ASTRANUCAP 2024

Structure beyond the neutron threshold in the nuclei of interest for the r-process produced at ALTO

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IJCLab – Nuclear pole - Team FIIRST

Outline

I. Physics case

a. Beta-delayed neutron emission
b. The ^{84}Ga case

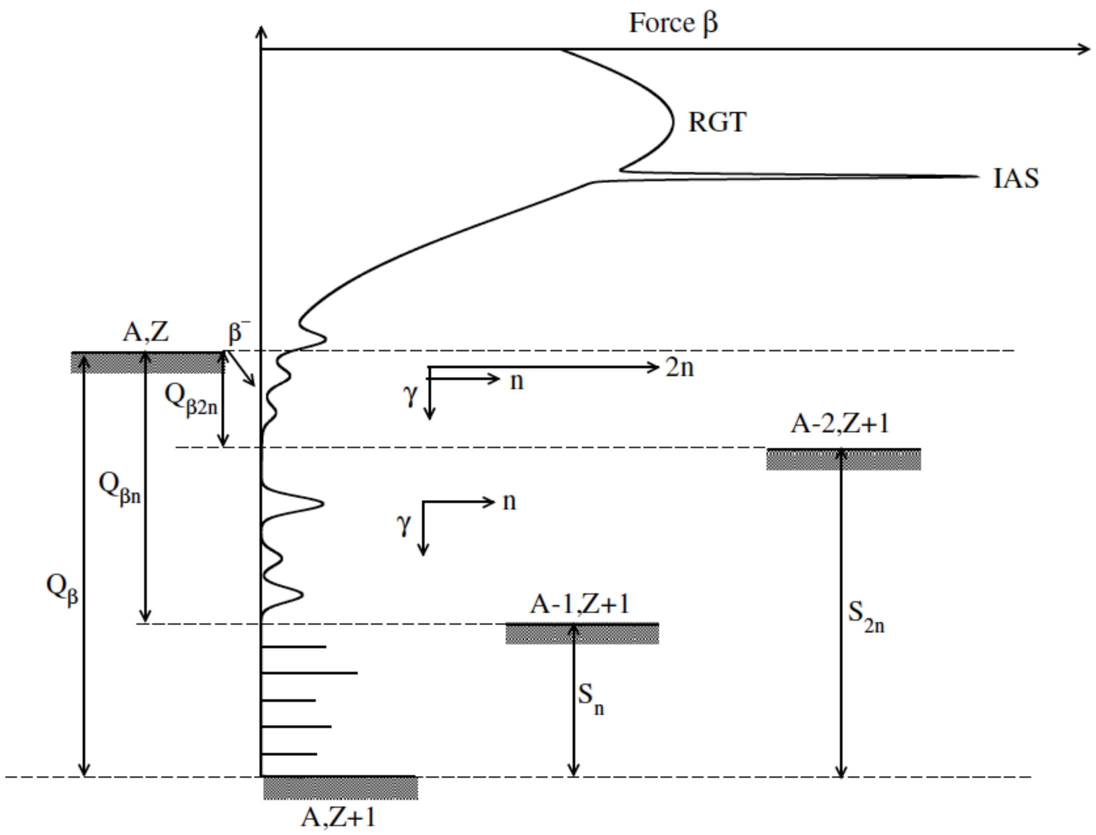
II. Beta-delayed 2-neutron emission of ^{84}Ga

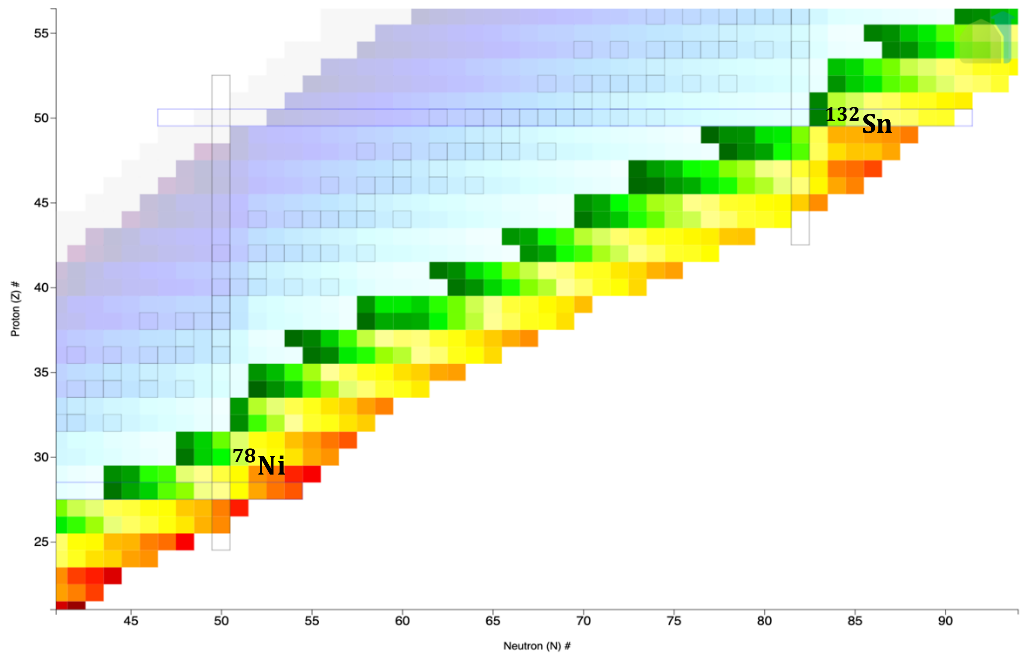
a. Experimental setup
b. Analysis
c. Results

III. Monte-Carlo simulations of TETRA

a. Geometry and physics lists
b. Ring ratio method
c. Results

Beta-delayed neutron emission





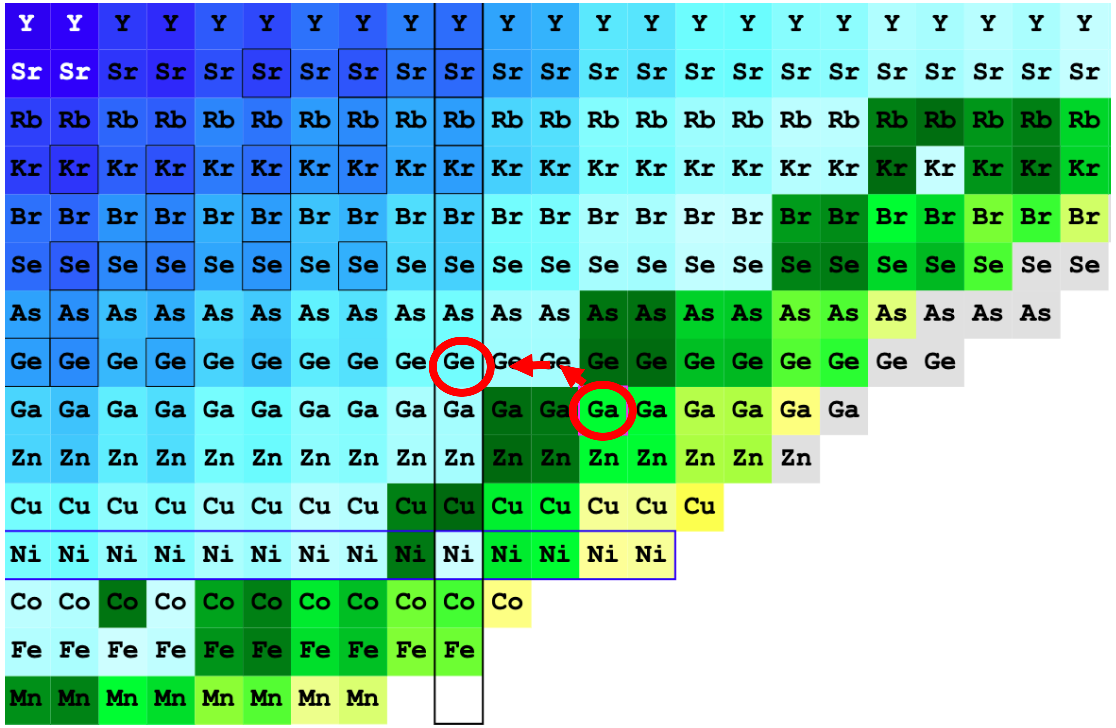
Beta-delayed neutron precursors

Cf. Roberts et al. (1939)

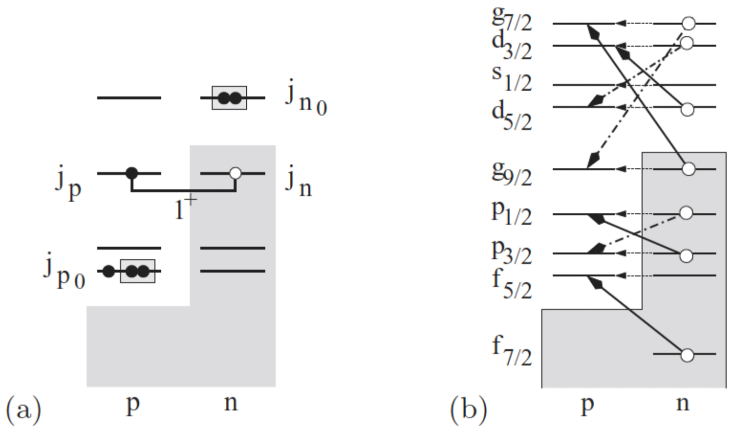
- $\mathbf{Q_{\beta-n} = Q_\beta - S_n}$ **: Available energy for neutrons**
- $\mathbf{P_n}$**: Probability for the daughter nucleus to emit at least one neutron after the beta decay**

The ^{84}Ga case

Cf. Verney et al. Physical Review C 95 (2017)
Cf. Heidemann et al. Physical Review C 108 (2023)
Cf. Xu et al. Physical Review Letters 133 (2024)



Gamow-Teller « Doorway » transitions



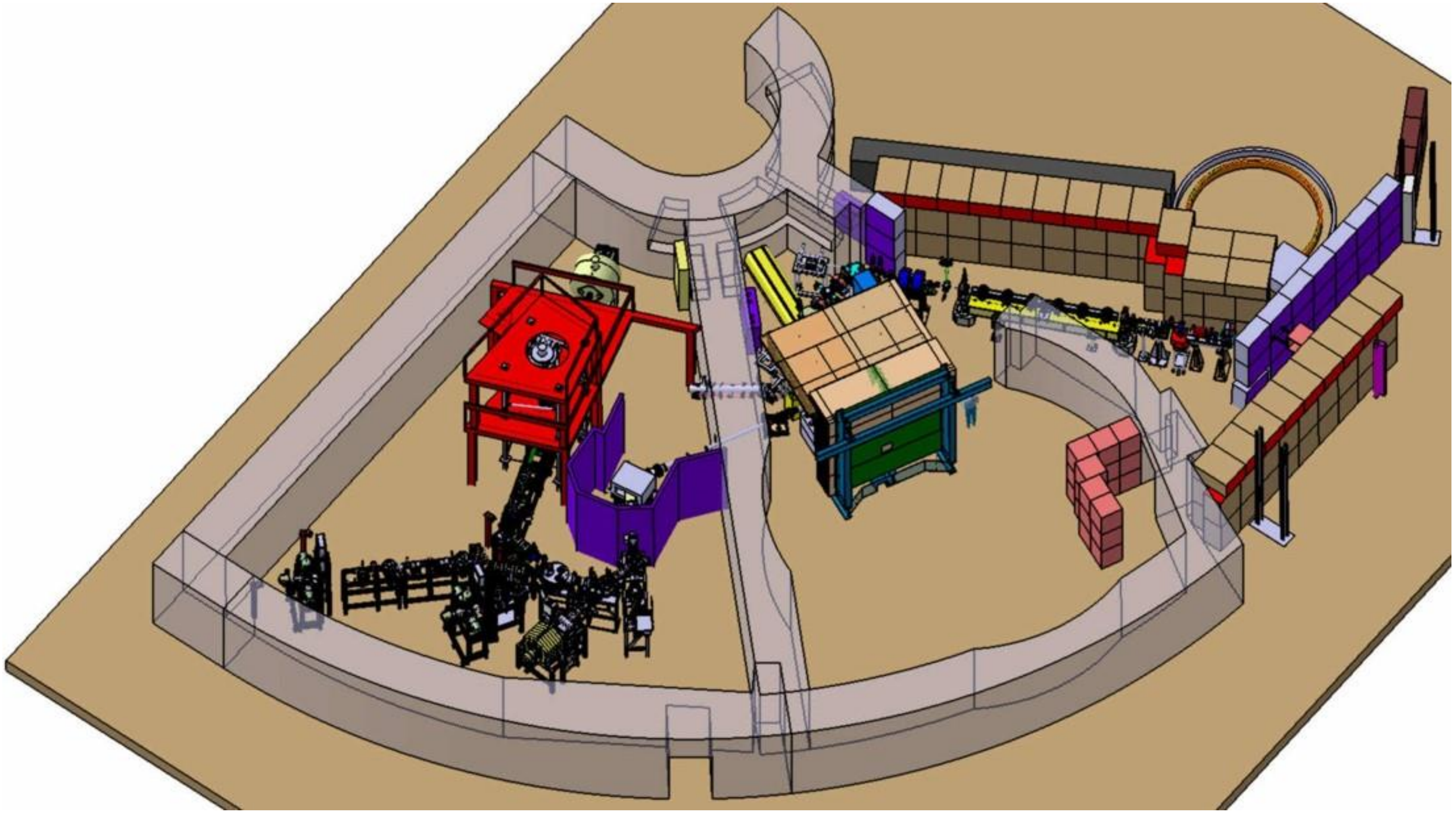
$$\Delta J = 0, 1 \qquad \Delta L = 0$$

^{84}Ga	$\xrightarrow{\beta^-}$	^{84}Ge	$\xrightarrow{2n}$	^{82}Ge
Z = 31		Z = 32		Z = 32
N = 53		N = 52		N = 50

- Near the doubly magic ^{78}Ni
- High probability of emitting 2 neutrons after beta decay
- A first tentative to explain 2–n emission in the doorway approach
- r-process modeling consequences

ALTO Low Energy Branch

An ISOL facility



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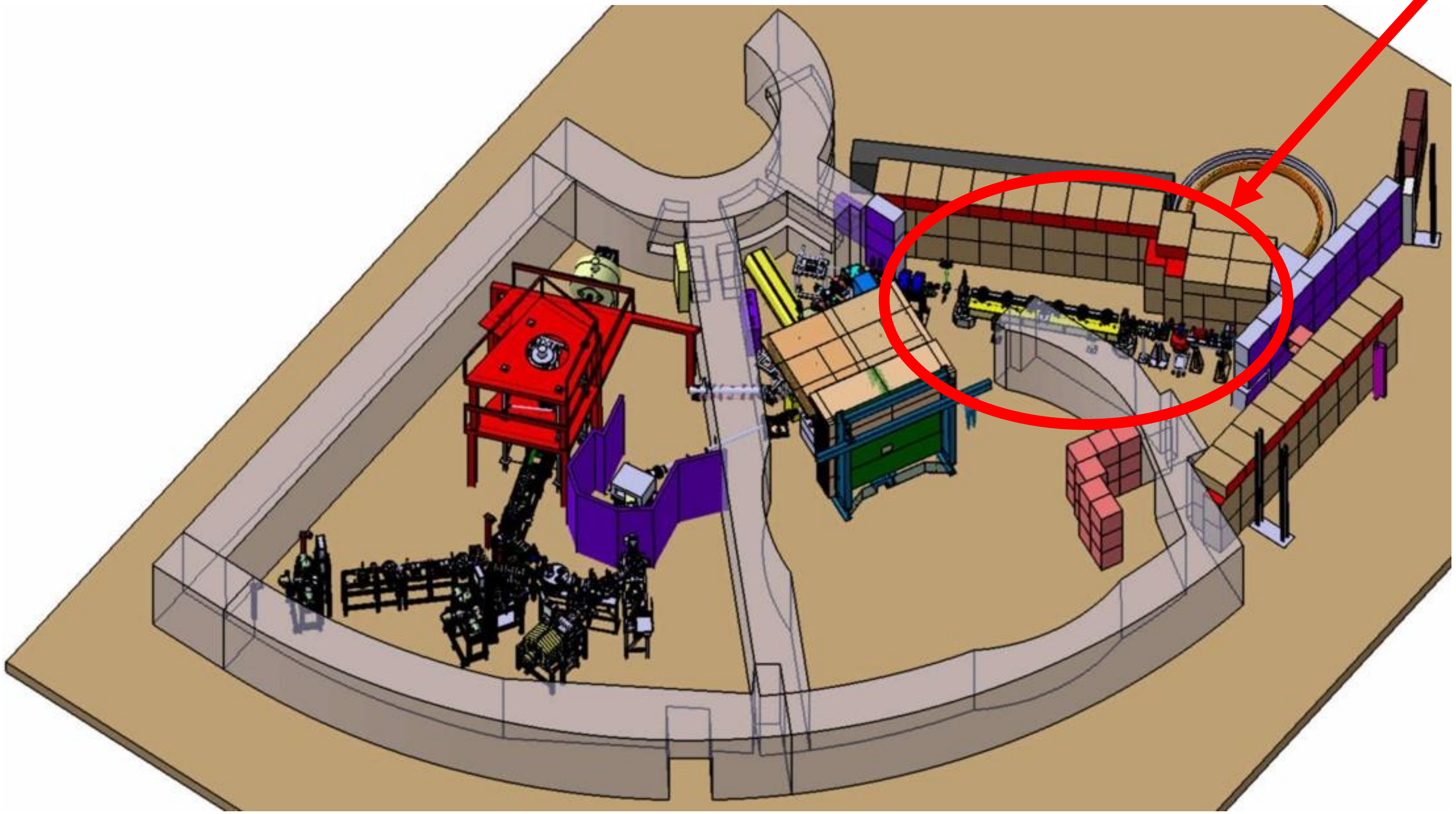

