Calibration of 100 eV Nuclear Recoil with the CRAB Method

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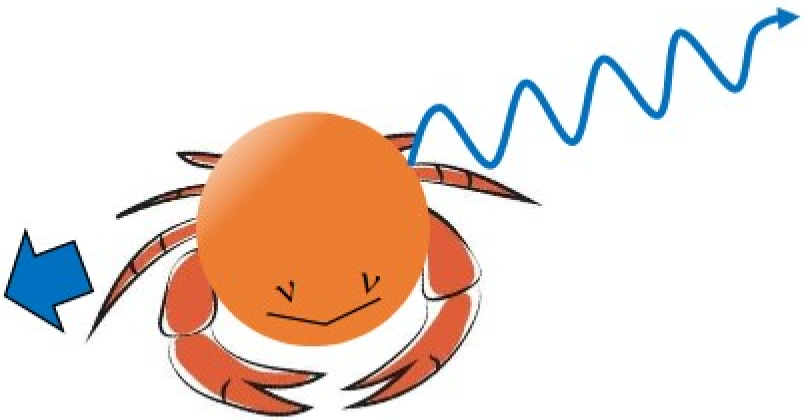
February 24th 2024

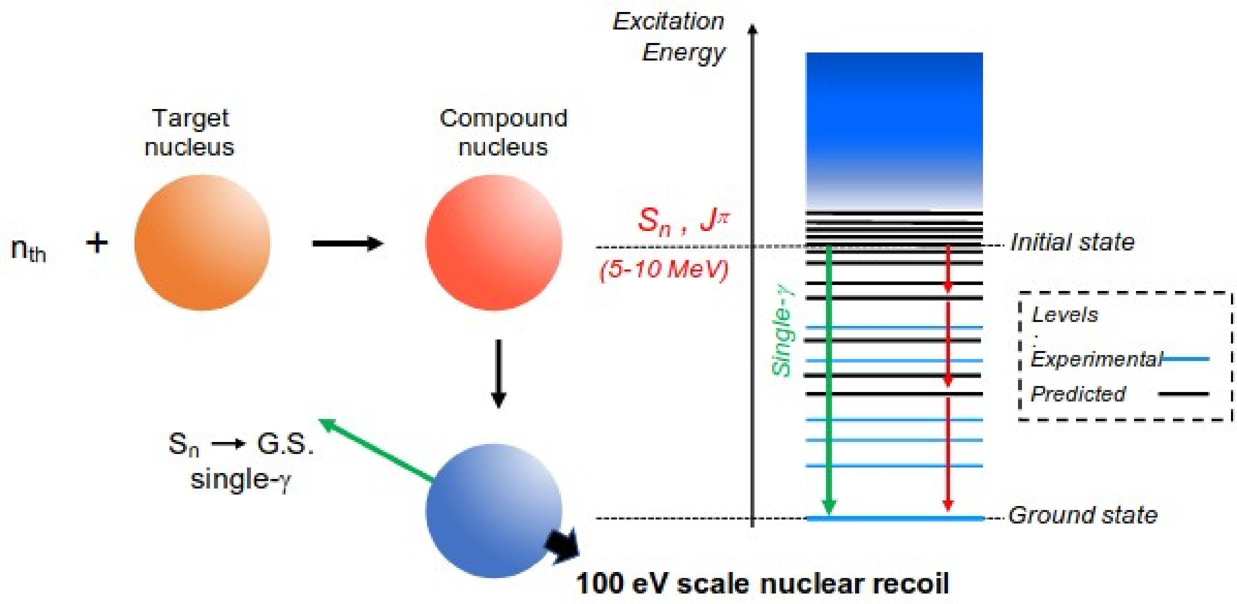


Motivations

- Bolometry is used in most of low background experiments, including research of dark matter or CEvNS
- Signature event is often a nuclear recoil (NR): calibration of NR in the crystal is then crucial
- Standard calibration: electronic recoil (X-rays, LED), sensitive to quenching effect
- Challenge: calibration of low energy nuclear recoil in all the crystal
- Calibrated Recoils for Accurate Bolometry (CRAB)

Calibration (CRAB)

- Thermal neutron capture followed by de-excitation: γ + NR
  - Single-γ : NR with well known energy $E_{NR}=E_{\gamma}^2/2M$ → calibration peak ~100 eV scale
  - Multi-γ: Depend on nuclear level energy (FIFRELIN)

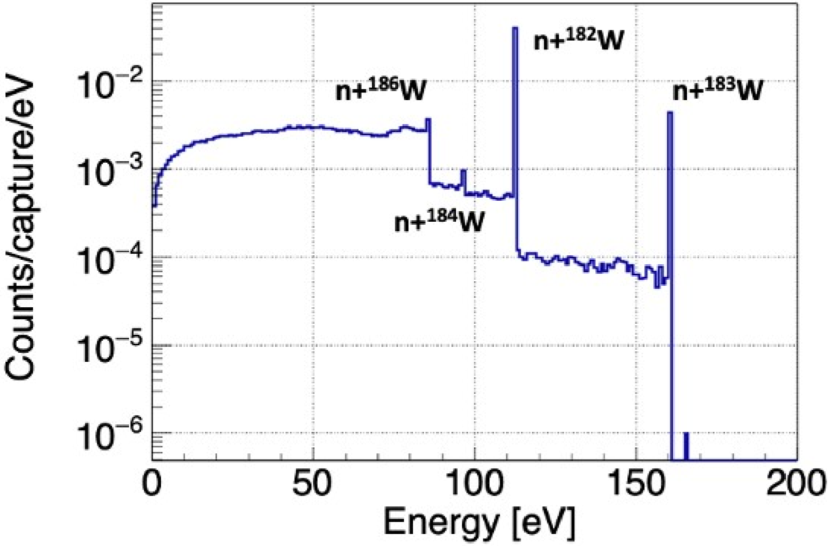


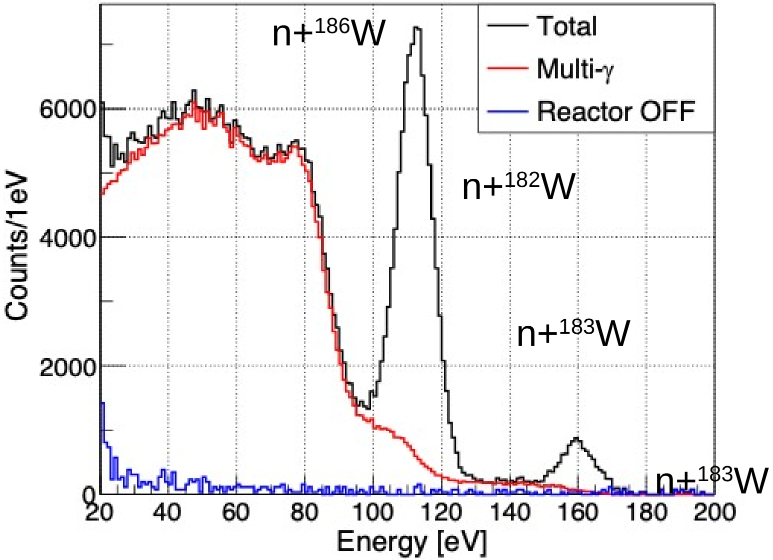
- Single-γ leave crystal without energy deposition
- Let's first focus on single-γ transition

