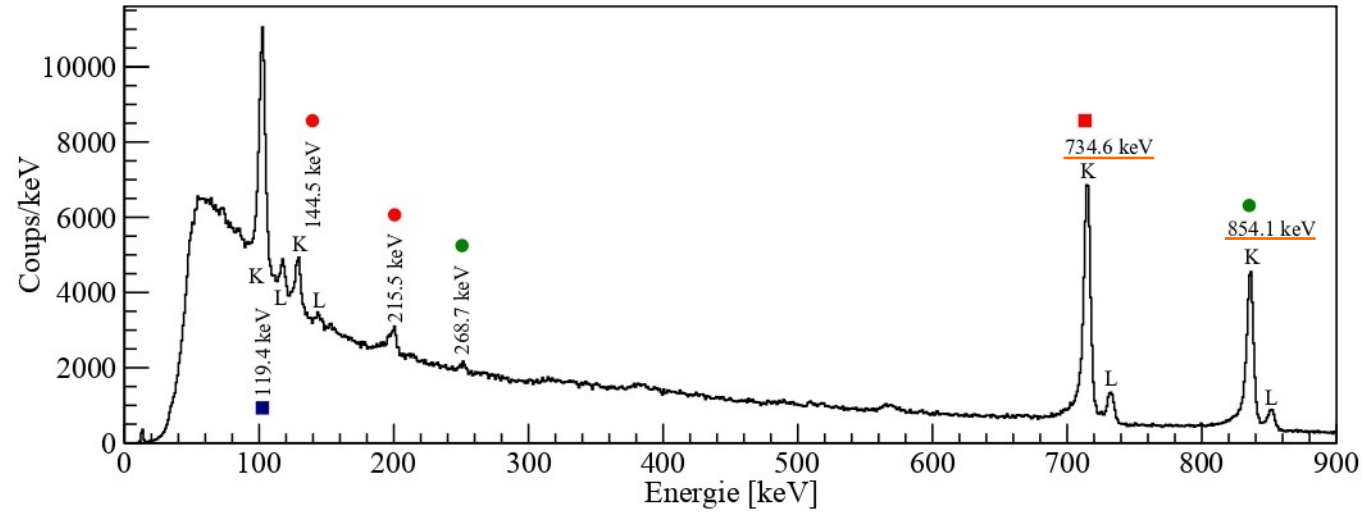


# Mass 98

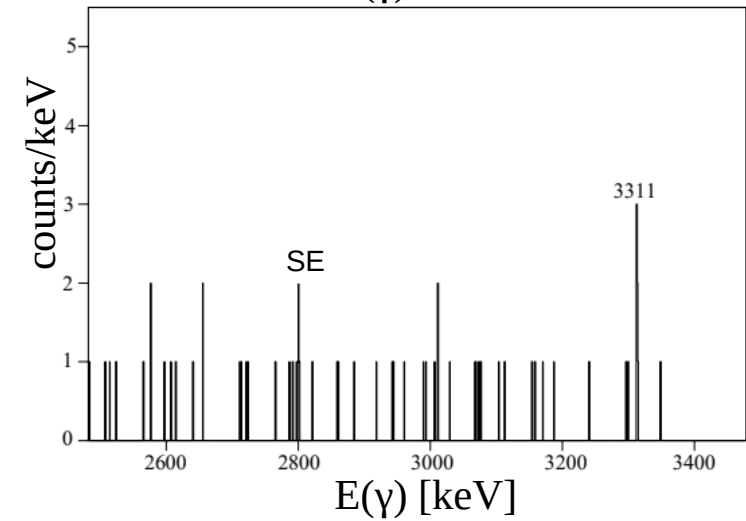
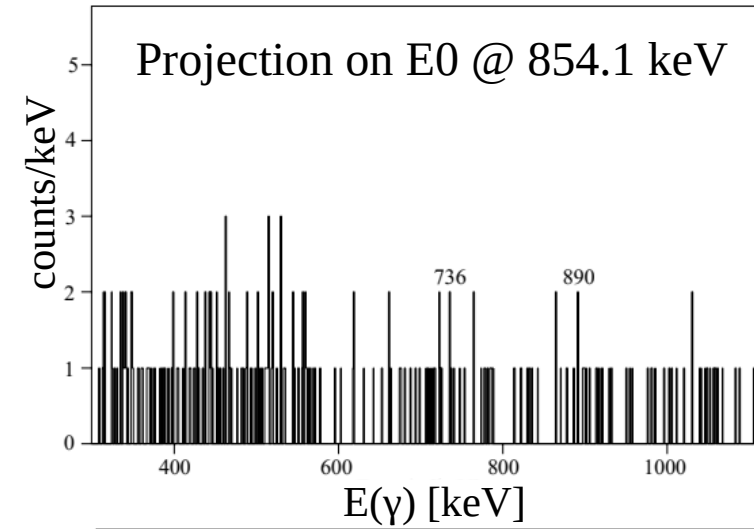