- Electron linear accelerator

- 50 MeV energy
- 10 μA current

ALTO Low Energy Branch

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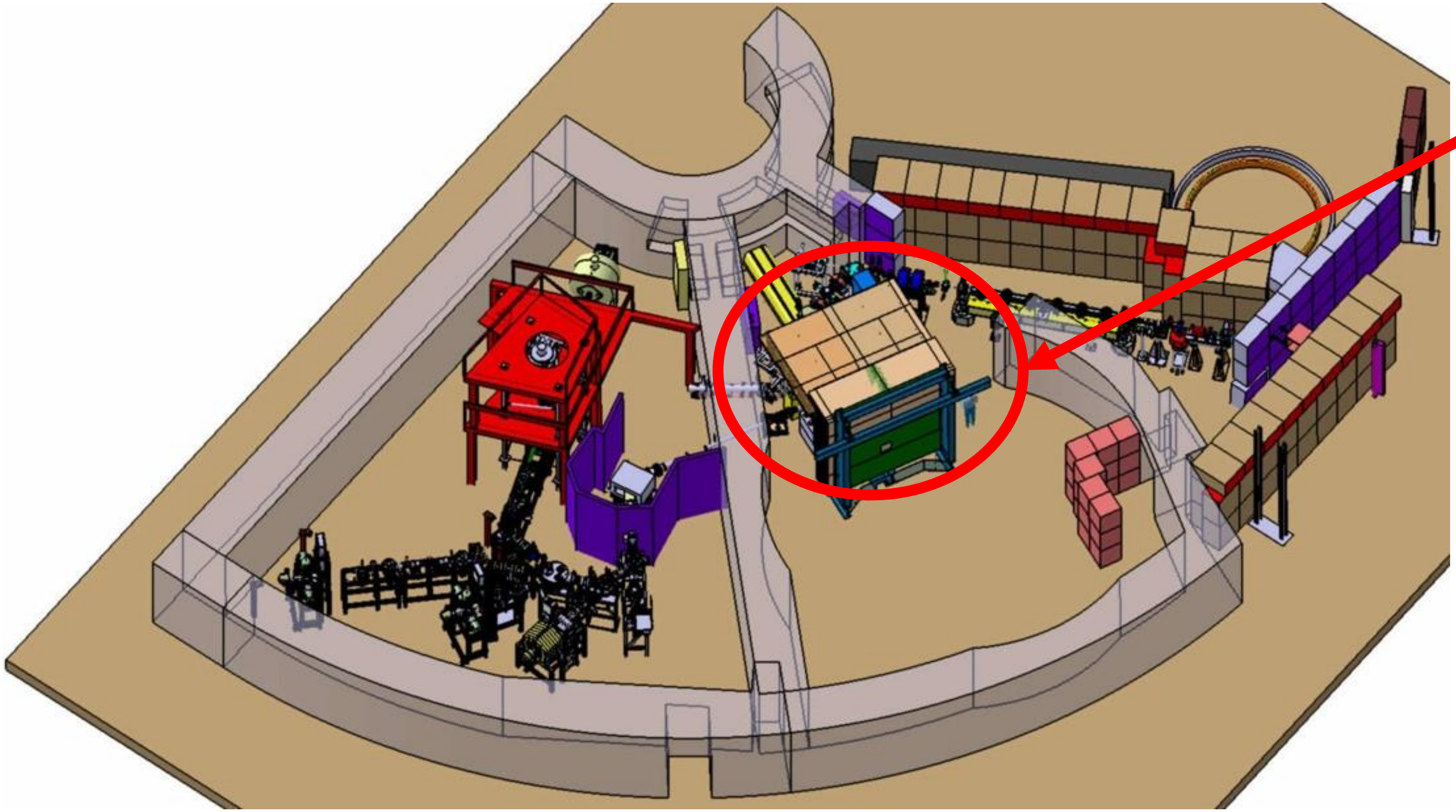
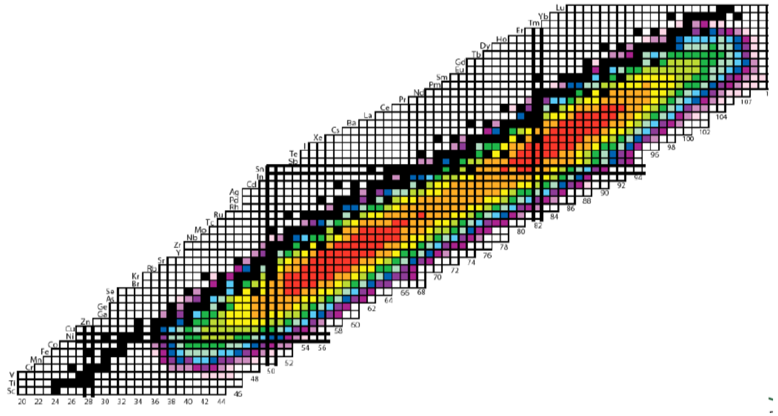


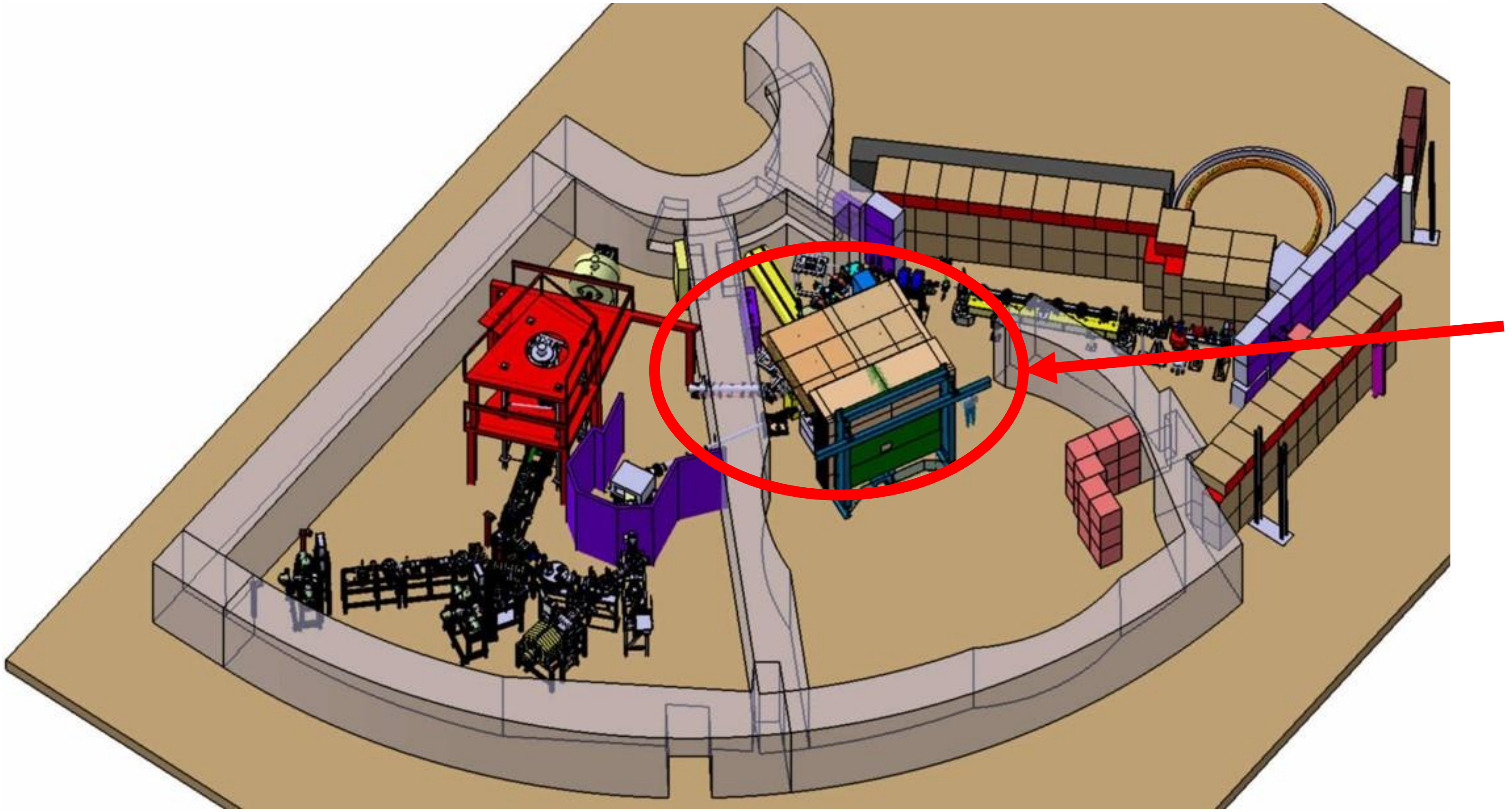
- **Electron linear accelerator**
  - 50 MeV energy
  - 10 µA current
- **Thick UCx target**
  - Photofission
  - Heated up to 2000 °C



No contribution in neutron deficient isotopes

ALTO Low Energy Branch

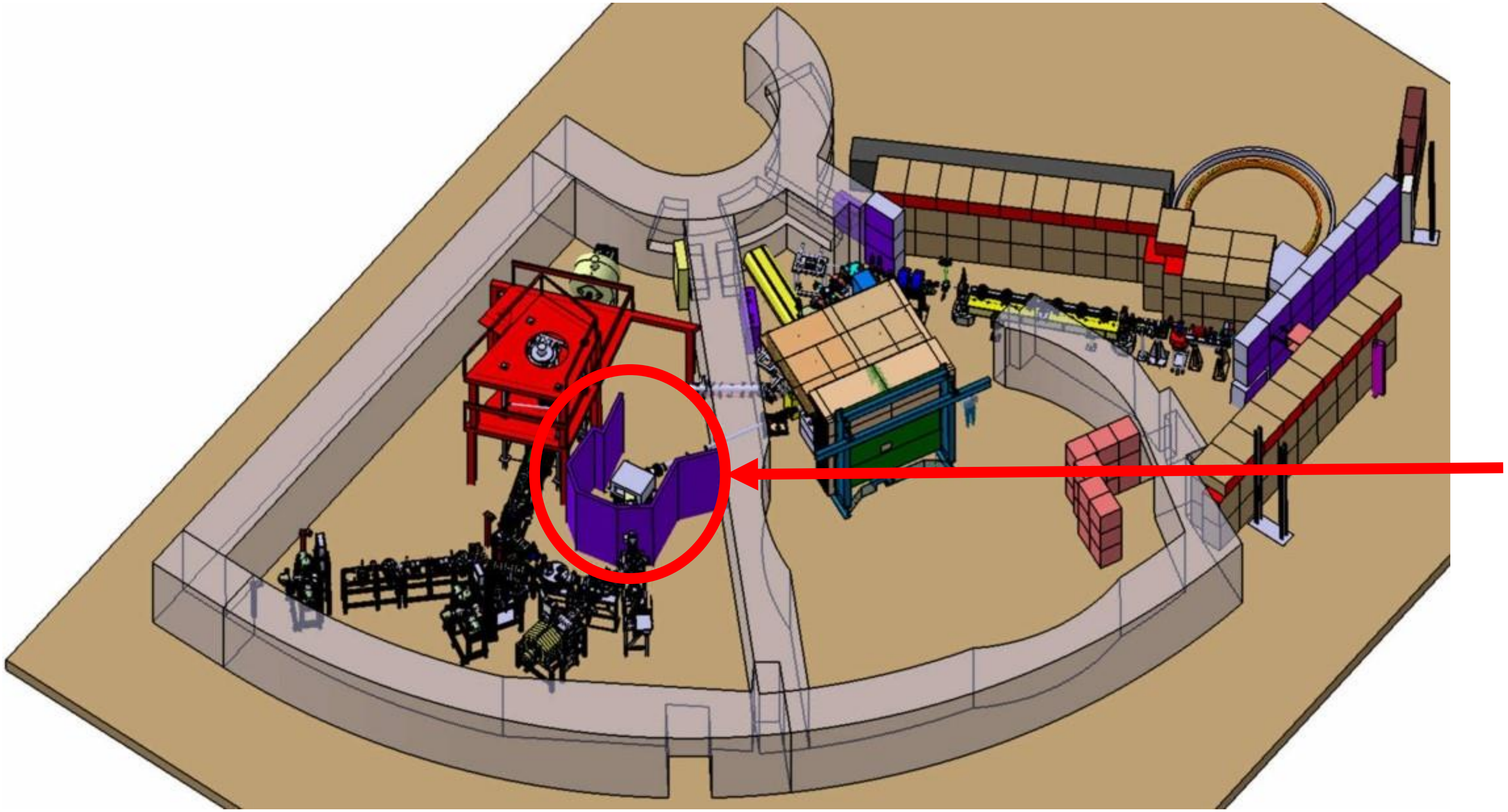
An ISOL facility



- **Electron linear accelerator**
  - 50 MeV energy
  - 10 µA current
- **Thick UCx target**
  - Photofission
  - Heated up to 2000 °C
- **Laser ionization**
  - Selection in Z

ALTO Low Energy Branch

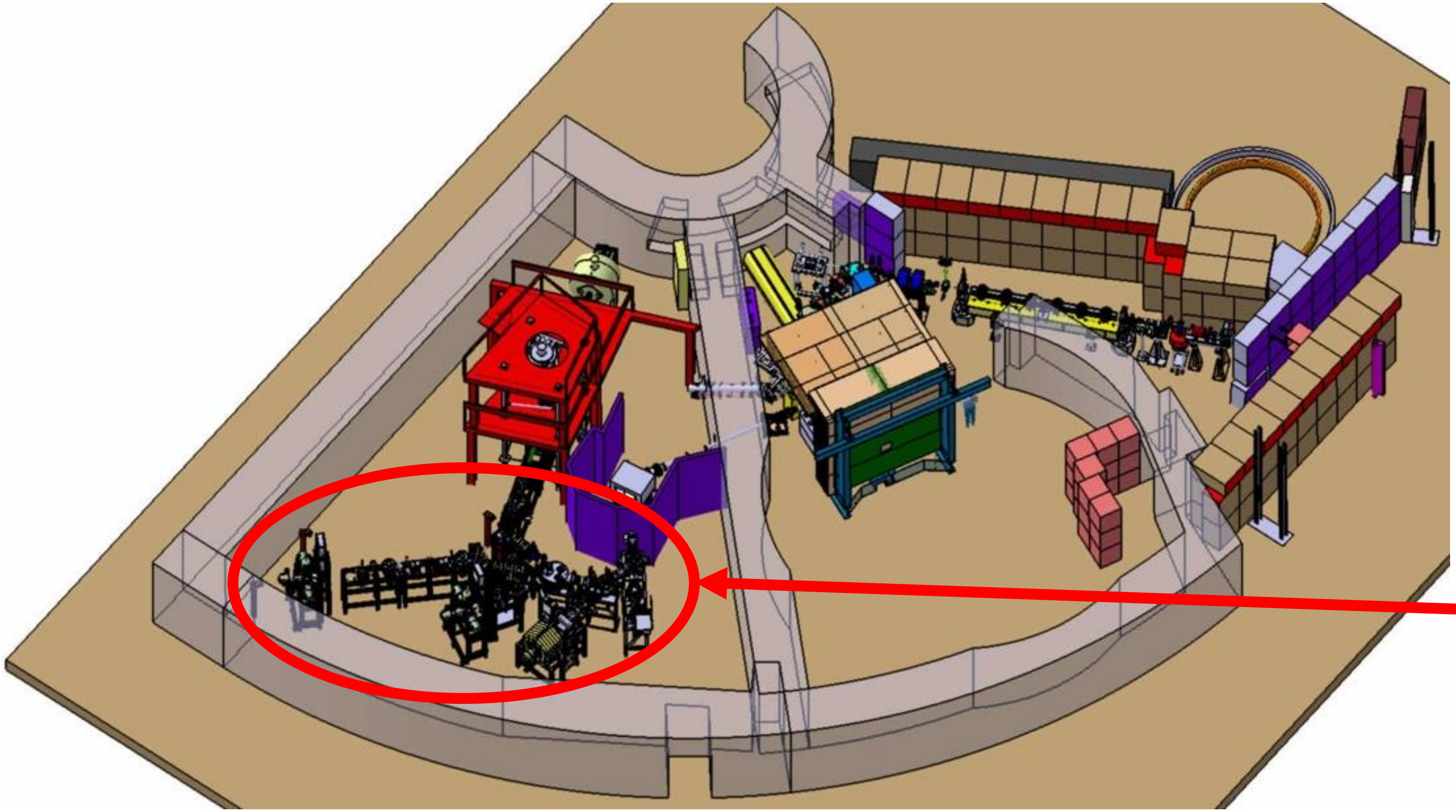
An ISOL facility



- **Electron linear accelerator**
  - 50 MeV energy
  - 10 µA current
- **Thick UCx target**
  - Photofission
  - Heated up to 2000 °C
- **Laser ionization**
  - Selection in Z
- **Mass separation**
  - Selection in A