Arxiv2011.13803 : Calibration of nuclear recoils at the 100 eV scale using neutron capture

Simulation of a Tungsten cube

- 3 main natural isotopes of W : ^{186}W, ^{182}W and ^{183}W : peaks at 81, 112 and 160 eV
- 81 eV peak stands on a large continuum of multi-gamma decay events → very sensitive to detector resolution

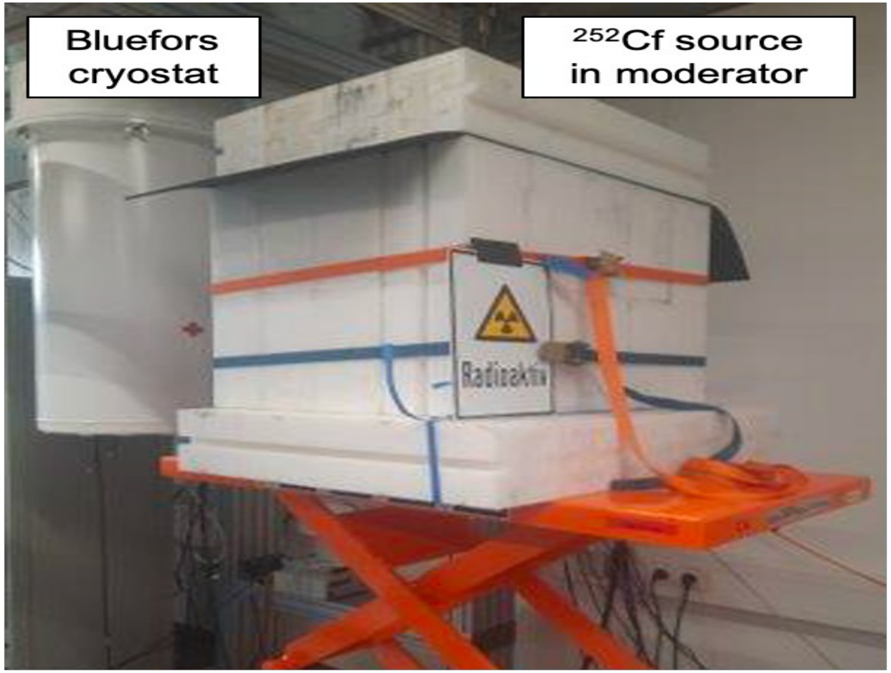


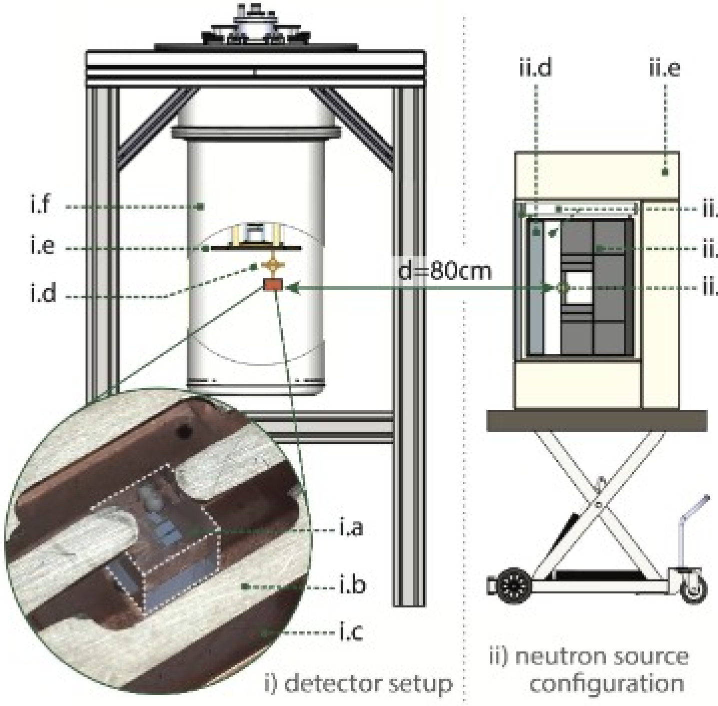


Left: Distribution of energy deposited in a CaWO4 crystal. Right: Detector signal with 5 eV resolution.

Experimental validation

- July 2022 at TUM (Munich) with neutron portable source
- 0.75 g CaWO4 crystal of 5x5x5mm³ from NUCLEUS

