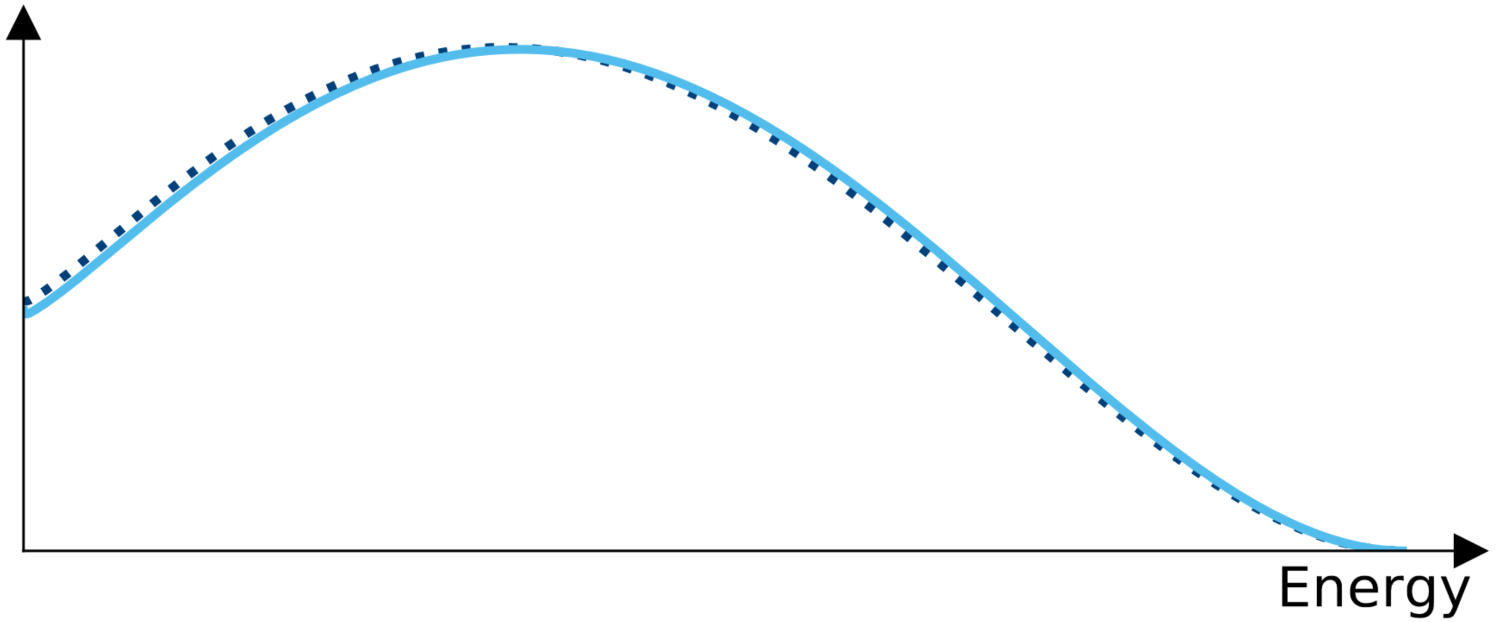
BETA SPECTRUM SHAPE MEASUREMENTS@WISARD

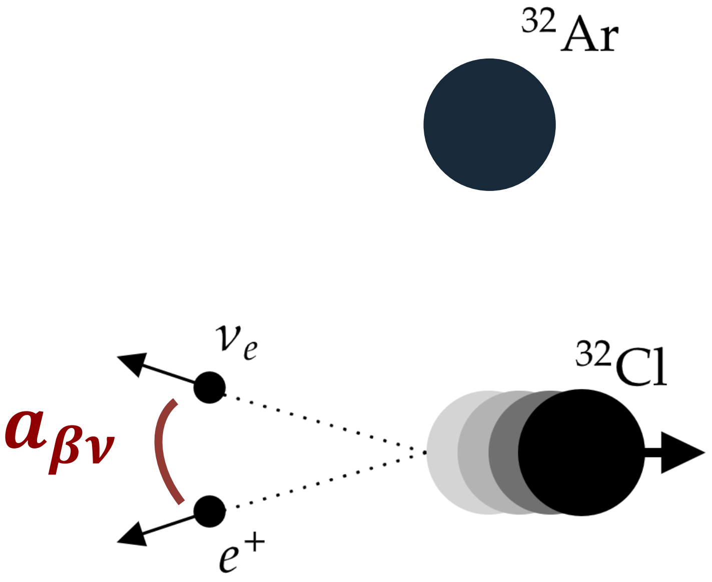
InESS@WISArD

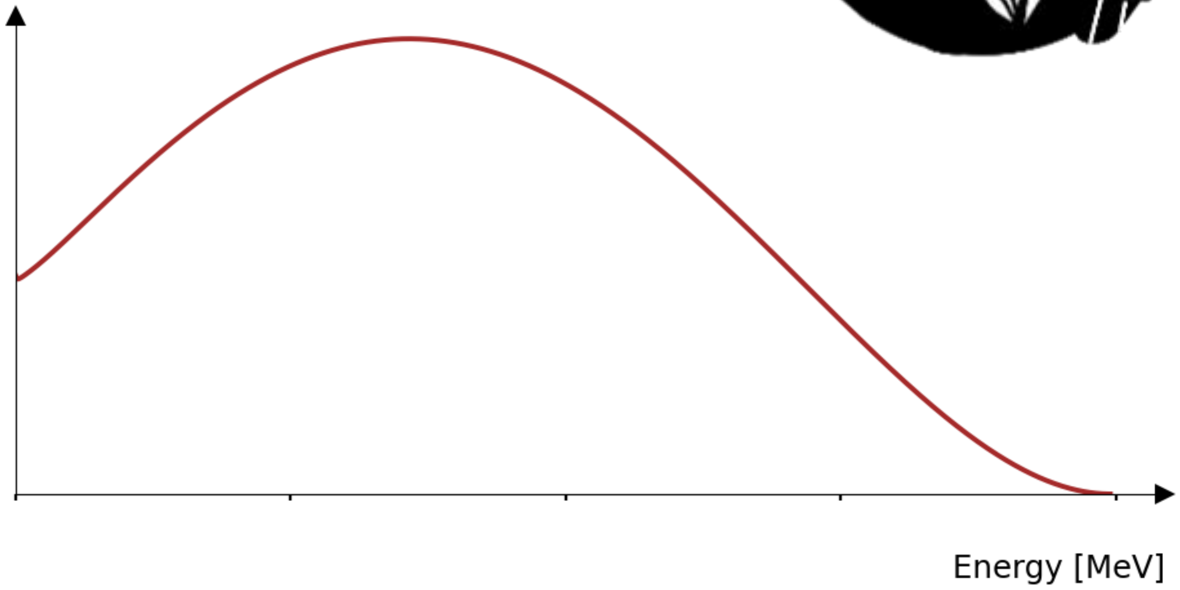


ISOL FRANCE
SIMON VANLANGENDONCK
28 MAY 2024

KU LEUVEN

BETA DECAY PRECISION EXPERIMENTS





?

High-precision experiments ⟷ Theoretical calculations

WHY SPECTRUM SHAPES?

Beyond Standard Model physics

- Fierz interference term
  Cirgiliano, V., et al. ArXiv:1907.02164.