ALTO Low Energy Branch

An ISOL facility



- Electron linear accelerator

- 50 MeV energy
- 10 µA current

- Thick UCx target

- Photofission
- Heated up to 2000 °C

- Laser ionization

- Selection in Z

- Mass separation

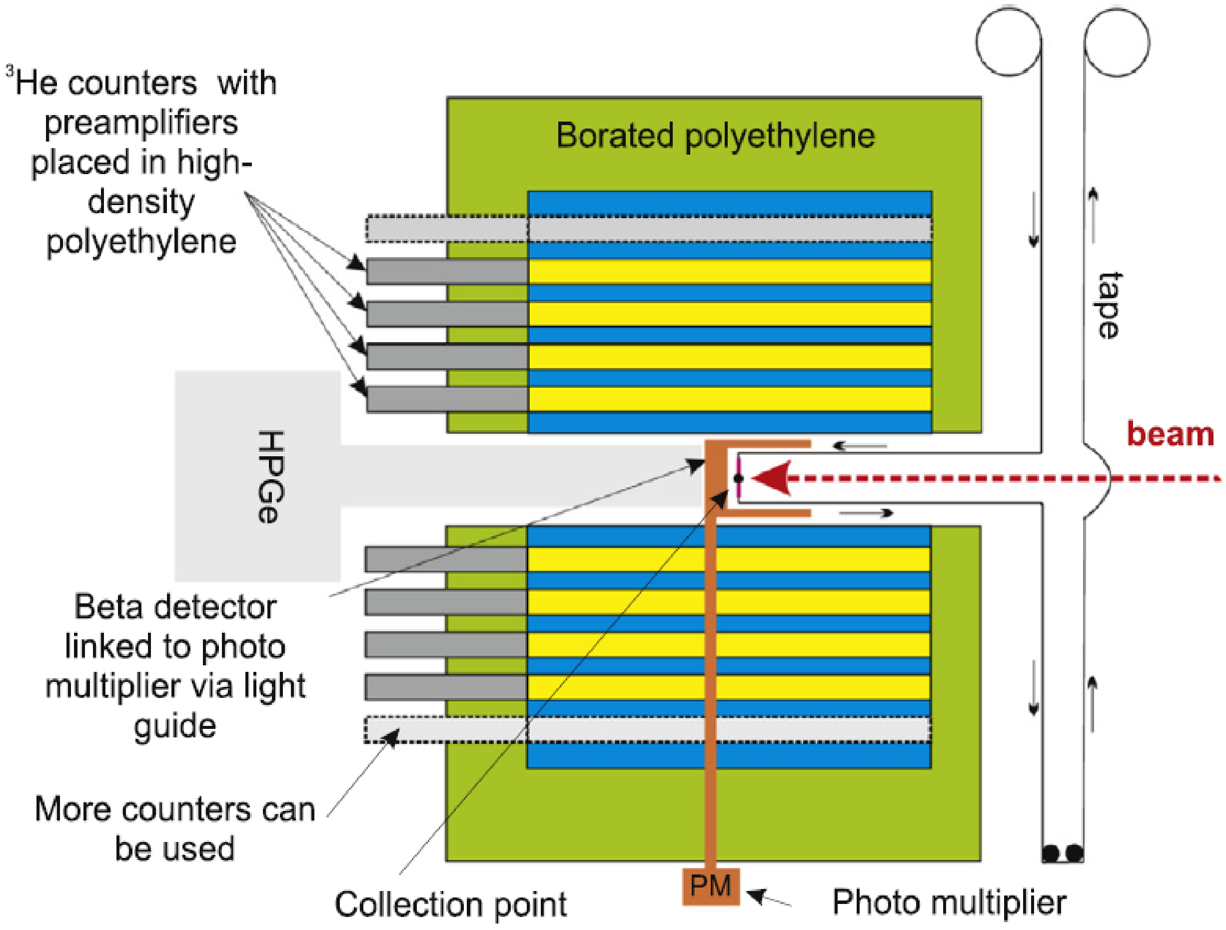
- Selection in A

- Decay stations

- Conversion electron (COeCO)
- Neutron counter (TETRA)
- Gamma spectroscopy (BEDO)

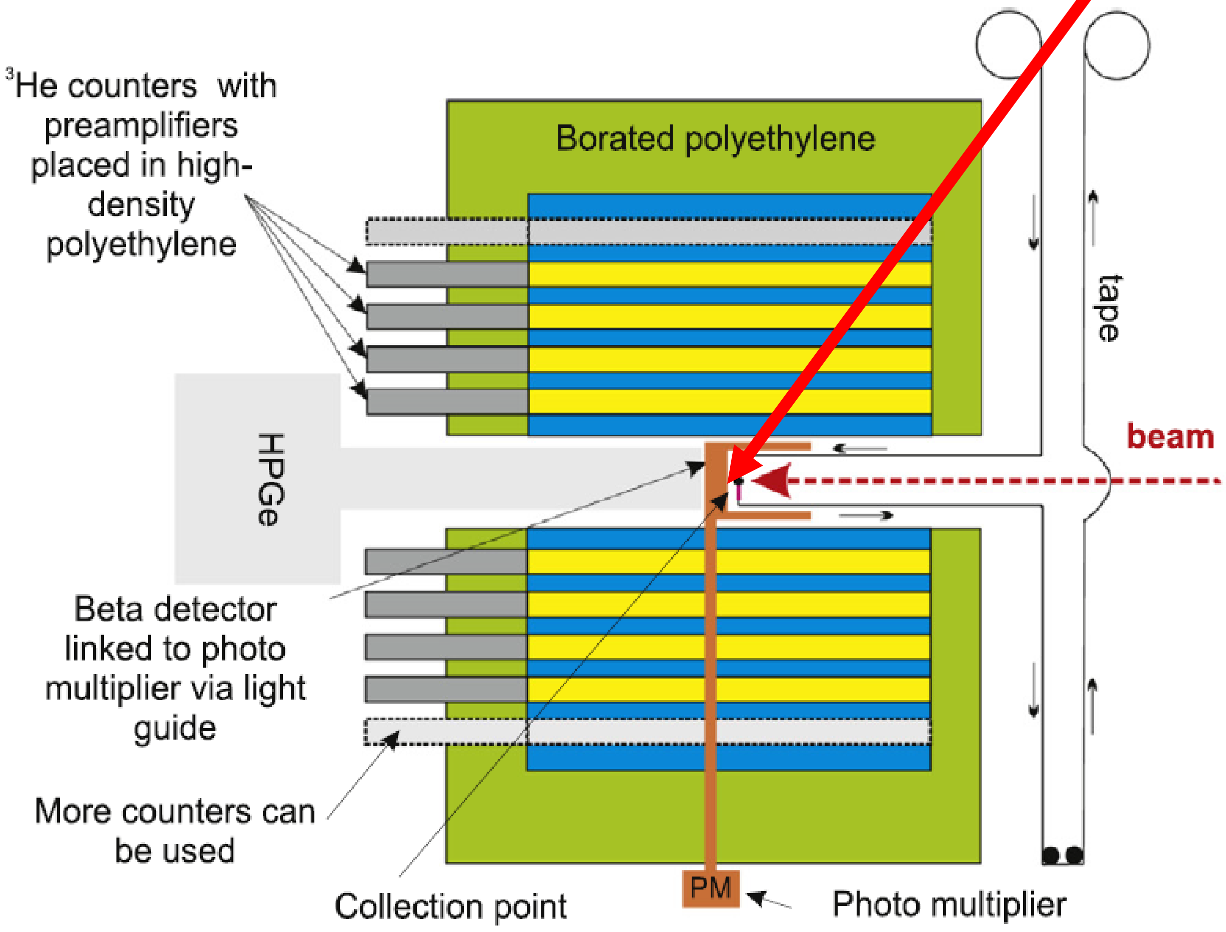
TETRA decay station

For beta-delayed neutron emission studies



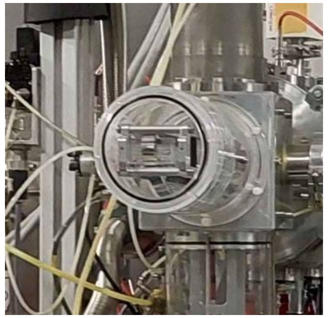
TETRA decay station

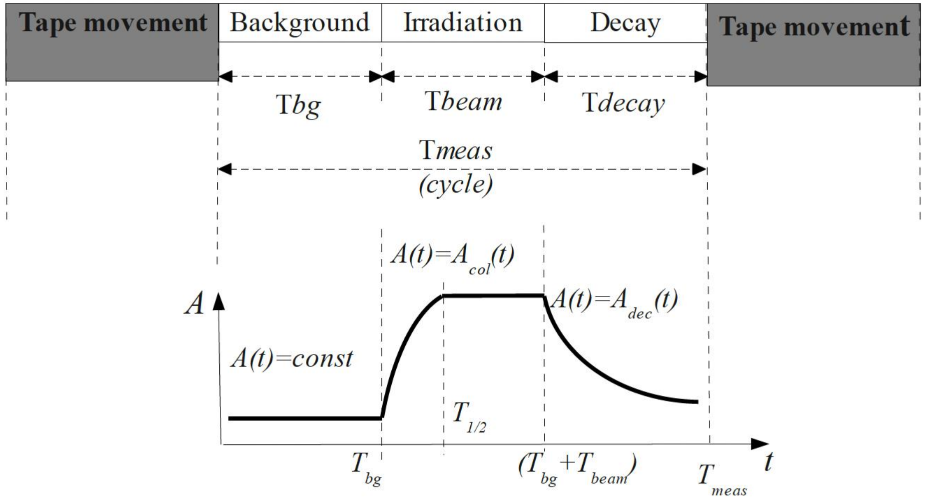
For beta-delayed neutron emission studies



Collection – Decay cycles

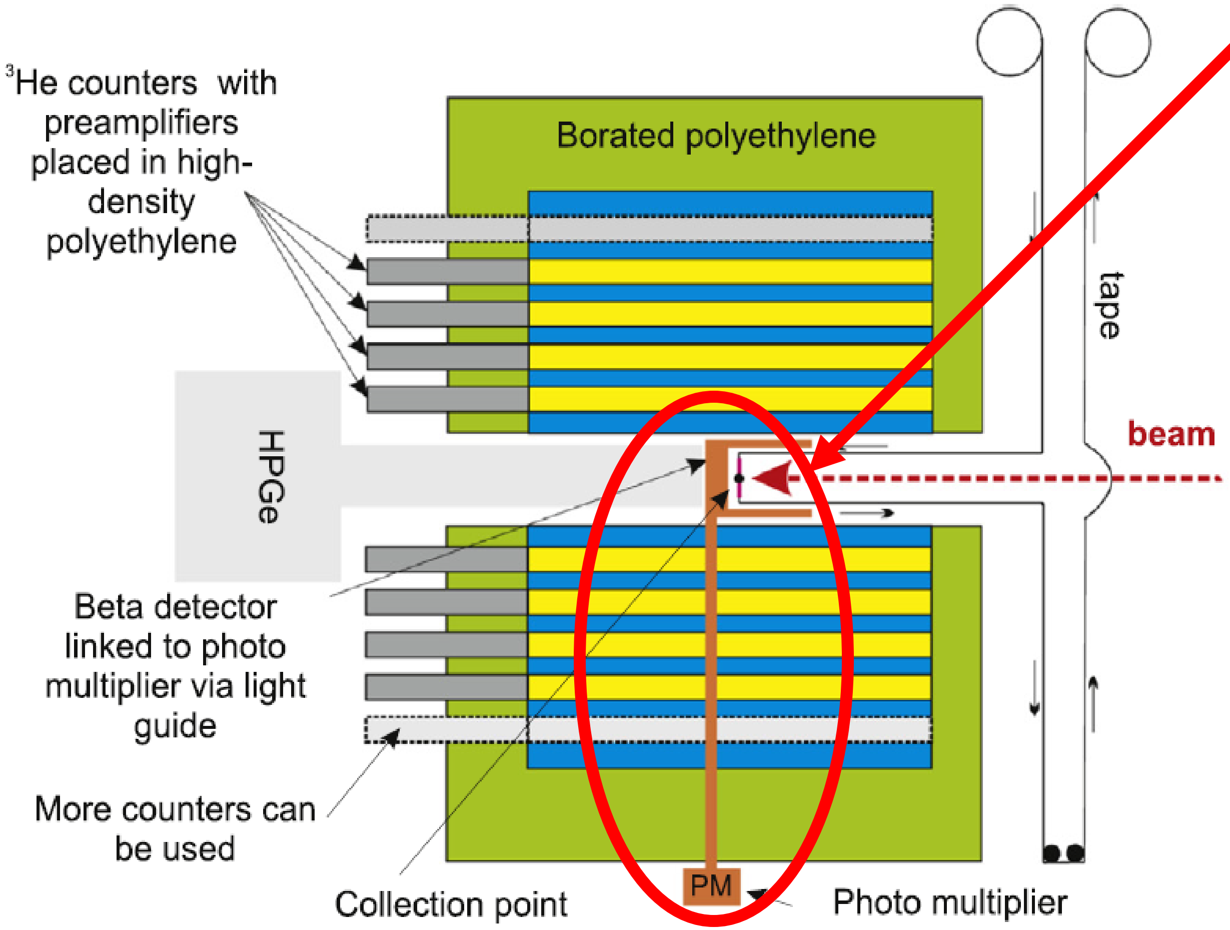
- Beam implanted on a mylar band
- No contamination from descendants with tape station





TETRA decay station

For beta-delayed neutron emission studies

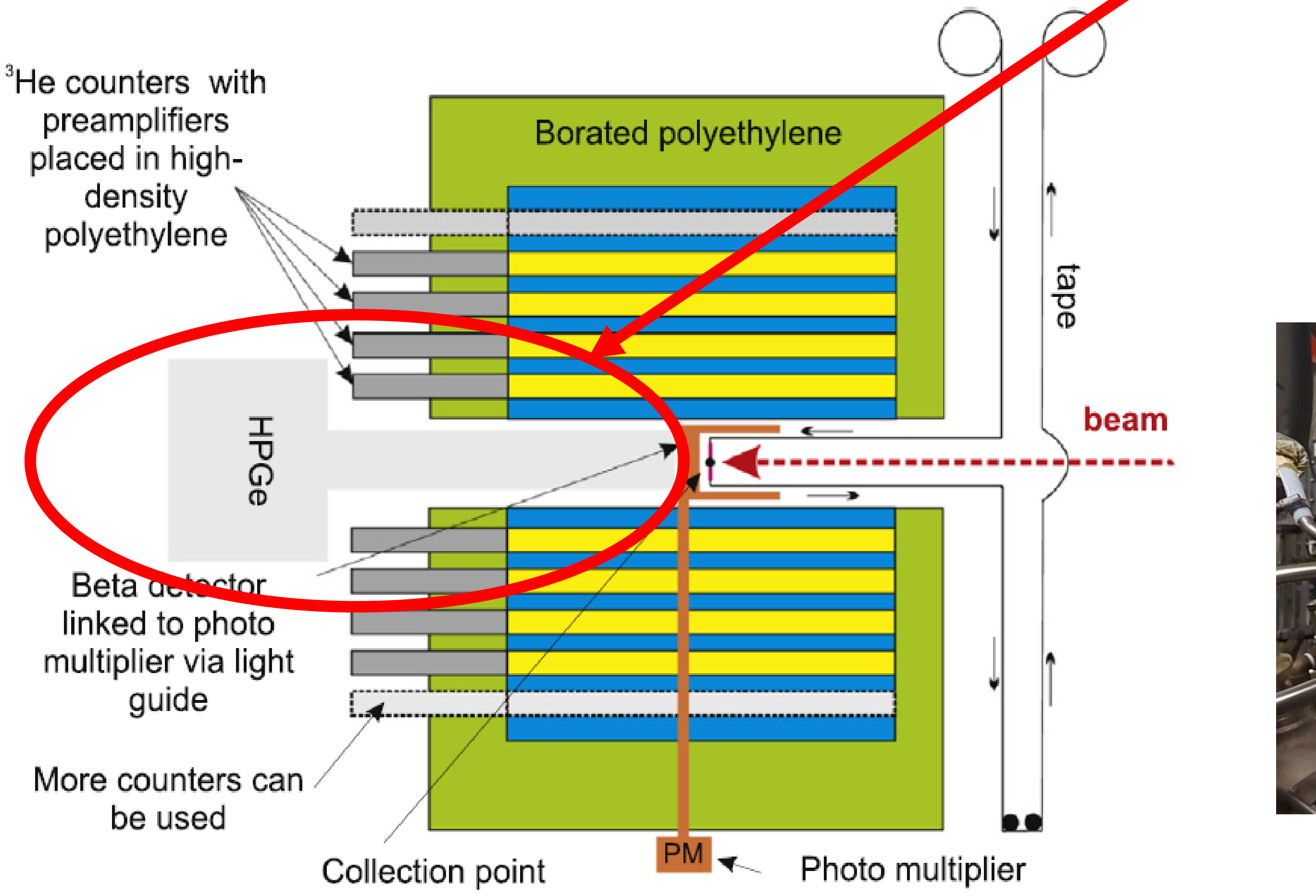


4πβ plastic scintillator

- Detection of β electrons
- BC408 plastic linked to a PM
- Around 70% efficiency