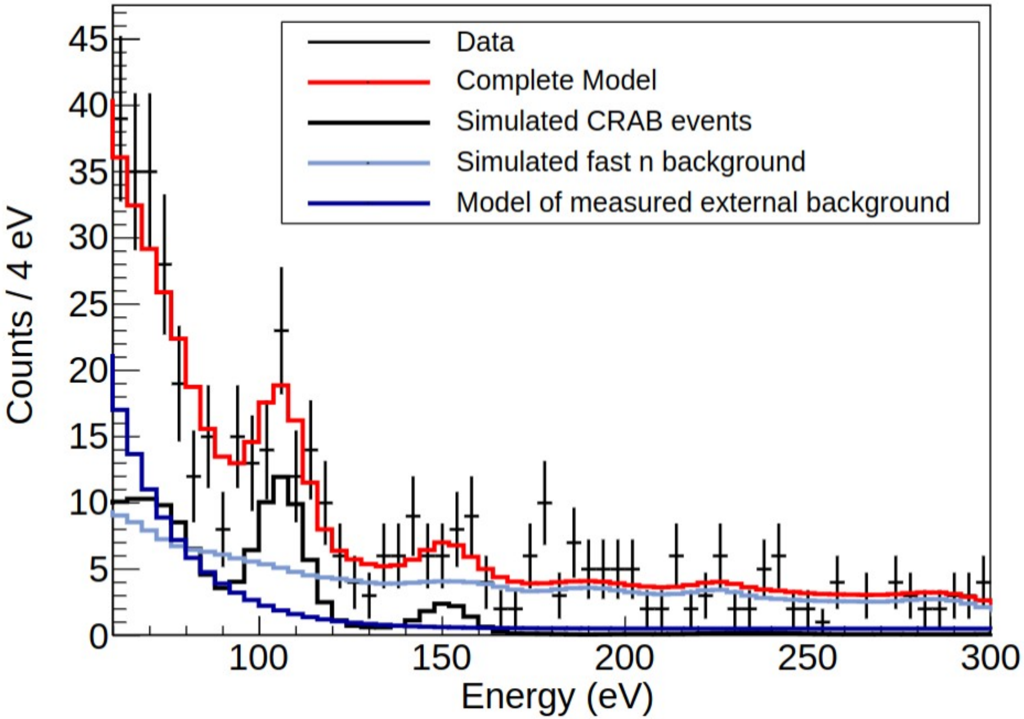




- Baseline resolution: ~6.5eV
- Measurements over 3 days

Experimental validation

- 112 eV peak detected at 3 σ significance
- CRESST collaboration also reported about the 112 eV peak
- Validation of the CRAB method !
- Open perspective for future run with more statistic (phase II)



PRL: Observation of a nuclear recoil peak at the 100 eV scale induced by neutron capture (PhysRevLett.130.211802)

PRD: Observation of a low energy nuclear recoil peak in the neutron calibration data of the CRESST-III experiment (Phys. Rev. D 108, 022005)

Extending the physics of CRAB measurements

Multi-gamma

- Prediction of the de-excitation cascades by the FIFRELIN code
  - Depend on nuclear data as intermediate energy levels, branching ratios, livetime...
- Multi γ de-excitations : recoil energy depends on γ energies
  - Continuum recoil energy spectra
- Multi γ continuum will constrain nuclear models

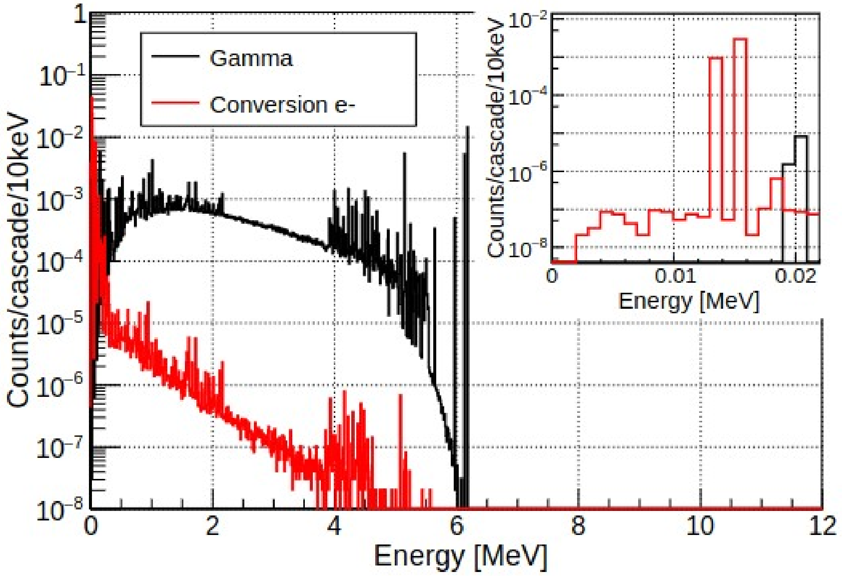
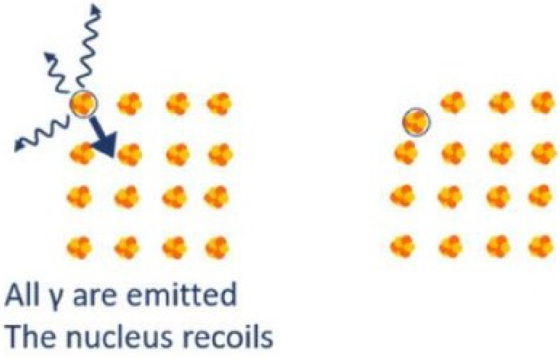