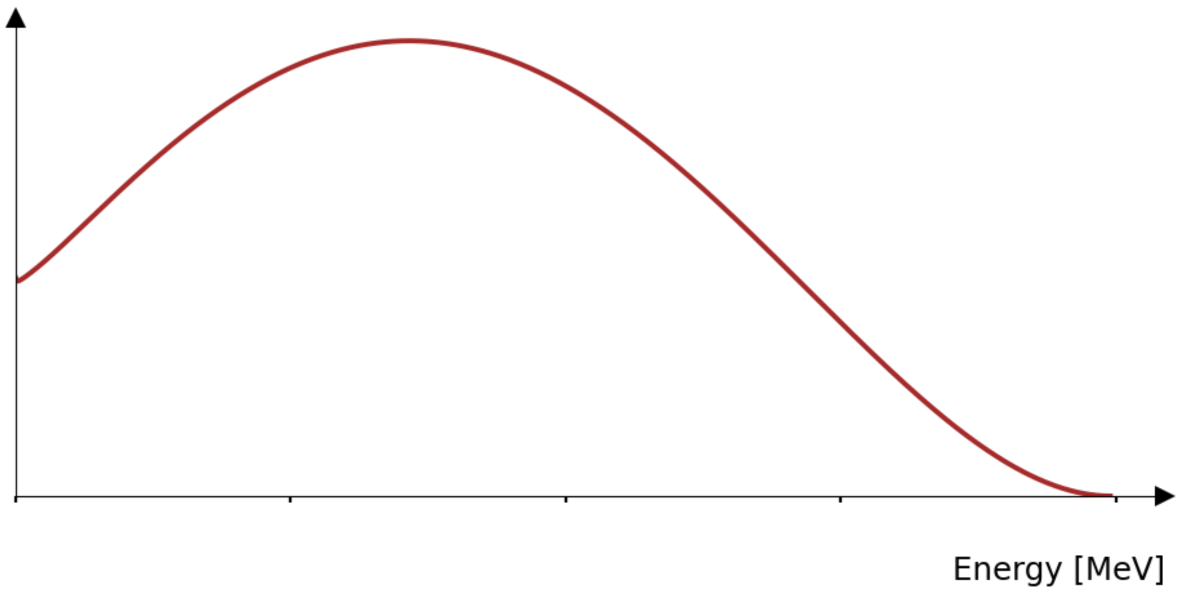
Reactor neutrino anomaly

- Calculations assume $\frac{b}{Ac} = 5$
  Wang X. B. et al. PRC 95 (2017)

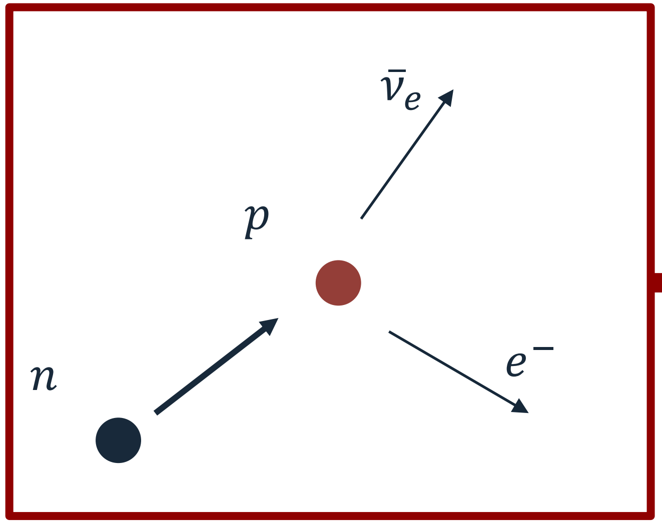
Nuclear theory

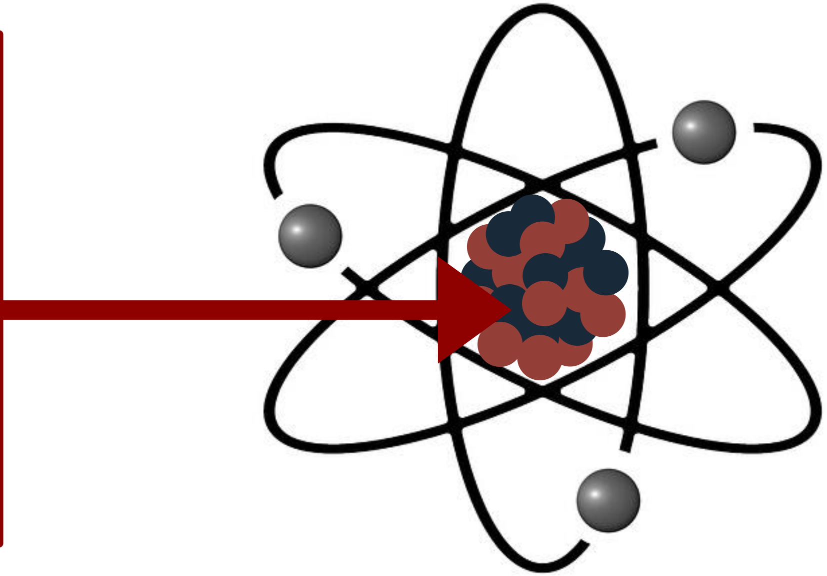
- Effective value of g_A
  Haaranen M. et al. PRC 93 (2016)

Metrology, neutrino physics, etc.



THEORETICAL DESCRIPTION

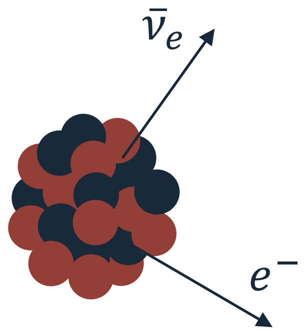




- ✓ Kinematics
- ✓ Electrostatics
- ✓ Radiative corrections (QED)
- ✓ Atomic and molecular effects
- ✓ **Nuclear effects: recoil-order corrections**
- ✓ Beyond Standard Model physics?