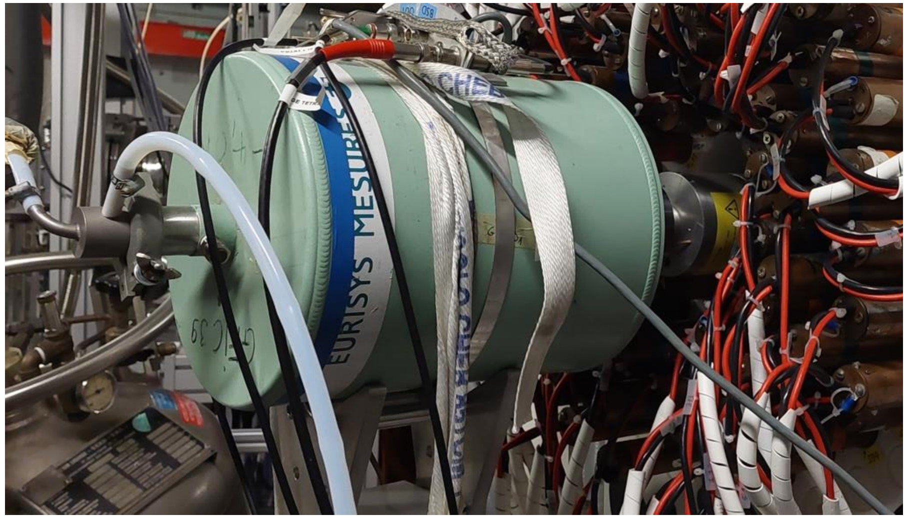
TETRA decay station

For beta-delayed neutron emission studies



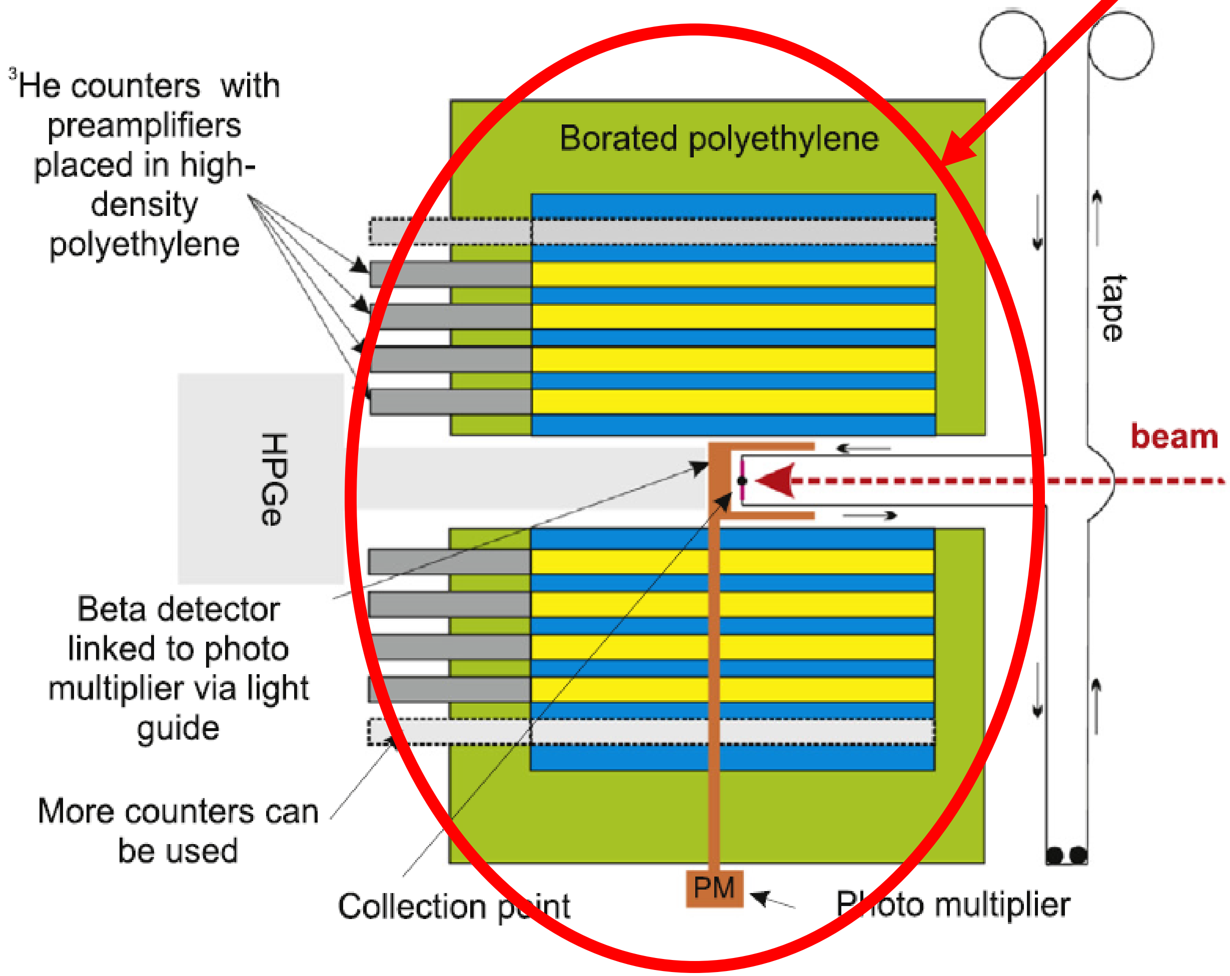
High purity Germanium detector

- Detection of γ rays
- Coaxial geometry
- 2 cm away from implementation point
- 0.66% efficiency @ 964.1 keV
- 2.4 keV resolution (FWHM) @ 964.1 keV



TETRA decay station

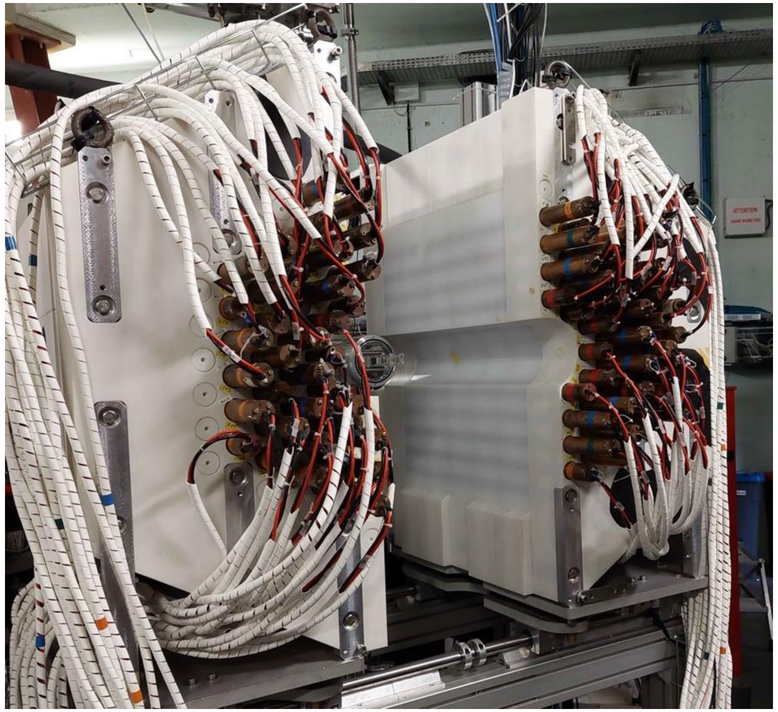
For beta-delayed neutron emission studies



Slow neutron counter TETRA

- Detection of neutrons
- HDPE moderator and 80 ^{3}He gas cells
- Around 52% efficiency
- No energy information

$$n + {}^3He \rightarrow p + {}^3H + 765\ keV$$



Cf. Testov et al. Nuclear Instruments and Methods in Physics Research A 815 (2016)

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Pn measurement

Overview

- $\mathbf{P_n \equiv P_{1n} + P_{2n} + \cdots + P_{in}}$
- $\mathbf{< n > \equiv P_{1n} + 2P_{2n} + \cdots + iP_{in}}$

Pn measurement

Overview

- $\mathbf{P_n \equiv P_{1n} + P_{2n} + \cdots + P_{in}}$
- $\mathbf{< n > \equiv P_{1n} + 2P_{2n} + \cdots + iP_{in}}$

- $\mathbf{P_{1n} = \frac{N_{1n}}{N_\beta} \times \frac{\varepsilon_\beta}{\varepsilon_n}}$

- $\mathbf{P_{2n} = \frac{N_{2n}}{N_\beta} \times \frac{\varepsilon_\beta}{\varepsilon_n^2}}$

Pn measurement

Overview

- $P_n \equiv P_{1n} + P_{2n} + \cdots + P_{in}$
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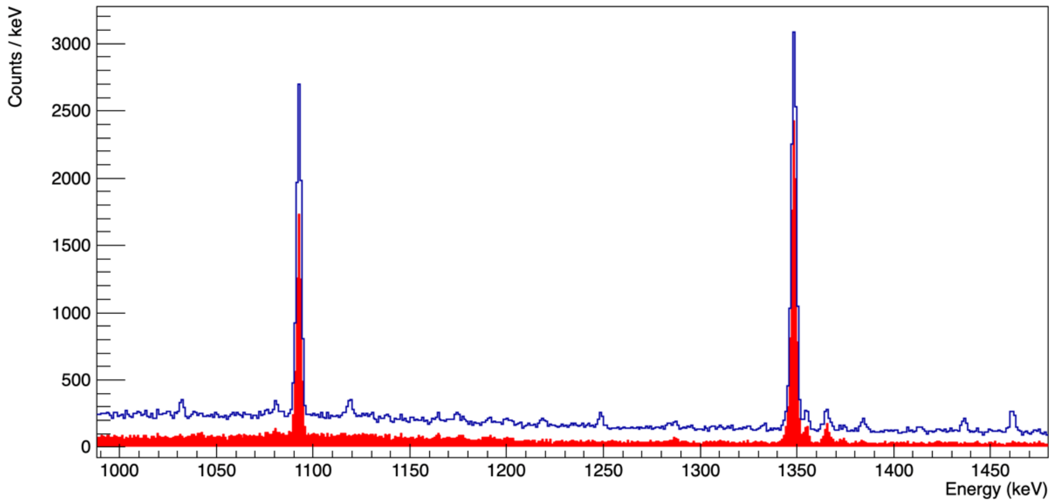
Efficiencies

- Obtained with γ energy spectra
- Double or triple coincidences

$$\frac{S_{xcond}}{S_{single}} = \varepsilon_x$$



Pn measurement

Overview

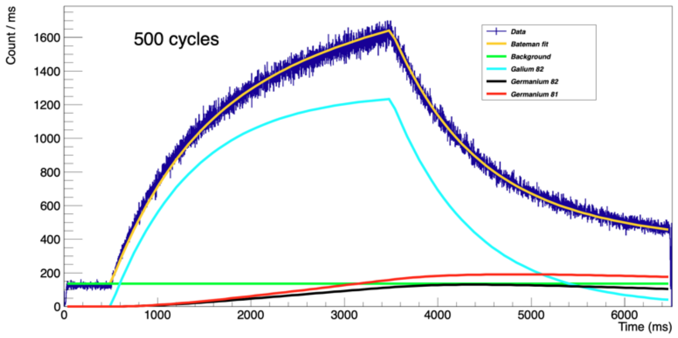
- $P_n \equiv P_{1n} + P_{2n} + \cdots + P_{in}$
- $< n > \equiv P_{1n} + 2P_{2n} + \cdots + iP_{in}$

- $P_{1n} = \frac{N_{1n}}{N_\beta} \times \frac{\varepsilon_\beta}{\varepsilon_n}$
- $P_{2n} = \frac{N_{2n}}{N_\beta} \times \frac{\varepsilon_\beta}{\varepsilon_n^2}$

Number of particles emitted

- Obtained with activity curves
- Bateman function fits

$$N_k(t) = N_1 \prod_{i=1}^{k-1} (b_{i,i+1}\lambda_i) \times \left(\sum_{i=1}^{k} \frac{e^{-\lambda_i t}}{\prod_{j=1 \neq i}^{k} (\lambda_j - \lambda_i)} \right)$$



$$\frac{N_n^{measured}}{N_\beta^{measured}} = P_{1n} + (1 + \varepsilon_n)P_{2n} + \cdots + (1 + i\varepsilon_n^i)P_{in} \equiv < n >*$$

Calibration isotope : ^{82}Ga

Cf. Liang et al. Nuclear Data Sheets 168 (2020)

Bateman fits

$$Q_{\beta-n} = 5.290\ \mathrm{MeV}$$

$$T_{\frac{1}{2}} = 599\ \mathrm{ms}$$

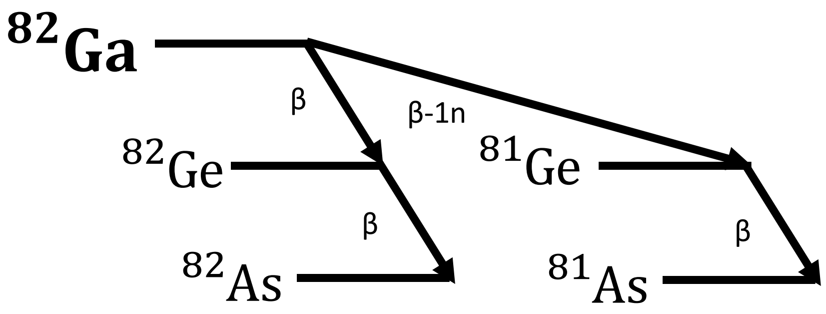


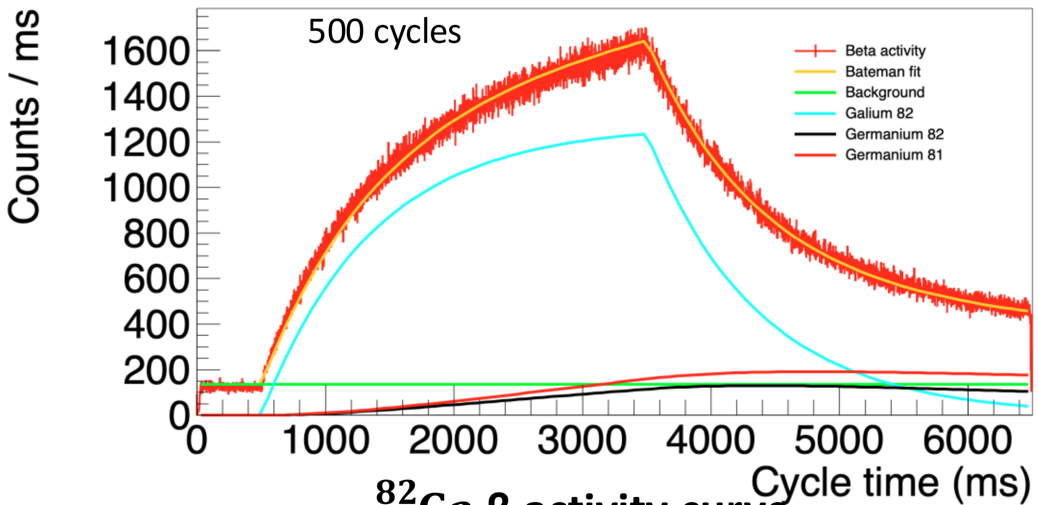
TABLE I. Table with P_{1n} standards and their corresponding half-lives as recommended from this CRP [35, 36].