Fig : ^{183}W de-excitation spectrum from FIFRELIN

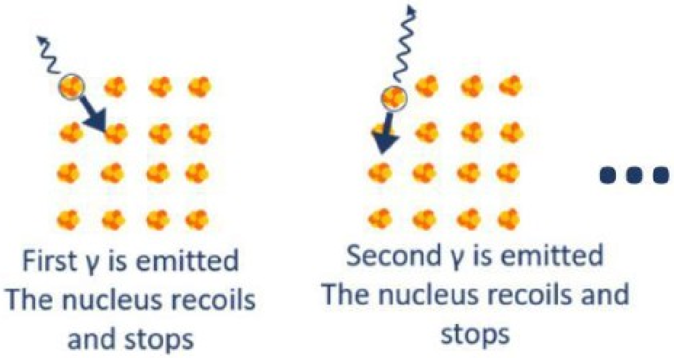
Timing effect for multi-γ

- **Prompt hypothesis : $\tau_\gamma \ll \tau_{recoil} \sim 10^{-13}$s**



$$E_{recoil} = \left(\sum_\gamma \vec{p}_\gamma\right)^2 / 2M_{nucleus}$$

- **Slow hypothesis : $\tau_{detector} \gg \tau_\gamma \gg \tau_{recoil}$**



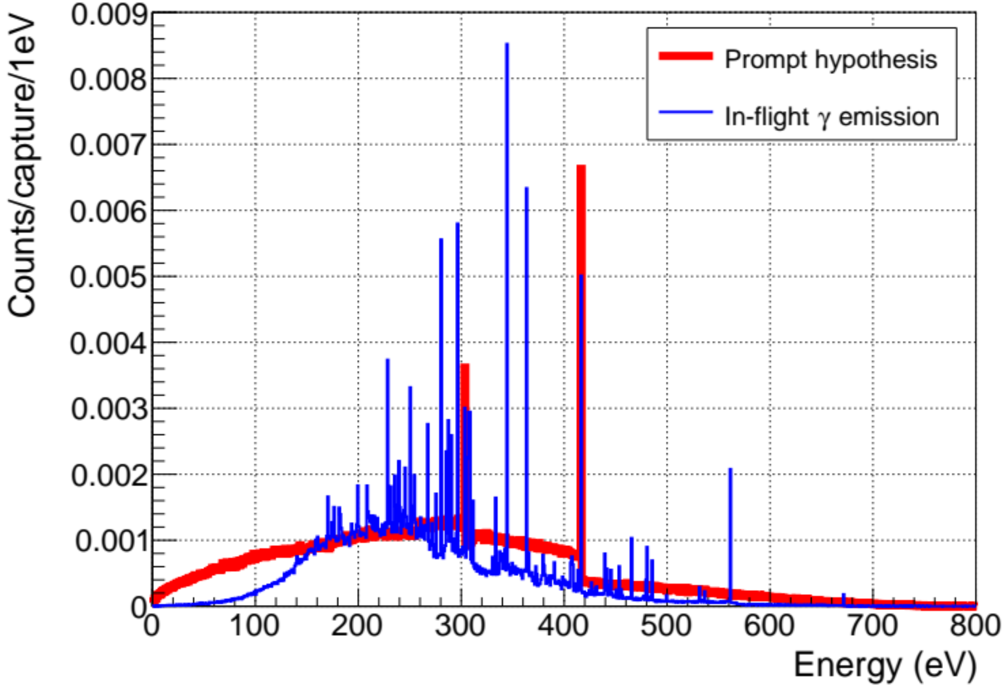
$$E_{recoil} = \sum_\gamma p_\gamma^2 / 2M_{nucleus}$$

- Intermediate case : de-excitation in flight → IRADINA
- IRADINA + FIFRELIN : FIFRADINA to simulate in-flight γ emission

Timing effect

- Timing changes the energy deposited in the bolometer for multi-γ transitions
- Timing effect does not affect single-γ calibration peaks
- Timing effect not negligeable for Germanium : provide additionnal calibration peaks

Ge spectrum



- PRD : Study of collision and γ-cascade times following neutron-capture processes in cryogenic detectors (Phys. Rev. D 108, 072009)

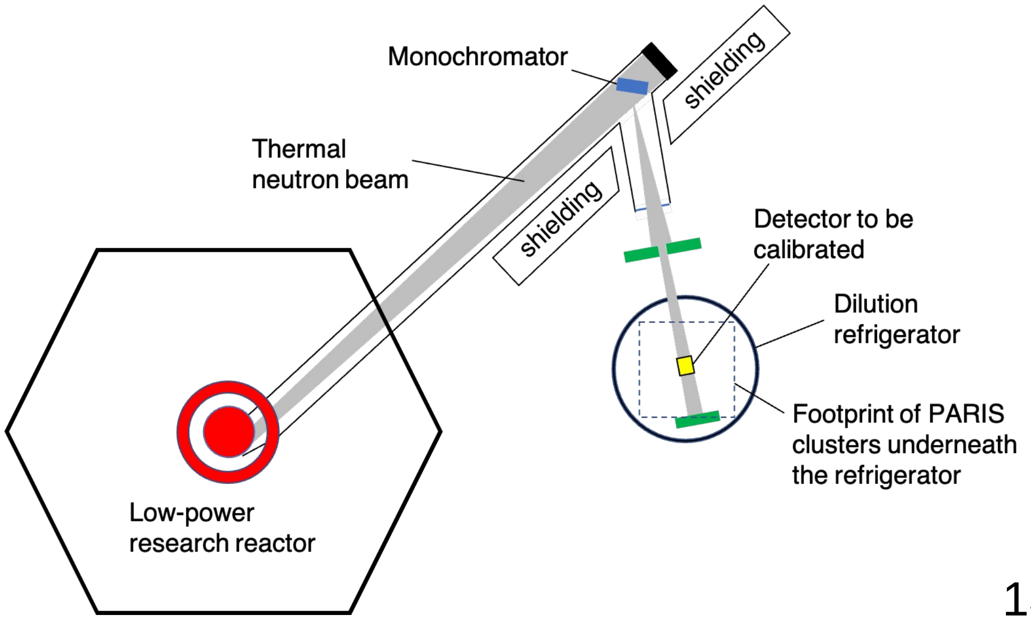
Study of linearity

- Readout channels at ~100eV scale :
  - Tungsten : phonons channel
  - Germanium : phonons and ionization channels
- For Tungsten, NR have very high energy → 0,1 or 2 crystal defect creation
  - Linearity measurements could show sensitivity to the creation of a single crystal defect.
- For Germanium, quenching factor can be probed by studying the linearity using the 4 main peak structures expected in the 300-700 eV range from CRAB events.

CRAB Phase II

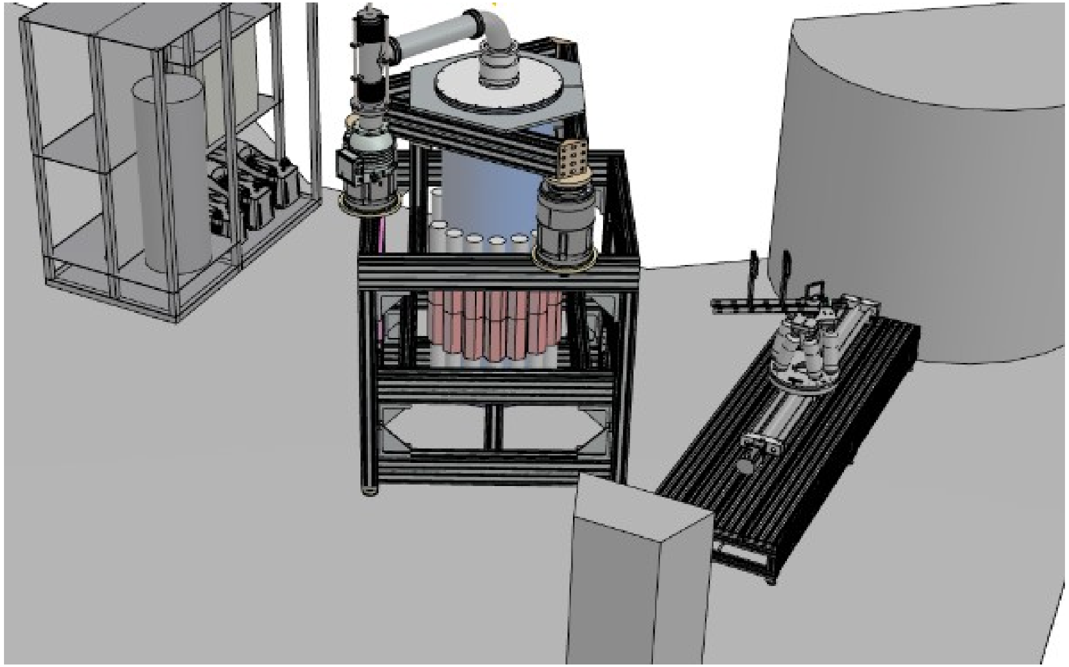
Phase II (TU Wien)