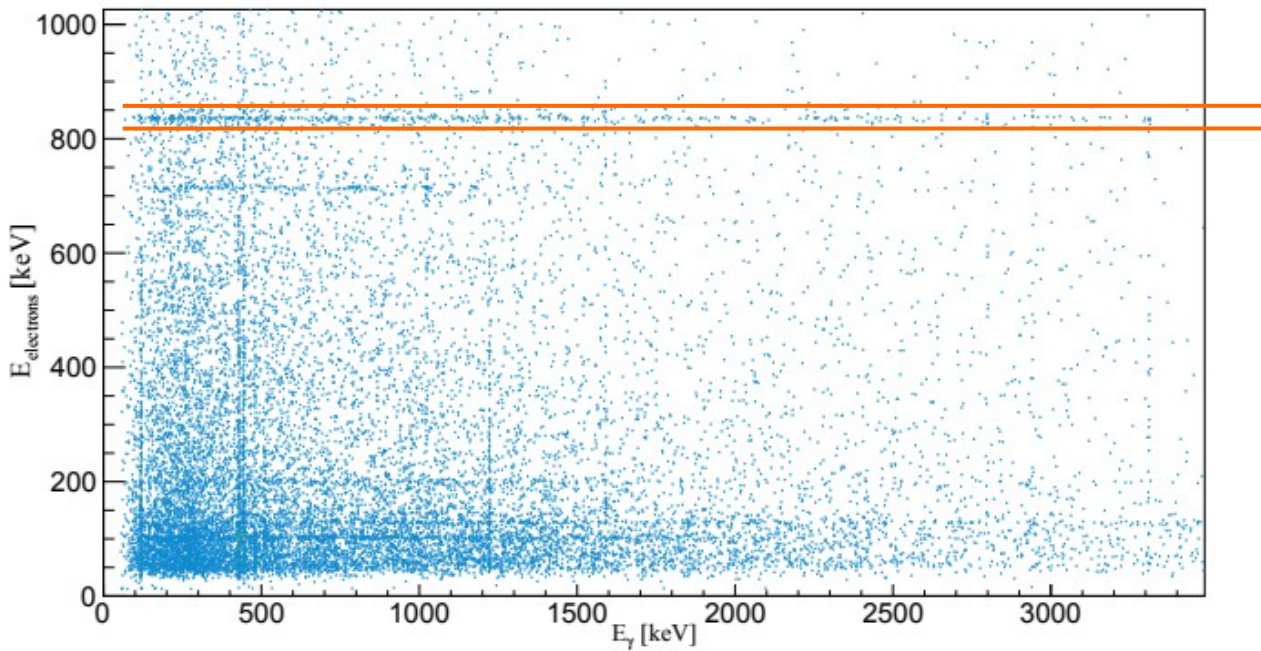




# Mass 98



# Mass 98



# $0_2^+ \rightarrow 0_1^+$ in $^{100}\text{Zr}$ @331 keV