Nuclide	Half-life (s)	P_{1n} (%)	Ref.
^{9}Li	0.1782(4)	50.5(10)	[35]
^{16}C	0.7546(80)	99.28(12)	[35]
^{17}N	4.171(4)	95.1(7)	[35]
^{49}K	1.263(50)	86(9)	[35]
^{82}Ga	0.601(2)	22.7(20)	[36]
^{87}Br	55.64(15)	2.53(10)	[36]
^{88}Br	16.29(8)	6.72(27)	[36]
^{94}Rb	2.704(15)	10.39(22)	[36]
^{95}Rb	0.378(2)	8.8(4)	[36]
^{137}I	24.59(10)	7.63(14)	[36]
^{145}Cs	0.582(6)	13.5(6)	[36]
^{146}Cs	0.3217(10)	14.3(8)	[36]
^{147}Cs	0.2295(10)	28.5(20)	[36]

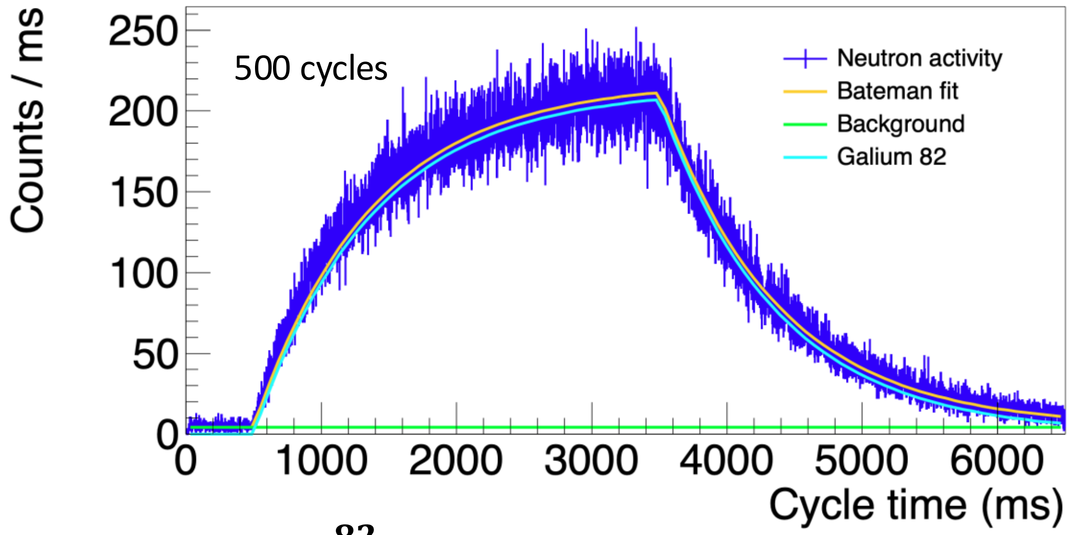
$$P_n = P_{1n} = 22.6 \pm 0.1\ \%$$

$$\bar{\varepsilon}_\beta = 73.1 \pm 0.1\ \%$$

$$\bar{\varepsilon}_n = 54.2 \pm 0.1\ \%$$



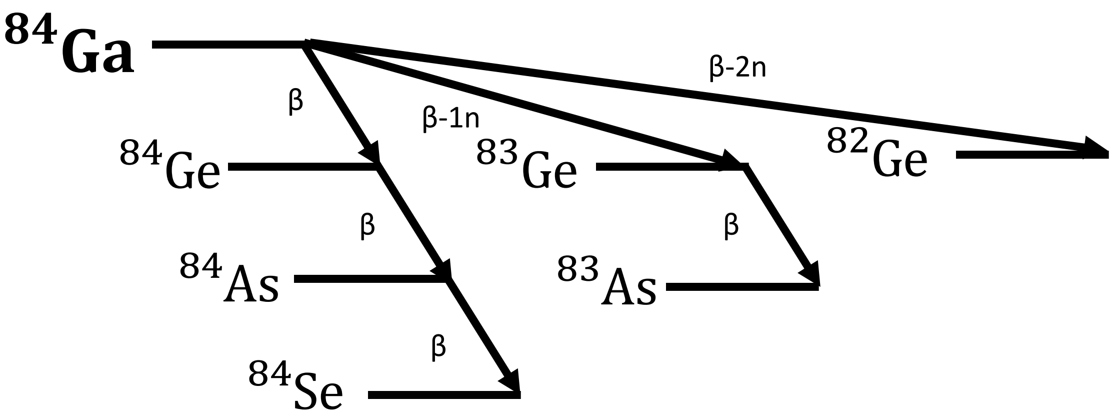
^{82}Ga β activity curve



^{82}Ga neutron activity curve

^{84}Ga

Bateman fits



$N_\beta(^{84}Ga)$	1107000 (1000)
$N_n(^{84}Ga)$	258100 (500)

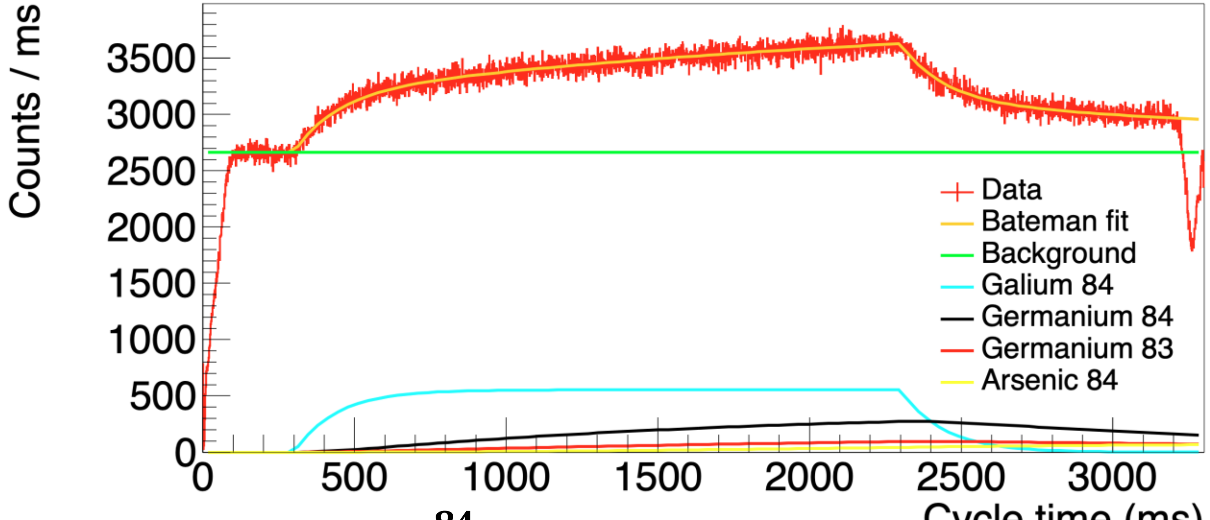
$Q_{\beta-1n} = 8.811$ MeV

$T_{\frac{1}{2}} = 97.1$ ms

$< n >* = 35.2 \pm 1.4\%$

20880 cycles

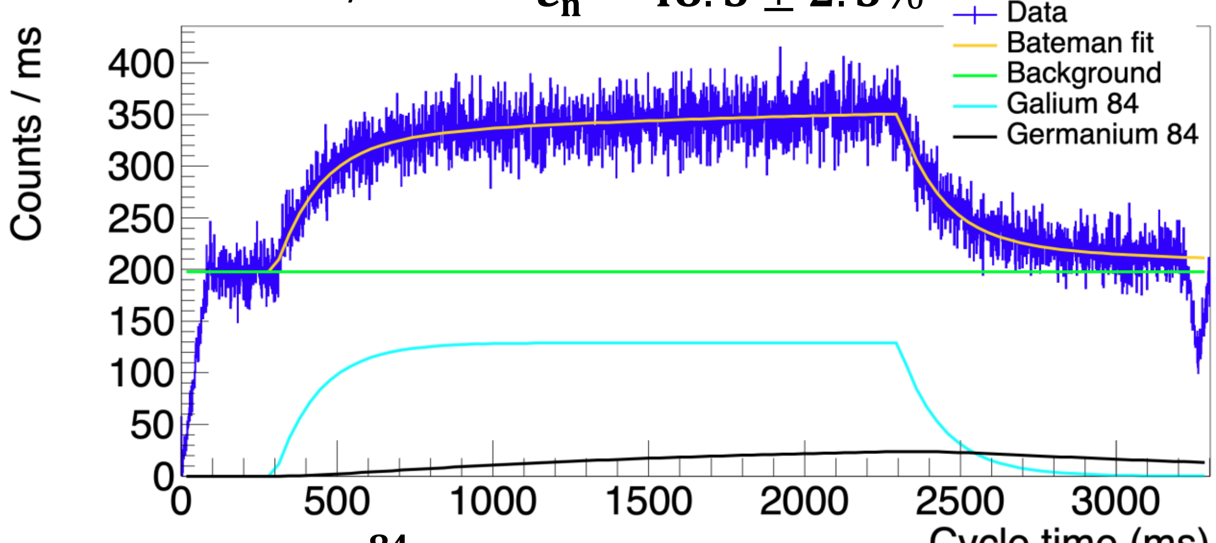
$\bar{R} = 1.51 \pm 0.06$



^{84}Ga β activity curve

20880 cycles

$\bar{\varepsilon}_n = 48.5 \pm 2.3\%$



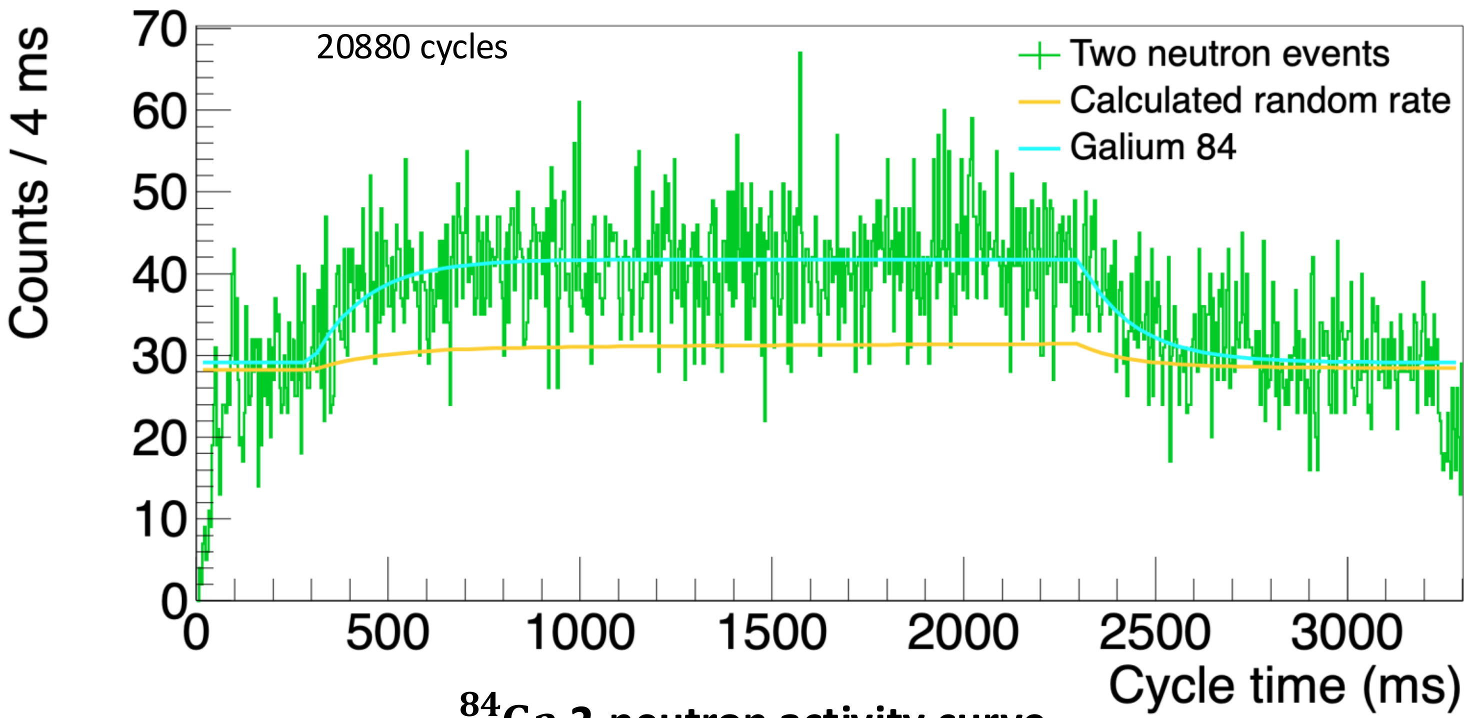
^{84}Ga neutron activity curve

^{84}Ga

Two neutron events

$Q_{\beta-2n} = 5.179\ \mathrm{MeV}$

$N_{2n}(^{84}Ga)$	5540 (70)



^{84}Ga 2-neutron activity curve

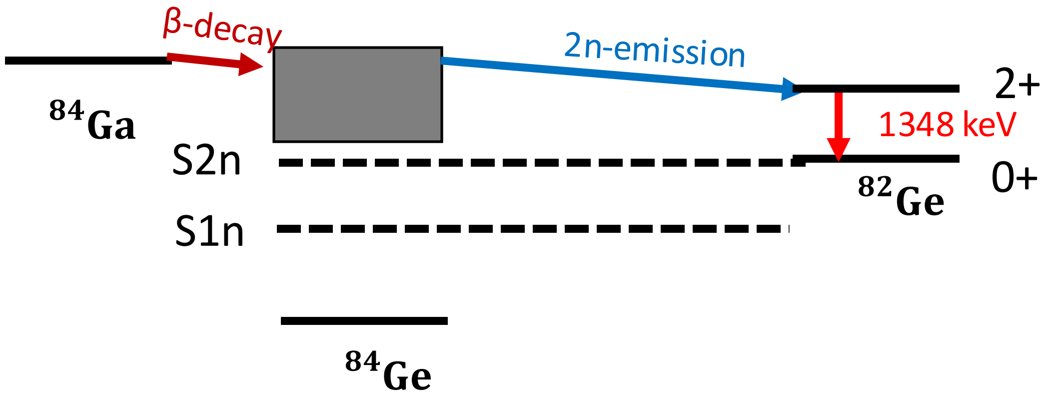
$$P_{2n} = 1.6 \pm 0.2\%$$

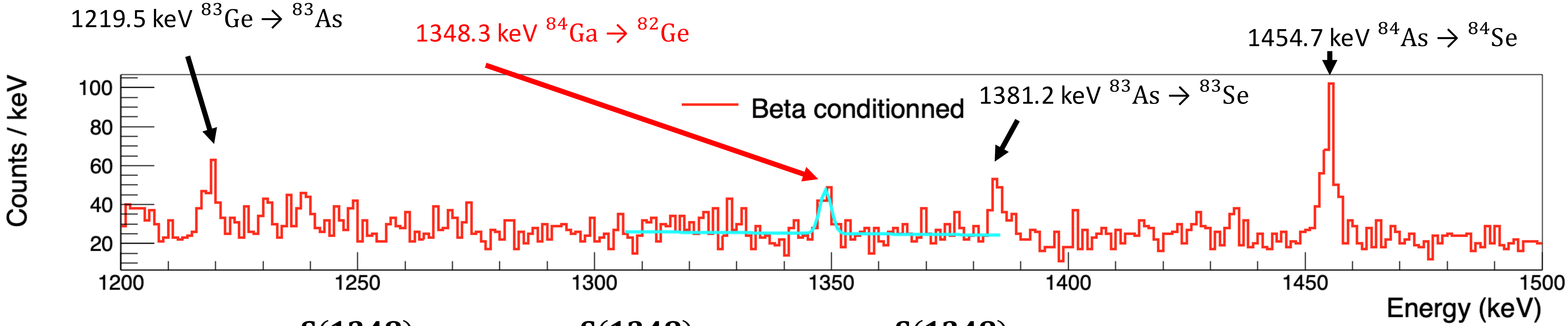
$$P_n = P_{1n} + P_{2n} = 34.4 \pm 1.4\ \%$$

Cf. Jonson et al. CERN (1981)

^{84}Ga

β-2n branching ratio





$$I^{abs}(1348) = \frac{S(1348)}{\varepsilon_\gamma \varepsilon_\beta N_\beta^{true}(^{82}Ga)} = \frac{S(1348)}{\varepsilon_\gamma \varepsilon_\beta P_{2n} N_\beta^{true}(^{84}Ga)} = \frac{S(1348)}{\varepsilon_\gamma P_{2n} N_\beta^{observed}(^{84}Ga)}$$

State populated	2^+ (1348 keV)
Absolute branching ratio (%)	95 ± 19 %

Preliminary

Interpretation under discussion !