- To probe all this physics, we need high statistic and a very good resolution
- Coincidence with emitted gamma allows to relax resolution constraint
- CRAB at atominstitute
  - Research reactor, P ~ 250 kW
  - Collimated thermal neutron beam
  - Neutron flux at crystal level ~ 100 n/cm²/s
  - Calibration of a $CaWO_4$ crystal in 2024



Gamma tagging

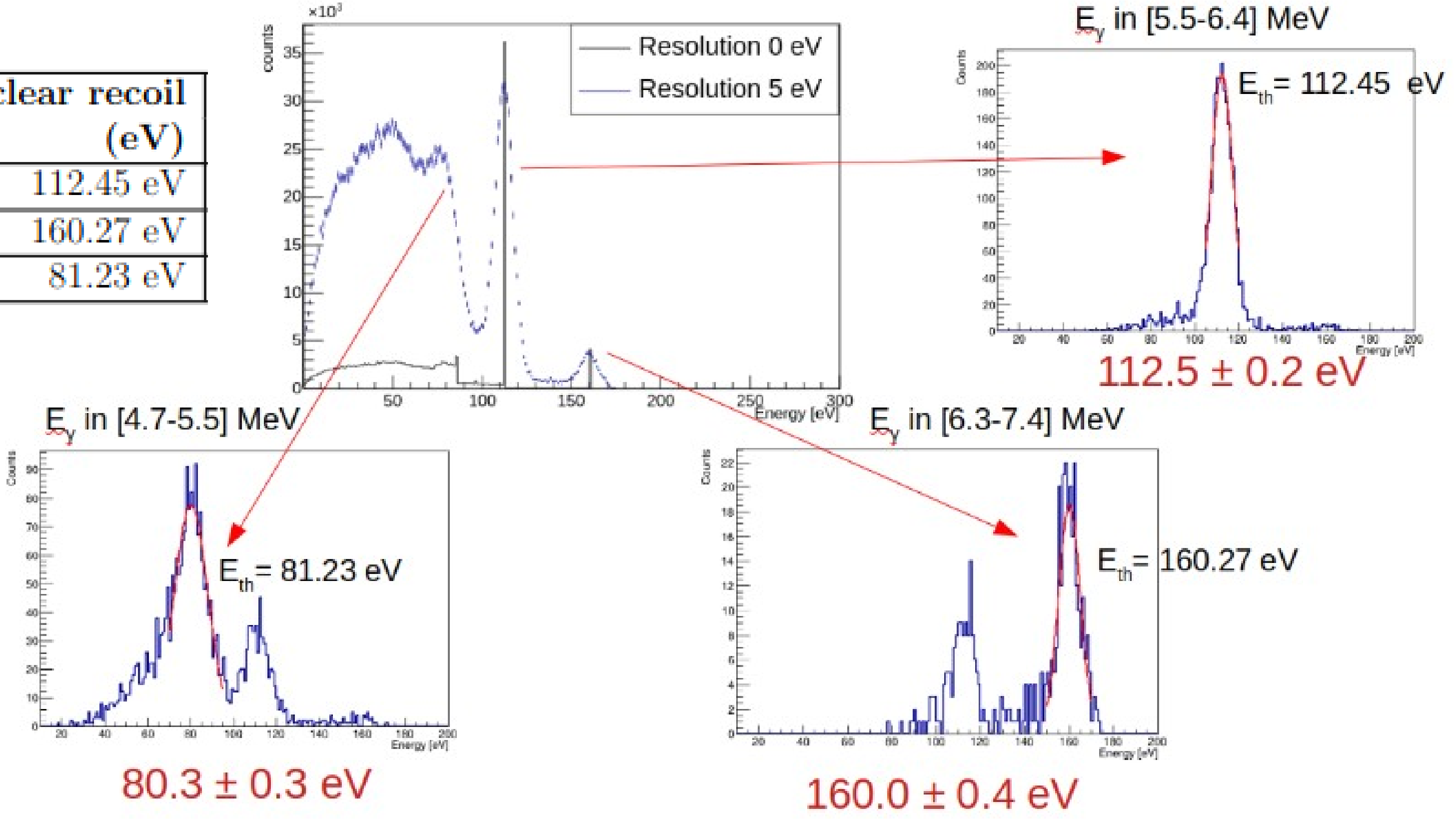
- CaWO4 : 81 eV peak can be detected with γ-tagging
- Crystal signal in coincidence with emitted γ allows to reduce multi-γ background



@ Andreas Erhart

Simulation GEANT4 : Reconstruction of CaWO4 peaks

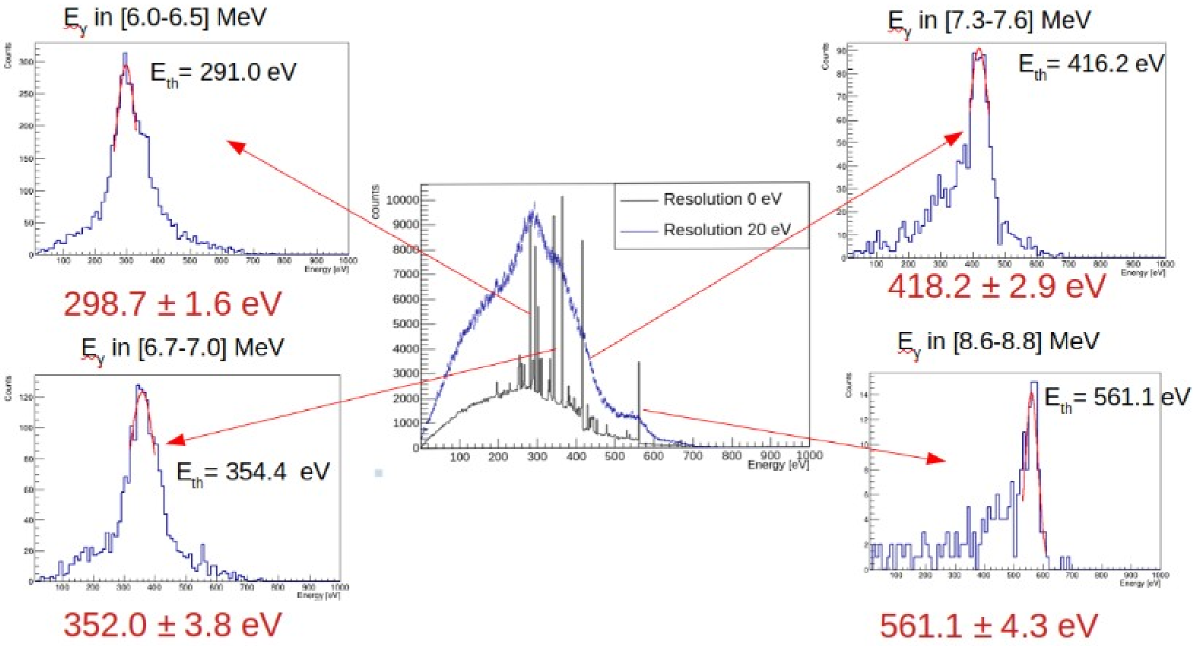
Target isotope	Emitted γ's (MeV)	Nuclear recoil (eV)
^{182}W	6.2	112.45 eV
^{183}W	7.4	160.27 eV
^{186}W	5.3 + 0.15	81.23 eV



Reconstruction of Ge peaks

- PRD : Study of collision and γ-cascade times following neutron-capture processes in cryogenic detectors

  (Phys. Rev. D 108, 072009)



Isotope Isotope	Primary E_γ (MeV)	Recoils (eV)	Mean recoil (eV)	Fit (eV)	Selection cut (MeV)
^{74}Ge	6.252	280.2			
^{70}Ge	6.117	295.7			
^{74}Ge	6.506	303.2	291.0	298.7 ±1.6	[6.0,6.5]
^{70}Ge	6.707	344.0			
^{70}Ge	6.916	363.5	354.4	352.0 ±3.8	[6.7,7.0]
^{70}Ge	7.416	416.2	416.2	418.2 ±2.9	[7.3,7.6]
^{73}Ge	8.732	561.2	561.2	561.1 ±4.3	[8.6,8.8]

Conclusion

- CRAB is an unique method to calibrate NR ~100 eV scale , already validated for CaWO4
- Open windows to study nuclear and solid state physics
- Phase II expected to start at end of 2024 at atominstitute in Vienna
  - High statistic and gamma tagging
- Gamma tagging will be very helpful to release constraint on detector resolution

Backup : target

Target nucleus (A)			Compound nucleus (A+1)			
Isotope	Y_{ab} [24] (%)	$\sigma_{n,\gamma}$ [25] (barn)	S_n [26] (keV)	I_γ^s [26, 27] (%)	Recoil (eV)	FoM (a.u.)
^{182}W	26.50	20.32	6191	13.94	112.5	7506
^{183}W	14.31	9.87	7411	5.83	160.3	823
^{184}W	30.64	1.63	5754	1.48	96.1	74
^{186}W	28.43	37.89	5467	0.26	85.8	280
^{70}Ge	20.53	3.05	7416	1.95	416.2	122
^{72}Ge	27.45	0.89	6783	0.0	338.7	0
^{73}Ge	7.76	14.70	10196	0.0	754.9	0
^{74}Ge	36.52	0.52	6506	2.83	303.2	54
^{76}Ge	7.74	0.15	6073	0.0	257.3	0

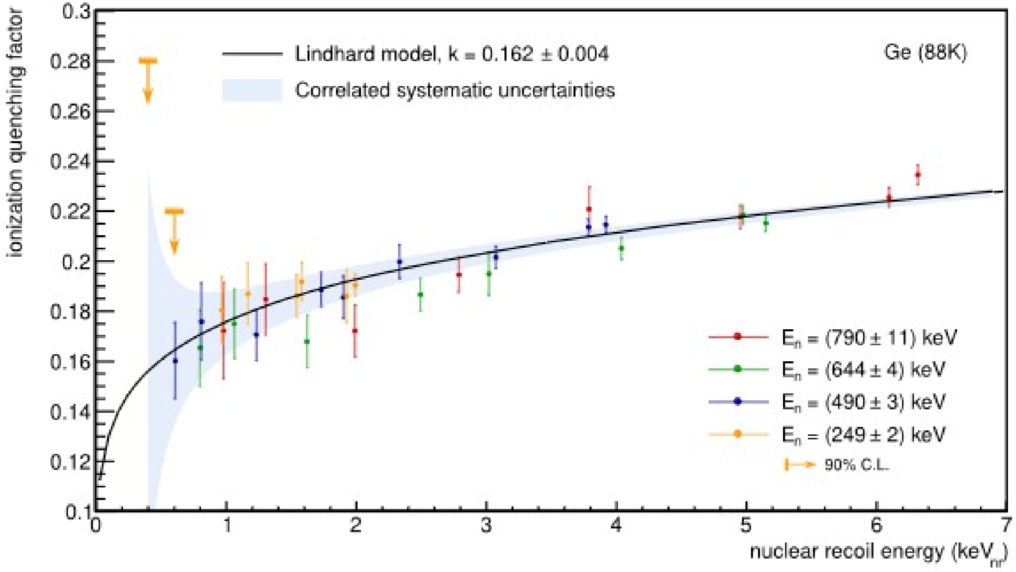
Backup : quenching for Ge

- Quenching factor is the ratio of ionization energy produced by NR/ER
- Lindhard model valid for keV region :

$$E_{ee} = q(E_{nr}) \cdot E_{nr} = \frac{k\,g(\varepsilon)}{1 + k\,g(\varepsilon)} \cdot E_{nr}$$