Cf. Yokoyama et al. Physical Review C 108 (2023)

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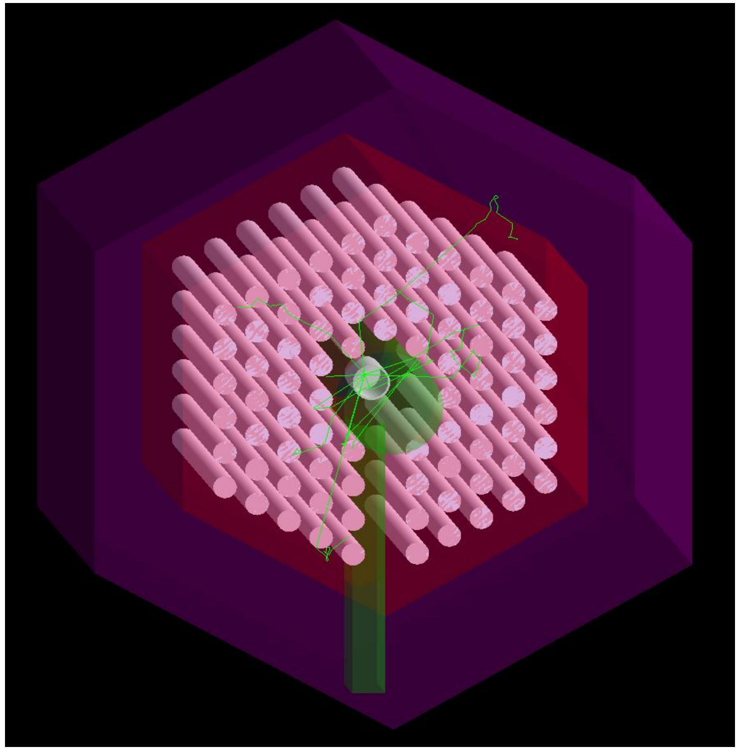
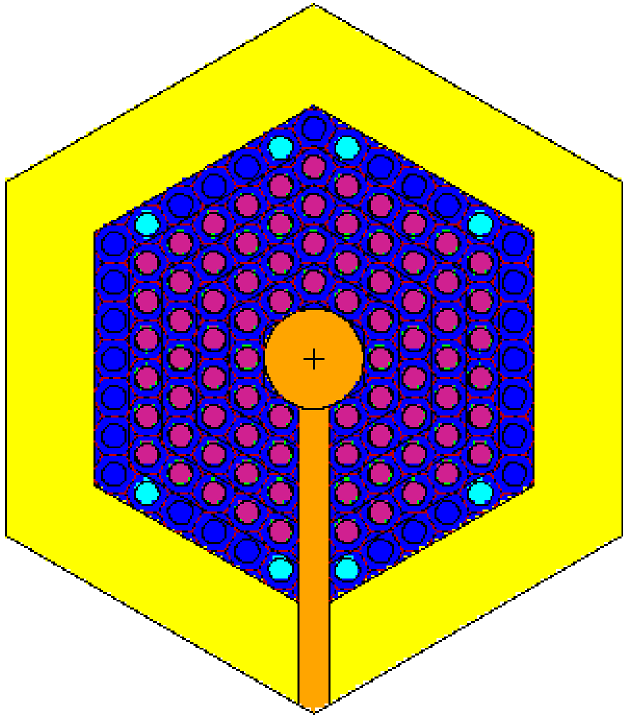
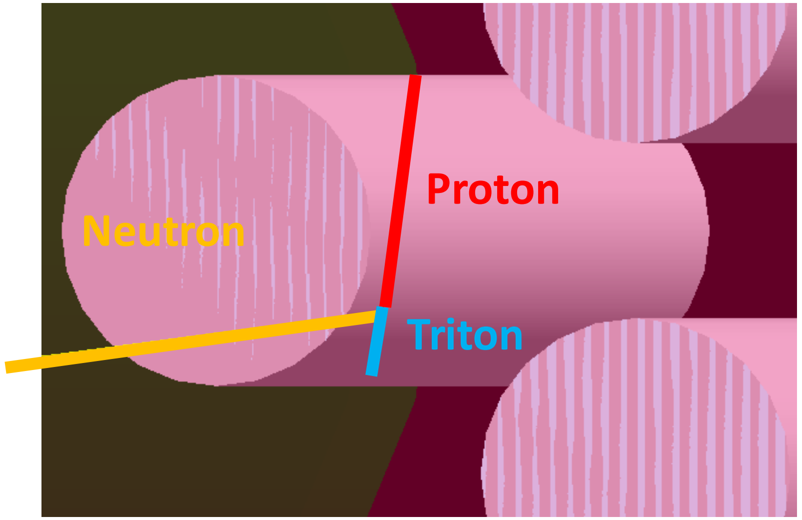
Geometry and physics list



Geant4



MCNP



MCNP has shown results closer to experimental data

Full geometry implemented

- 80 cells arranged in 4 rings
- Thermal neutron physics
- Realistic pressure in cells (around 2bars)
- 99% ^{3}He and 1% CO_2 mixture

Ring ratio method

Neutron energy distribution

Examples from litterature

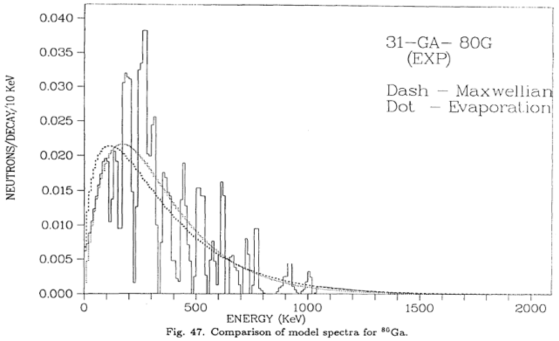


Fig. 47. Comparison of model spectra for ^{80}Ga.

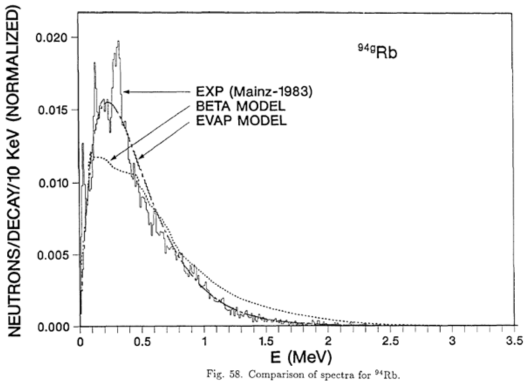
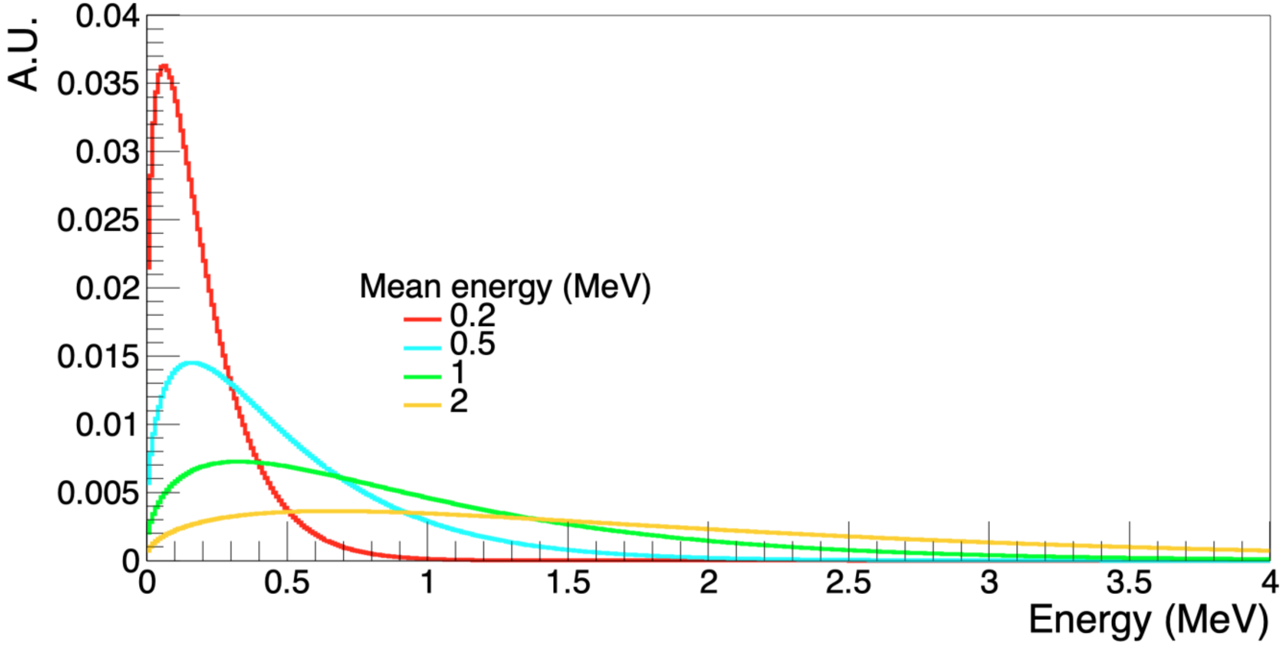


Fig. 58. Comparison of spectra for ^{94}Rb.

Simulated spectra



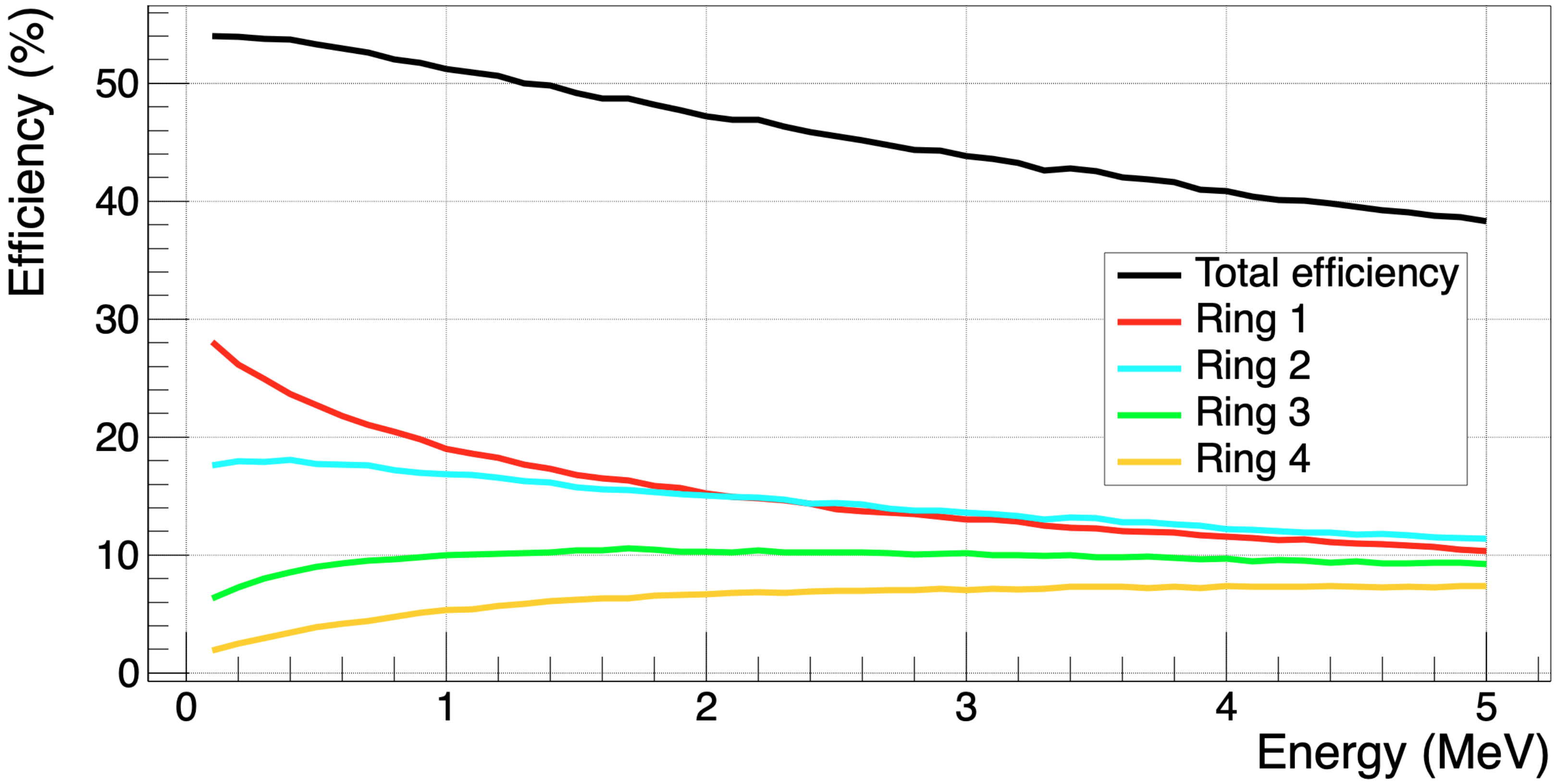
- Maxwellian approximation at first order

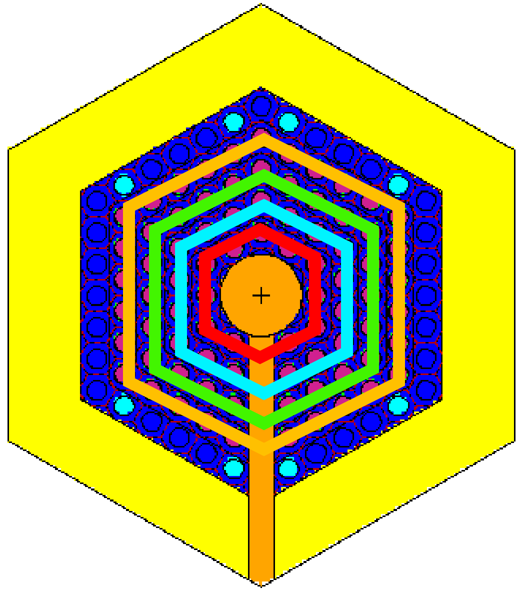
$$f(E) \propto \sqrt{E}e^{-\frac{E}{T}} \qquad \bar{E} = \frac{3T}{2}$$

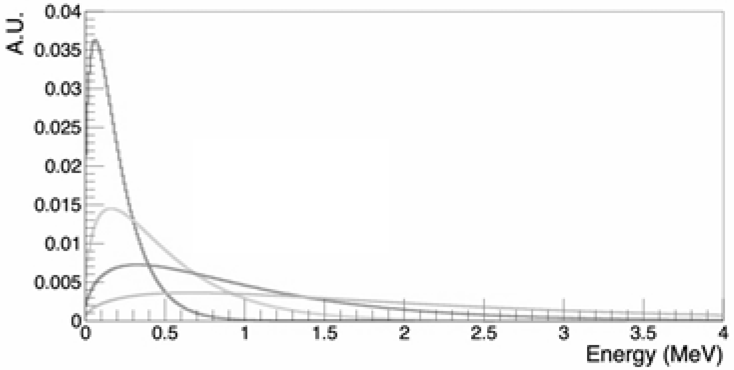
cf. "Evaluation and Application of Delayed Neutron Precursor Data" Michaele Clarice Brady