$\varepsilon = 11.5\ Z^{-7/3}\ E_{nr}$

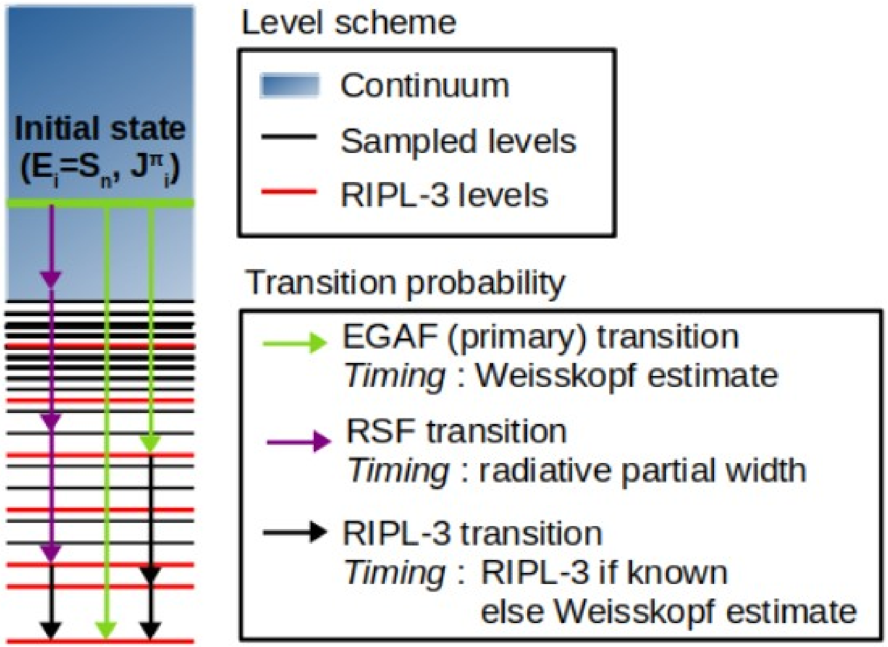
$g(\varepsilon) = 3\ \varepsilon^{0.15} + 0.7\ \varepsilon^{0.6} + \varepsilon$



A.Bonhomme et al. Eur.Phys.J.C 82 (2022) 9, 815

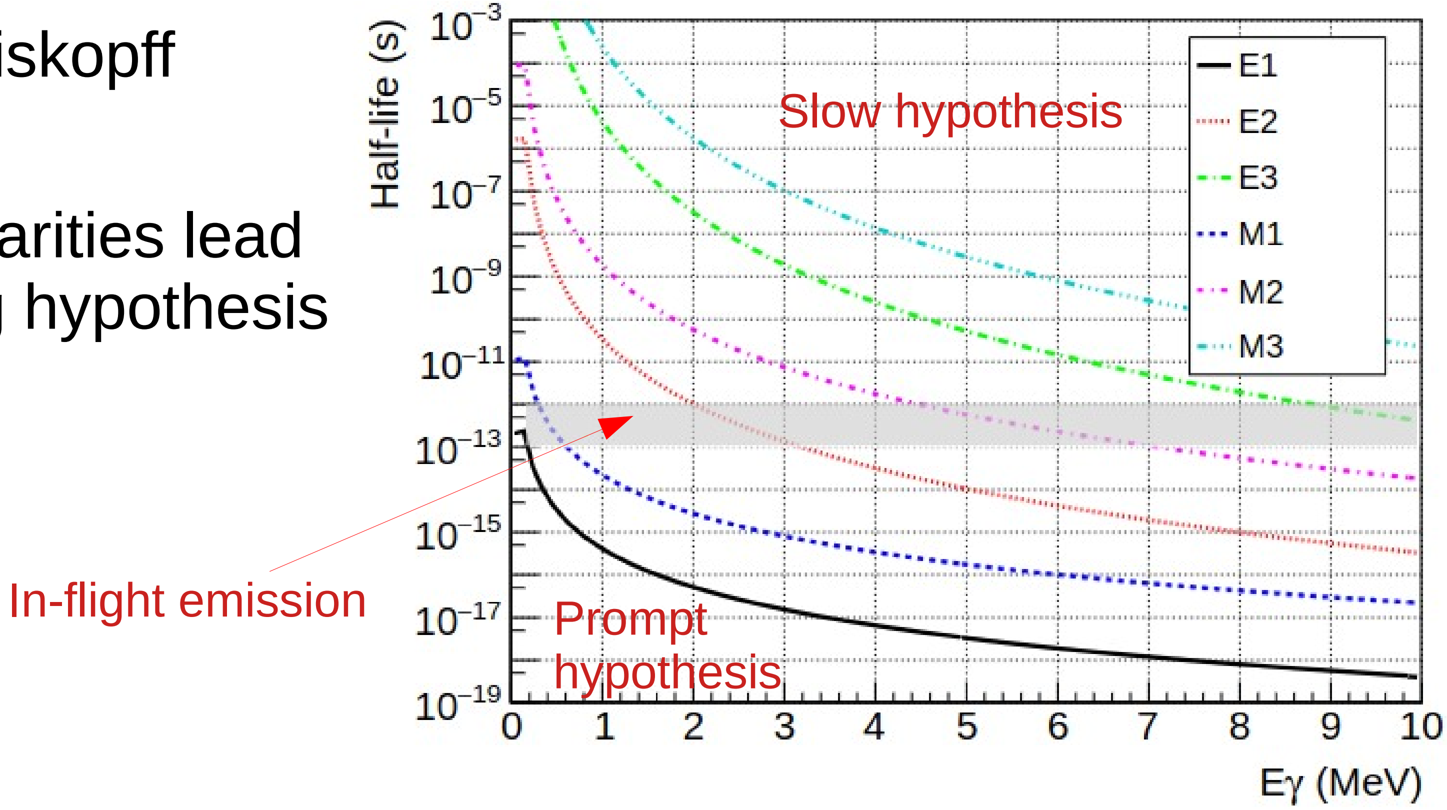
Backup : FIFRELIN

- 3 steps :
  - Compute the initial coumpound state
  - Build nuclear level scheme
  - Generate cascades with Monte Carlo process from Sn towards ground state
- FIFRELIN builds the level scheme with nuclear data and complete with theoretical level density models