Ring ratio method

Efficiency as a function of mean neutron energy



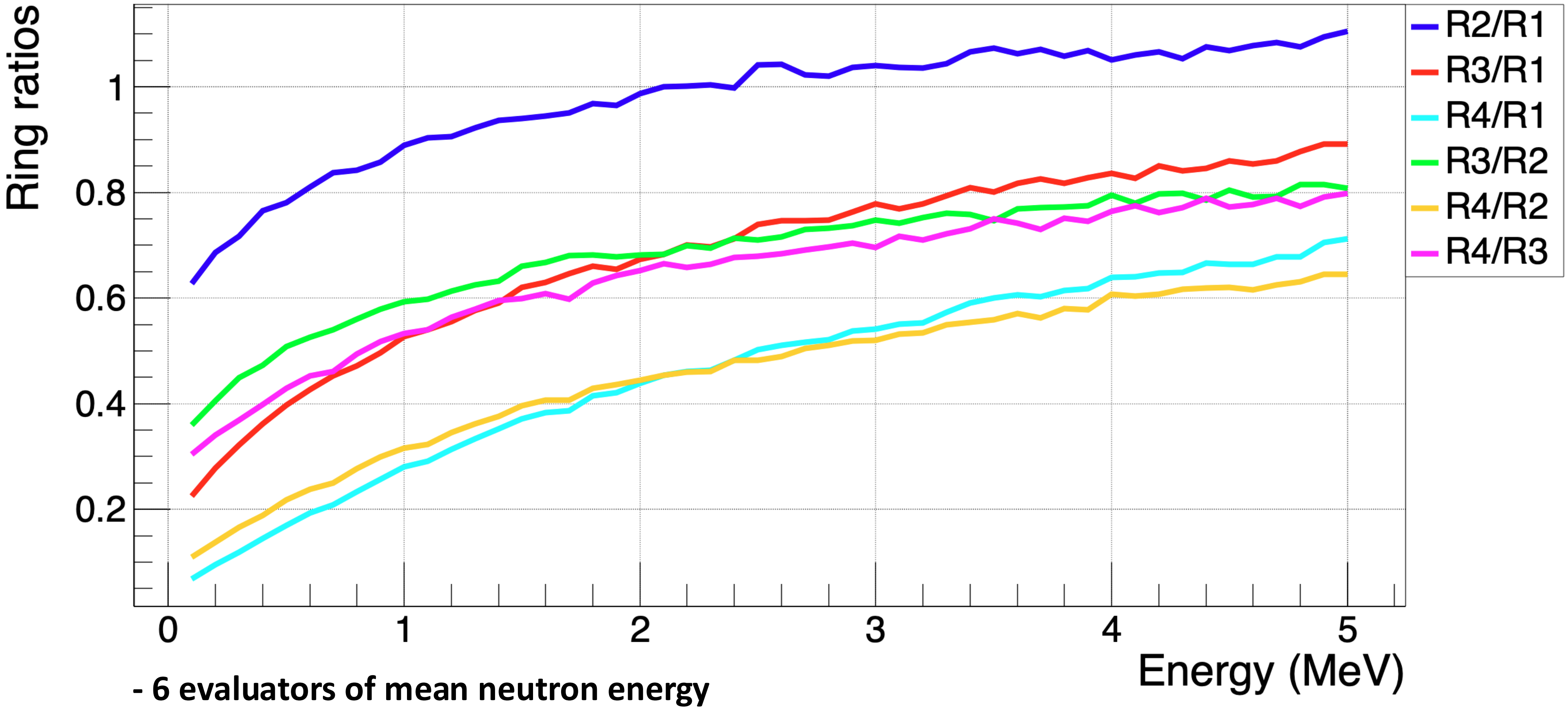




- TETRA efficiency under control
- Neutron penetration increases with energy

Ring ratio method

Ring ratios as a function of mean neutron energy

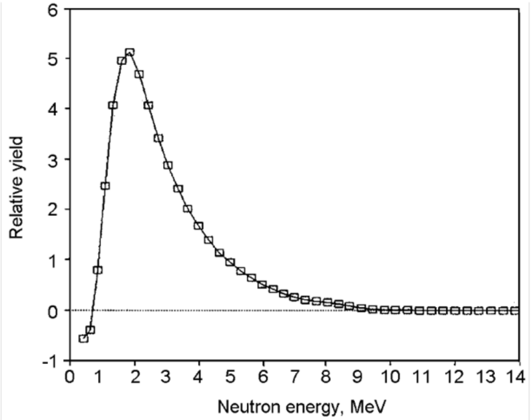


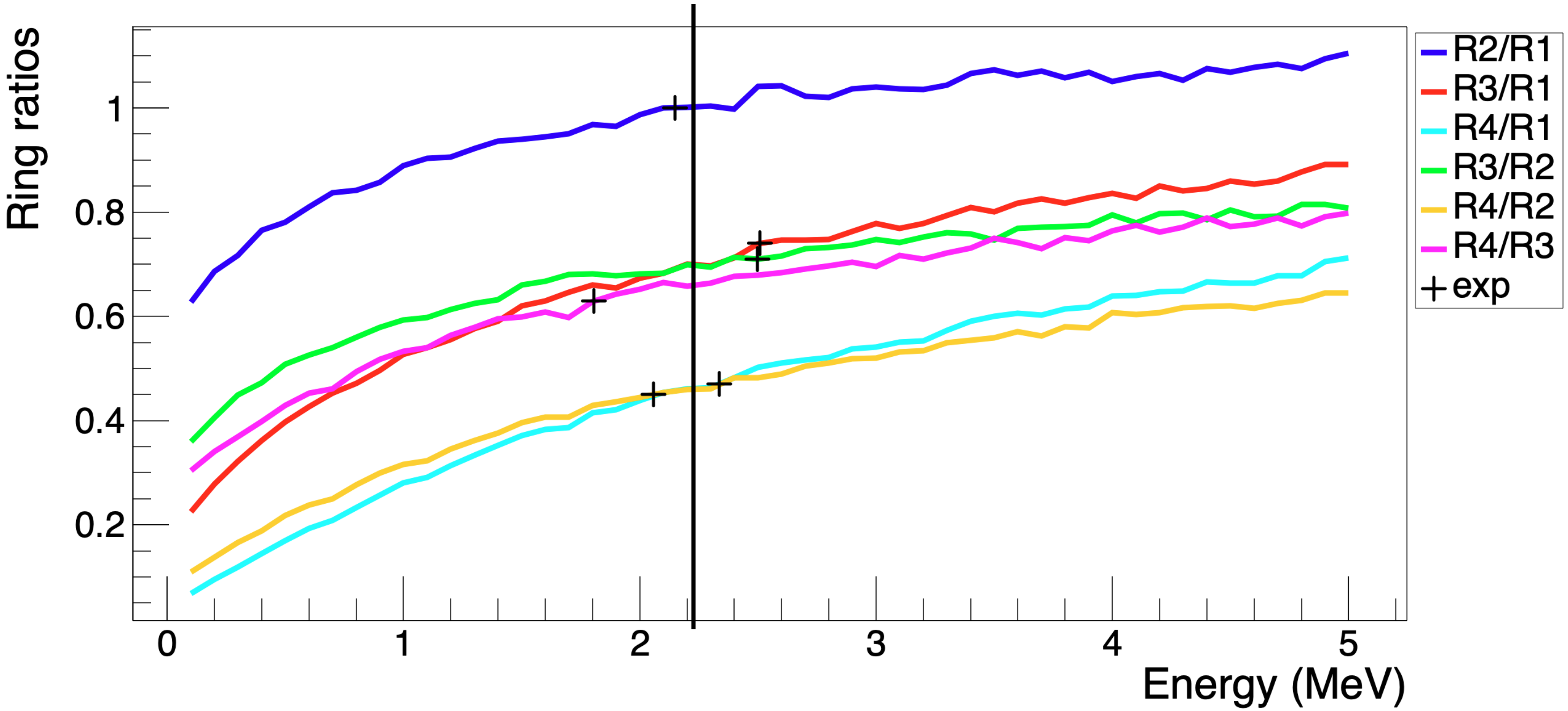
- 6 evaluators of mean neutron energy

Ring ratio method

The ^{252}Cf benchmark

	R2/R1	R3/R1	R4/R1	R3/R2	R4/R2	R4/R3
Ring Ratio (exp)	1.0	0.74	0.47	0.71	0.45	0.63
Energy (MeV)	2.1	2.5	2.3	2.5	2.1	1.8



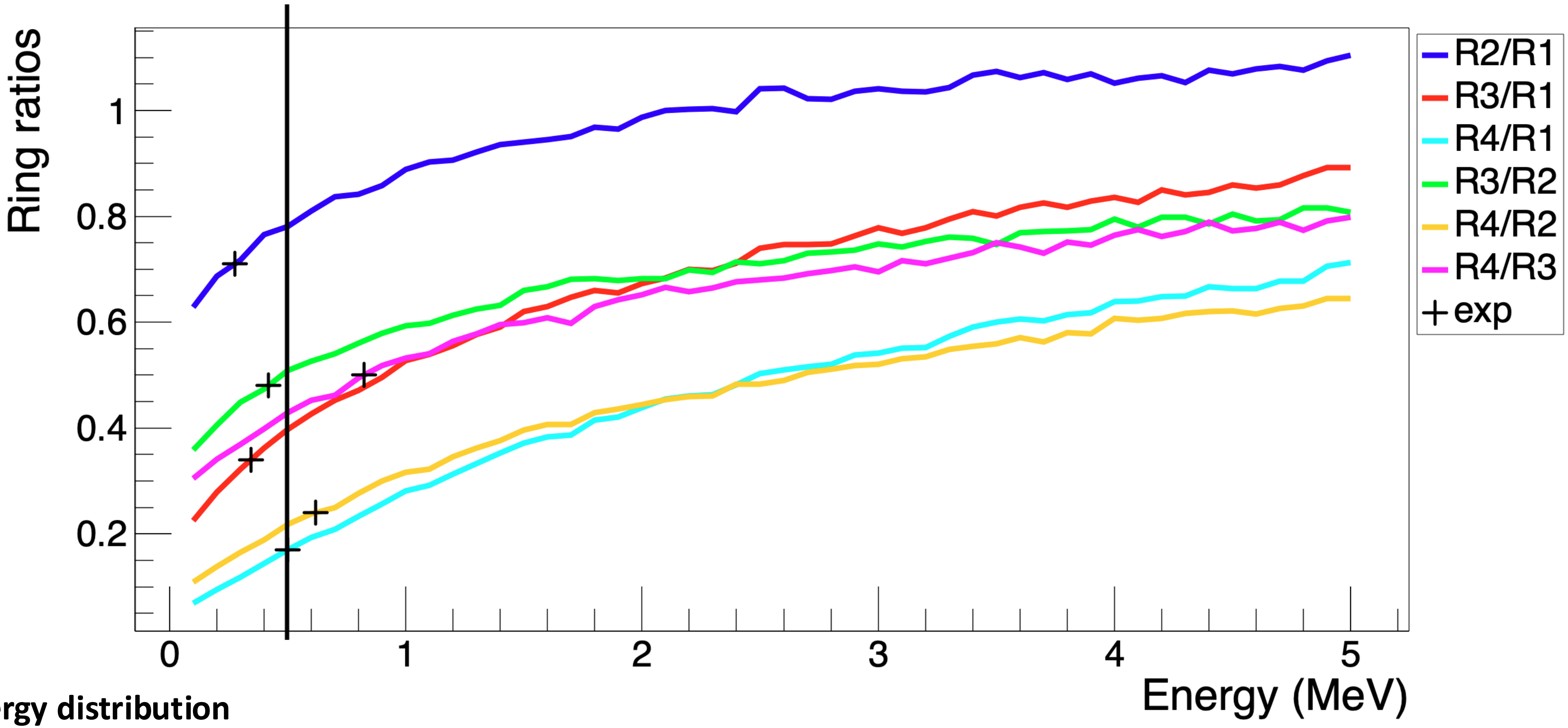


- **Know Maxwellian-like distribution with 2.1 mean energy**
- **D : Deviation from a pure Maxwellian distribution**

$$\bar{\mathbf{E}} = \mathbf{2.2\ MeV} \qquad \mathbf{D = 0.05}$$

Results

^{82}Ga



- **Unknown energy distribution**
- **Less Maxwellian than ^{252}Cf**

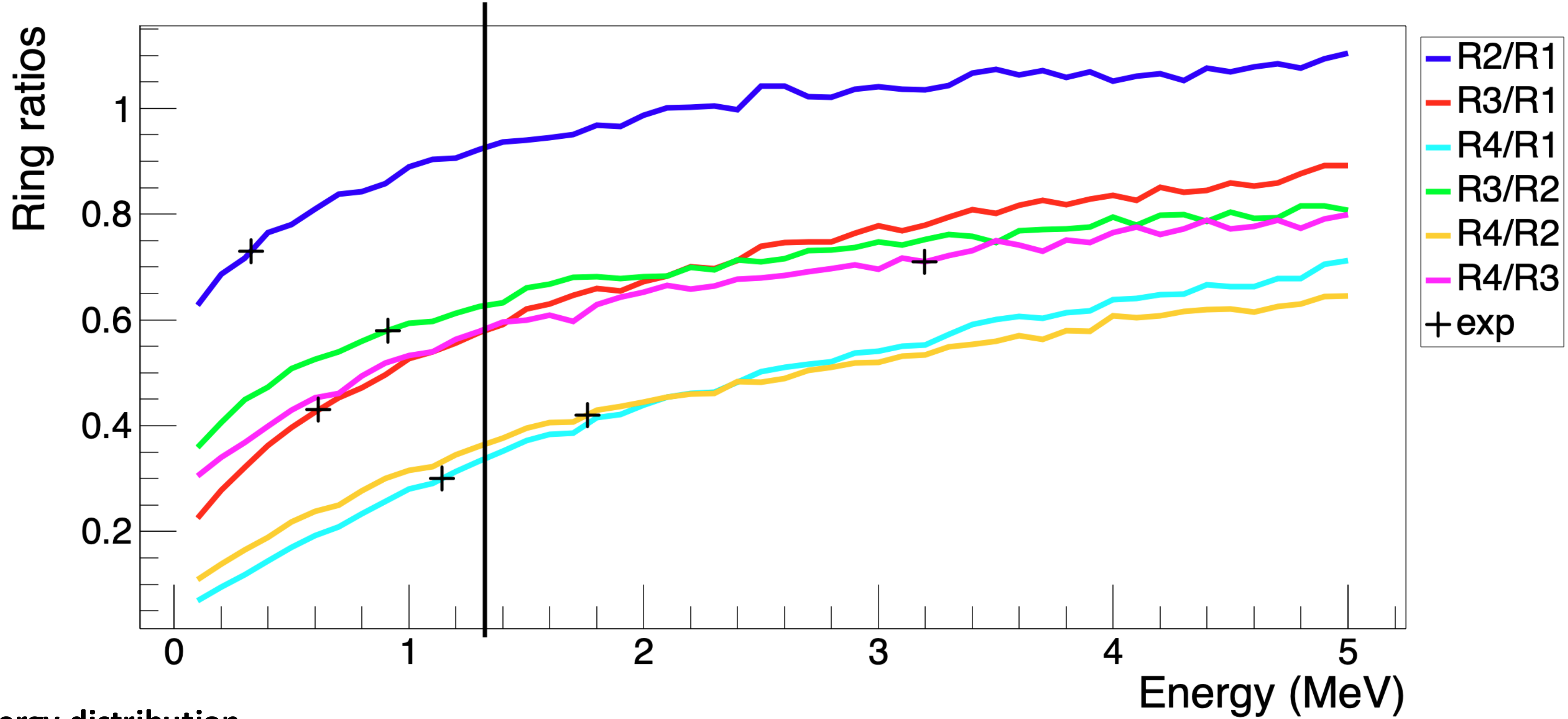
$$\bar{E} = 0.50\,\text{MeV} \quad D = 0.12$$

Preliminary

	R2/R1	R3/R1	R4/R1	R3/R2	R4/R2	R4/R3
Ring Ratio (exp)	0.71	0.34	0.17	0.48	0.24	0.50
Energy (MeV)	0.28	0.345	0.50	0.42	0.62	0.82

Results

^{84}Ga



- Unknown energy distribution
- Highly non Maxwellian

$\bar{E} = 1.3\ \text{MeV} \quad D = 0.29$

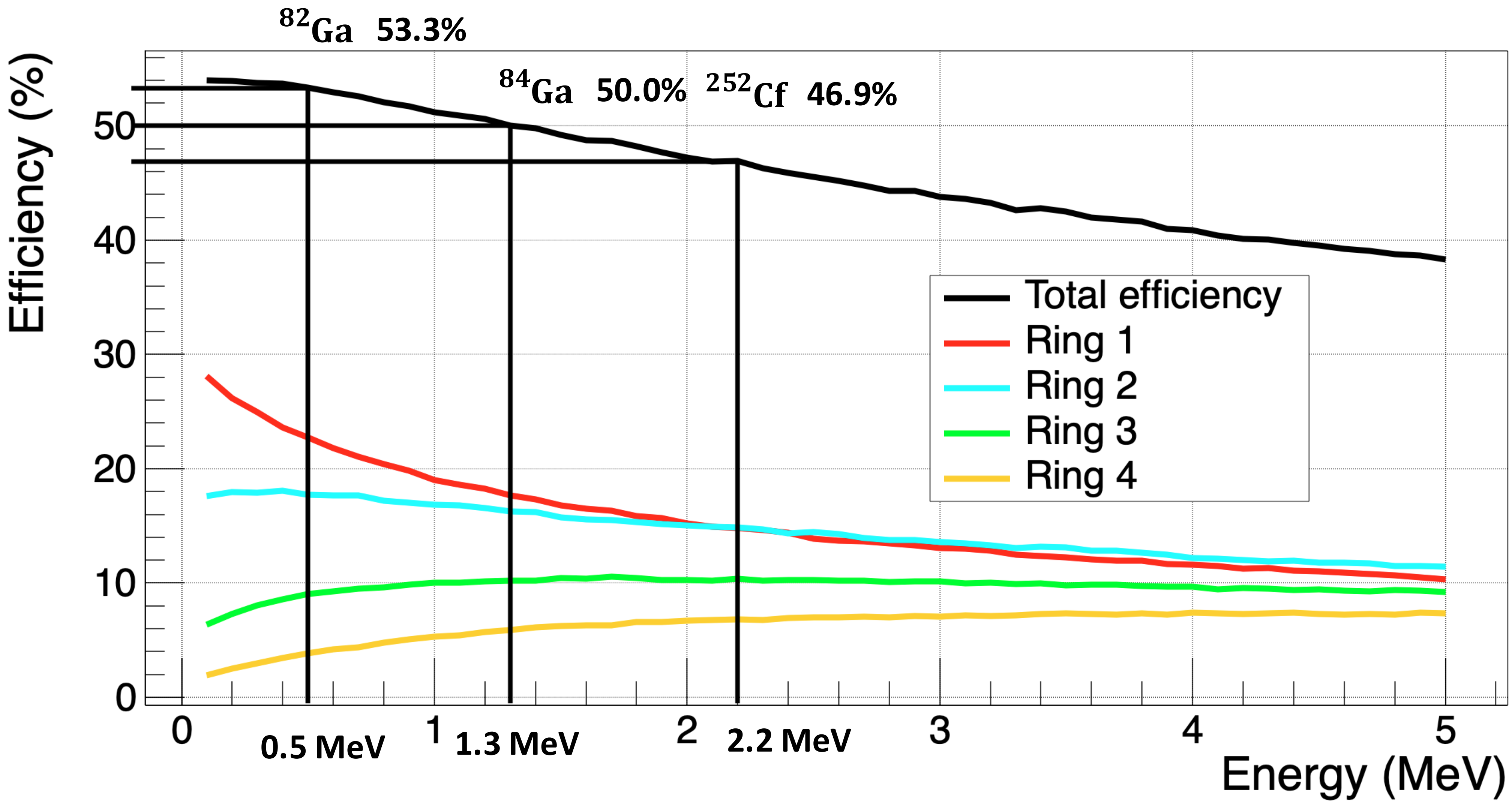
Preliminary

	R2/R1	R3/R1	R4/R1	R3/R2	R4/R2	R4/R3
Ring Ratio (exp)	0.73	0.43	0.3	0.58	0.42	0.71
Energy (MeV)	0.33	0.61	1.1	0.91	1.8	3.2