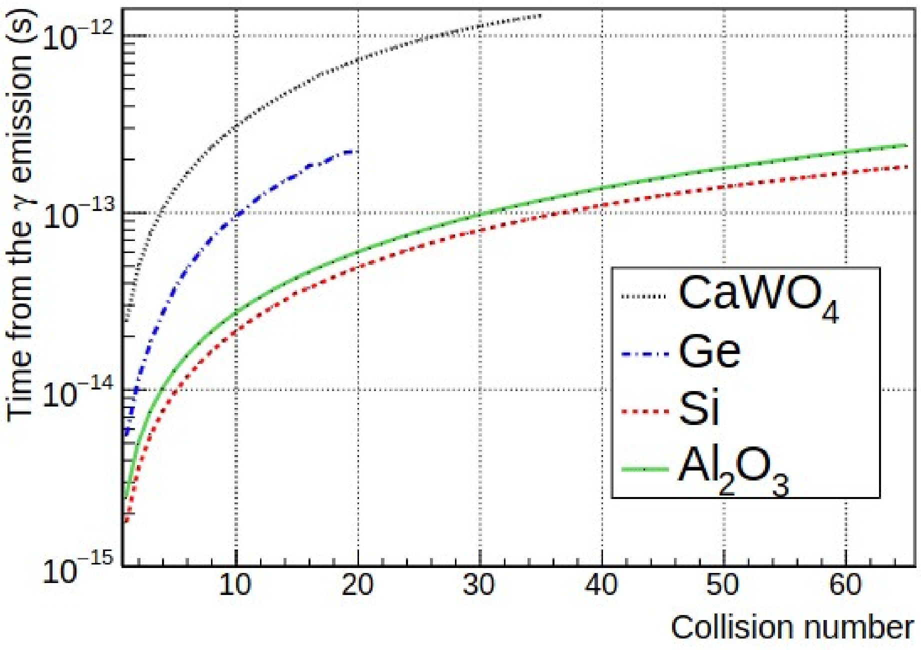
Backup : Nuclear level half-lives

- Half-life from Weiskopff formula
- Different multipolarities lead to different timing hypothesis



Backup : IRADINA

- Binary Collision Approximation
  - Serie of two-body collisions
- IRADINA compute the time of the NR



C. Borschel and C. Ronning. Ion beam irradiation752 of nanostructures

Backup : Constrain nuclear model

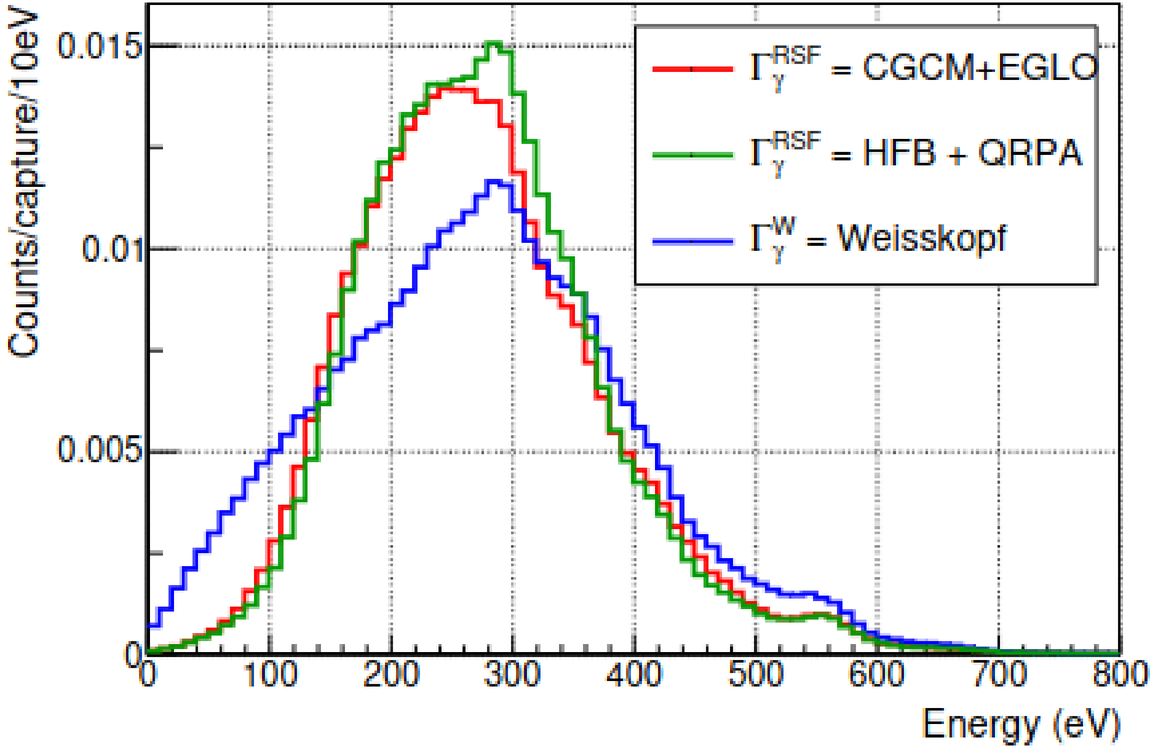


Fig : Germanium spectra for differents nuclear models

Backup : Germanium peaks

Detector Crystal	Size (mm^3)	Target Isotope	F.O.M.	E_γ (keV)	Half-life (ps)	Nuclear Recoil (eV)
Al_2O_3	$5 \times 5 \times 5$	^{27}Al	79	7693	-	
				$\hookrightarrow$ 30.6	2070 ± 50	1135.7
			616	7724	-	1144.8
Si	$20 \times 20 \times 20$	^{28}Si	116	7200	-	
				$\hookrightarrow$ 1273	0.29 ± 0.01	990.4
		^{28}Si	36	8474	-	1330.1
Ge	$20 \times 20 \times 20$	^{74}Ge	220	6253	-	
				$\hookrightarrow$ 253	1.36 (W)	280.6
		^{70}Ge	261	6117	-	
				$\hookrightarrow$ 1299	0.42 ± 0.09	296.0
		^{74}Ge	54	6506	-	303.2
		^{70}Ge	287	6708	-	
				$\hookrightarrow$ 708	<10.70	344.3
		^{70}Ge	238	6916	-	
				$\hookrightarrow$ 500	0.18 (W)	363.9
		^{70}Ge	122	7416	-	416.2
		^{73}Ge	117	8733	-	
				$\hookrightarrow$ 868	1.53 ± 0.10	
				$\hookrightarrow$ 596	12.41 ± 0.09	561.8
$CaWO_4$	$5 \times 5 \times 5$	^{186}W	2260	5262	-	
				$\hookrightarrow$ 205	2.6 (W)	79.6
		^{186}W	2159	5321	-	
				$\hookrightarrow$ 146	7.1 (W)	81.4
		^{182}W	7506	6191	-	112.5
		^{183}W	823	7411	-	160.3