Results

Efficiency validation

- Coherent results with measured efficiencies



Conclusion and perspectives

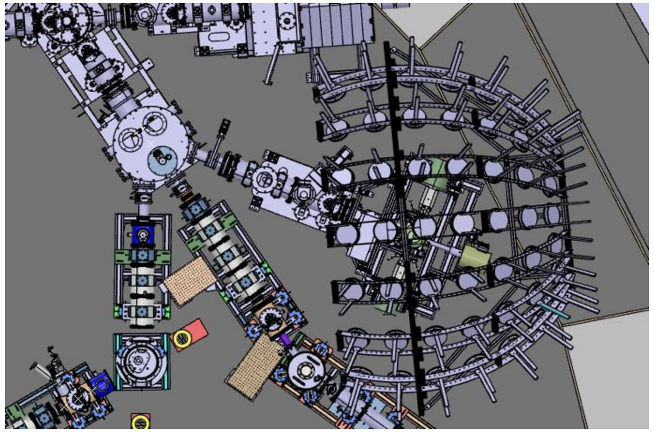
- **Measurement of the absolute branching ratio of the ^{84}Ga beta-2n branch.**

- **Development of a new technique to measure mean neutron energies using slow neutron counters.**

- **Measurement of mean neutron energies of ^{82}Ga and ^{84}Ga.**

- **MONSTER at Alto expriments planned in February 2025 in order to directly measure beta-delayed neutrons energy spectra.**

Cf. Martinez et al. Nuclear Data Sheets 120 (2014)



Backup

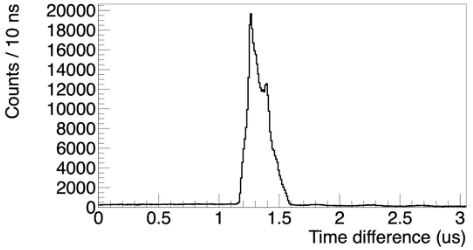
Formula

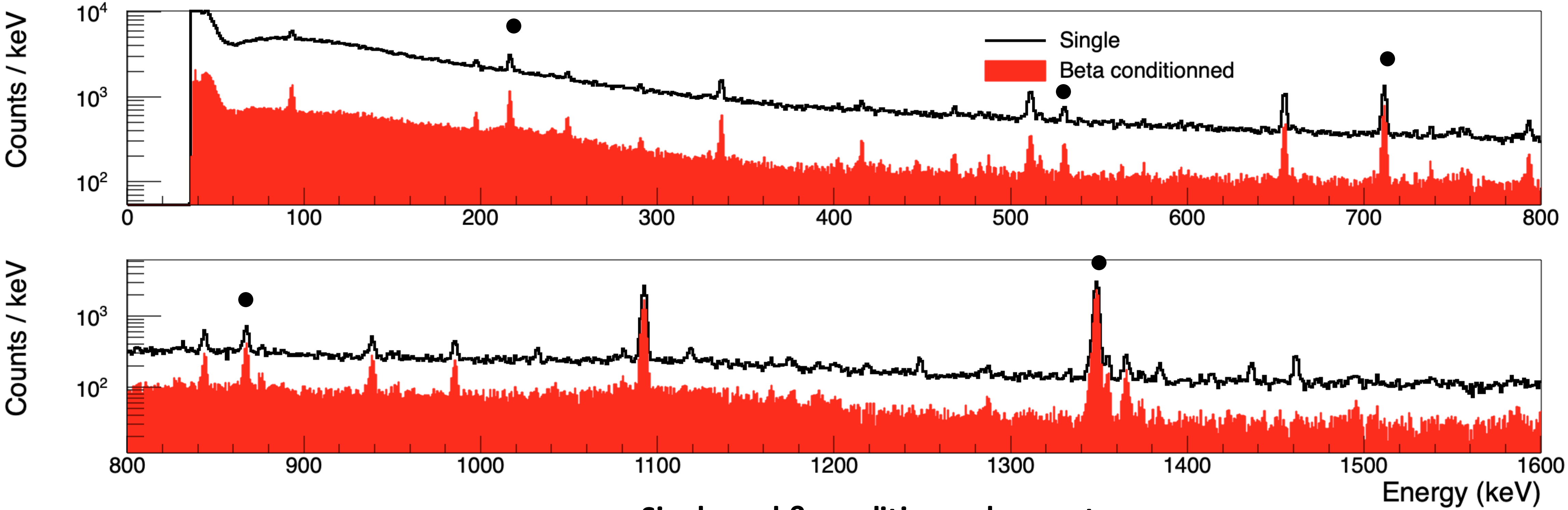
- $\mathbf{D} = \sqrt{(\mathbf{R}_1^{\mathbf{exp}} - \mathbf{R}_1^{\mathbf{Maxw}})^2 + \cdots + (\mathbf{R}_6^{\mathbf{exp}} - \mathbf{R}_6^{\mathbf{Maxw}})^2}$

- $\boldsymbol{\lambda}_{\mathbf{rand\ 2n}} = \boldsymbol{\lambda}_{\mathbf{1n}}^{\mathbf{2}} \boldsymbol{\theta} \mathbf{e}^{-\boldsymbol{\lambda}_{\mathbf{1}} \boldsymbol{\theta}}$

Calibration isotope : ^{82}Ga

4πβ efficiency





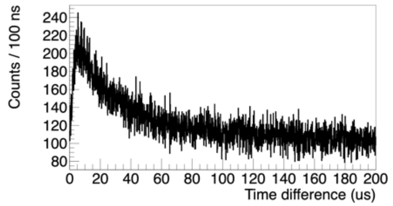
Single and β conditionned γ spectra

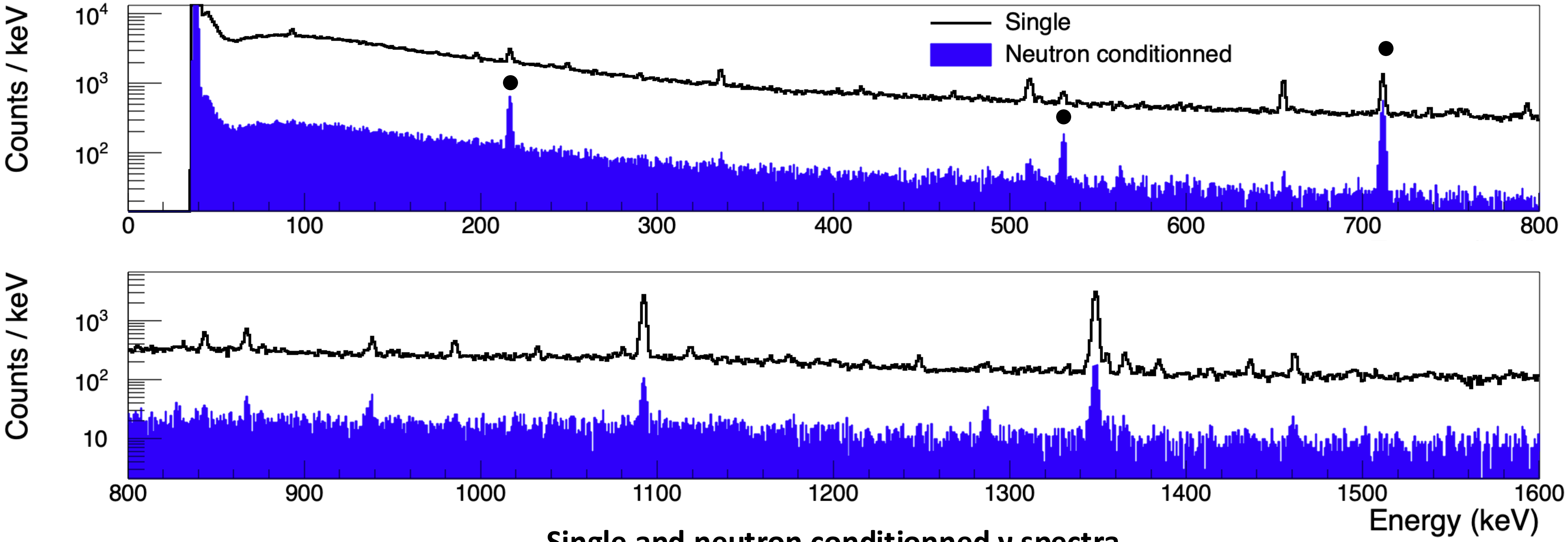
Energy (keV)	216.6	530.4	711.4	867.2	1348.5
4πβ efficiency (%)	**66.8**	**74.9**	**71.3**	**76.2**	**76.5**

$$\bar{\varepsilon}_\beta = 73.1 \pm 0.1\ \%$$

Calibration isotope : ^{82}Ga

TETRA efficiency





Single and neutron conditionned γ spectra

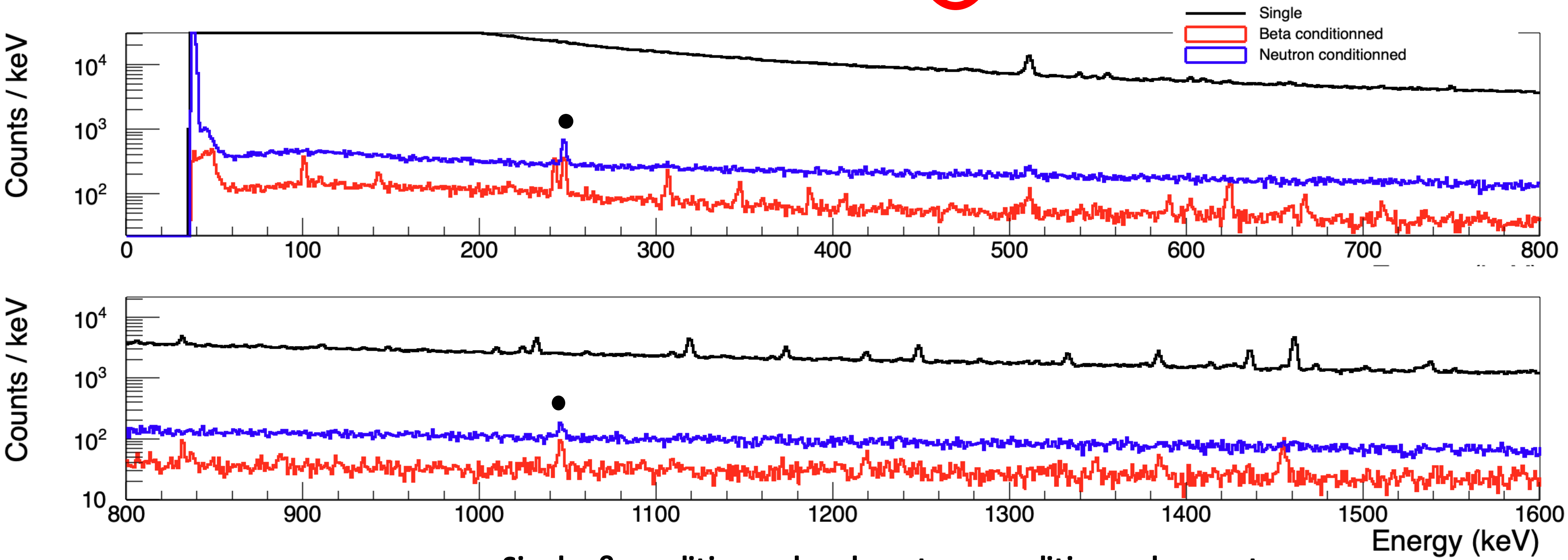
Energy (keV)	216.6	530.4	711.4
TETRA efficiency (%)	**51.5**	**55.6**	**55.5**

$$\bar{\varepsilon}_n = 54.2 \pm 0.1\ \%$$

^{84}Ga

Efficiency ratio

- $P_{1n} = \frac{N_{1n}}{N_\beta} \times \frac{\varepsilon_\beta}{\varepsilon_n}$
- $R \equiv \frac{\varepsilon_\beta}{\varepsilon_n}$



Single, β conditionned and neutron conditionned γ spectra

Energy (keV)	247.7	1046
R	**1.56**	**1.45**

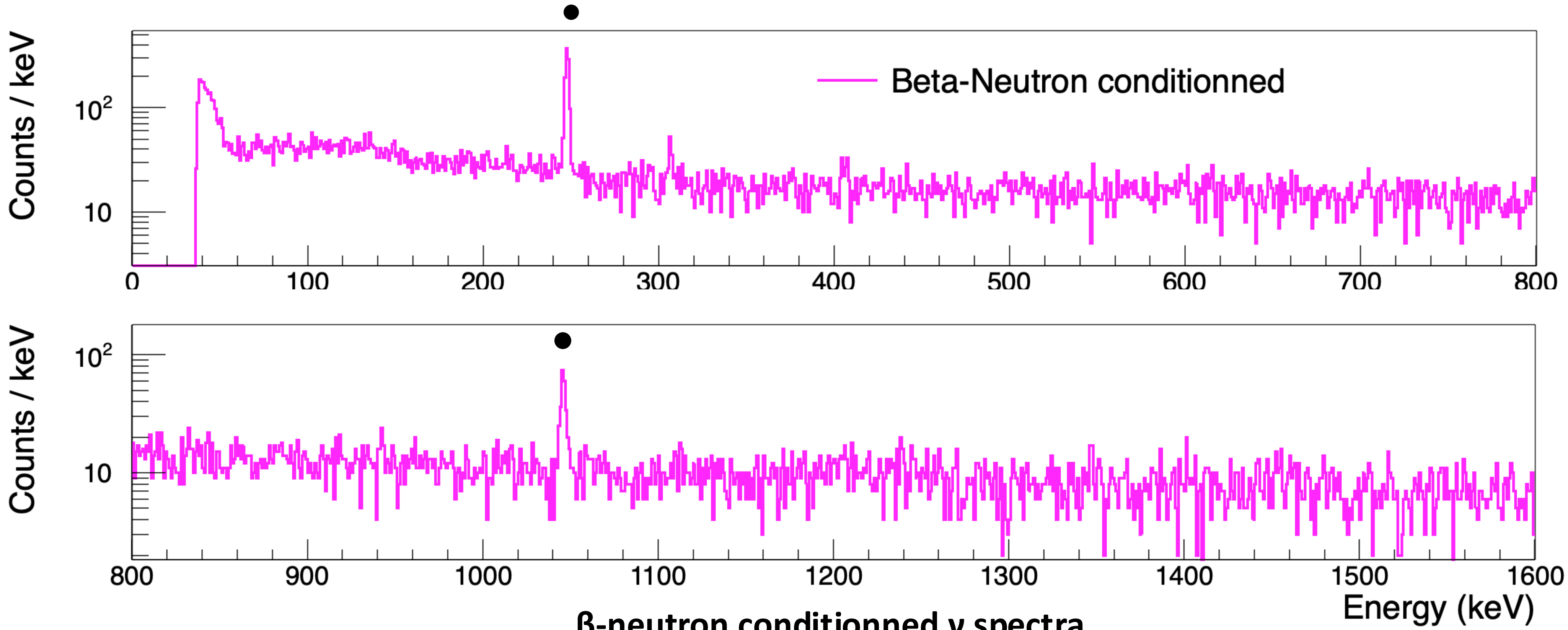
$$\bar{R} = 1.51 \pm 0.06$$

^{84}Ga

TETRA efficiency

- $P_{2n} = \frac{N_{2n}}{N_\beta} \times \frac{\varepsilon_\beta}{\varepsilon_n^2}$

$$\frac{S_{(x+y)cond}}{S_{xcond}} = \varepsilon_y$$



β-neutron conditionned γ spectra

Energy (keV)	247.7	1046
TETRA efficiency (%)	**50.4**	**46.6**

$$\bar{\varepsilon}_n = 48.5 \pm 2.3\%$$