High precision analytical description of the allowed β spectrum shape L. Hayen *et al*., Reviews of Modern Physics 90(1), 15008 (2018).

NUCLEAR EFFECTS

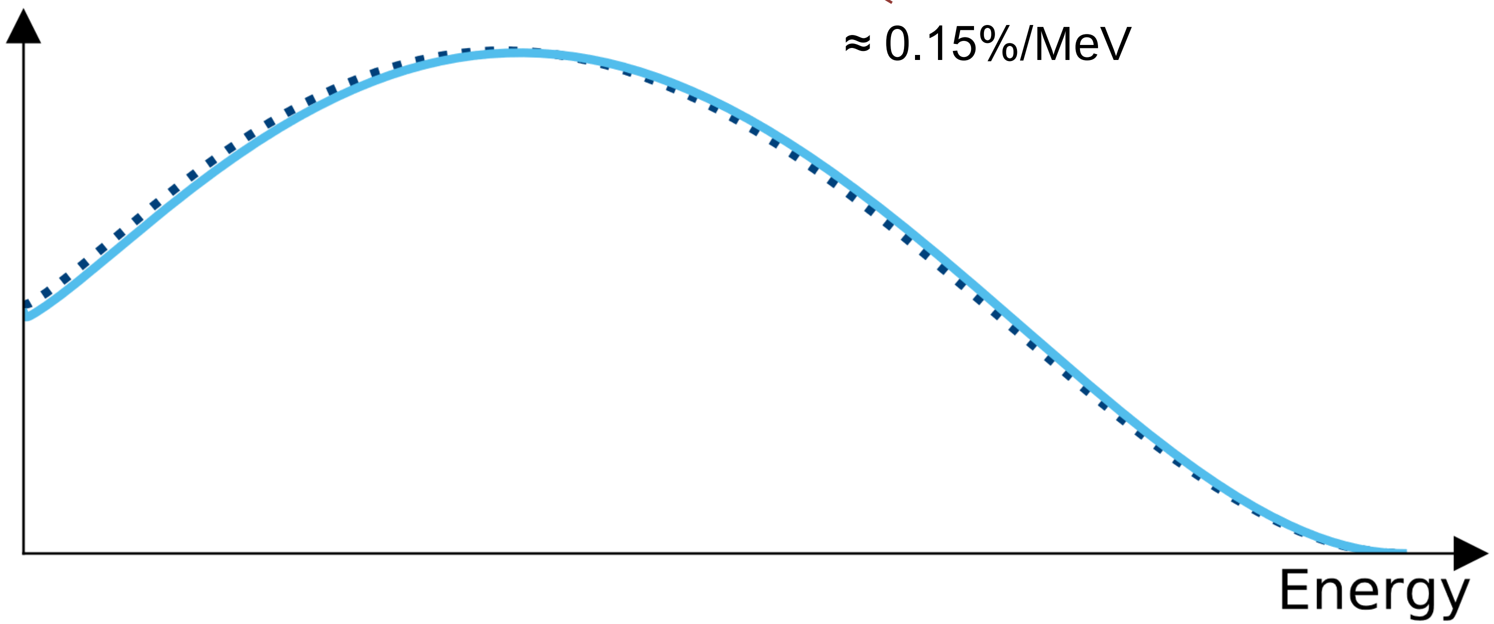


Look for the influence of nuclear effects on the decay

- Weak-Magnetism (b_{WM})

$$N(E) \propto N(E)\left(1 + \frac{4}{3M_N}\frac{b_{WM}}{Ac}E\right)$$

≈ 0.15%/MeV



High precision analytical description of the allowed β spectrum shape L. Hayen *et al.*, Reviews of Modern Physics 90(1), 15008 (2018).

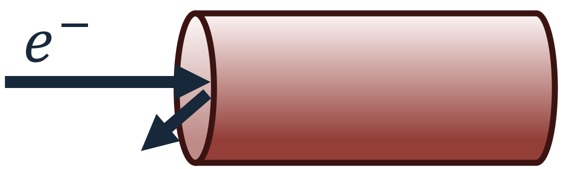
PRECISION SPECTRUM MEASUREMENT

Goal:

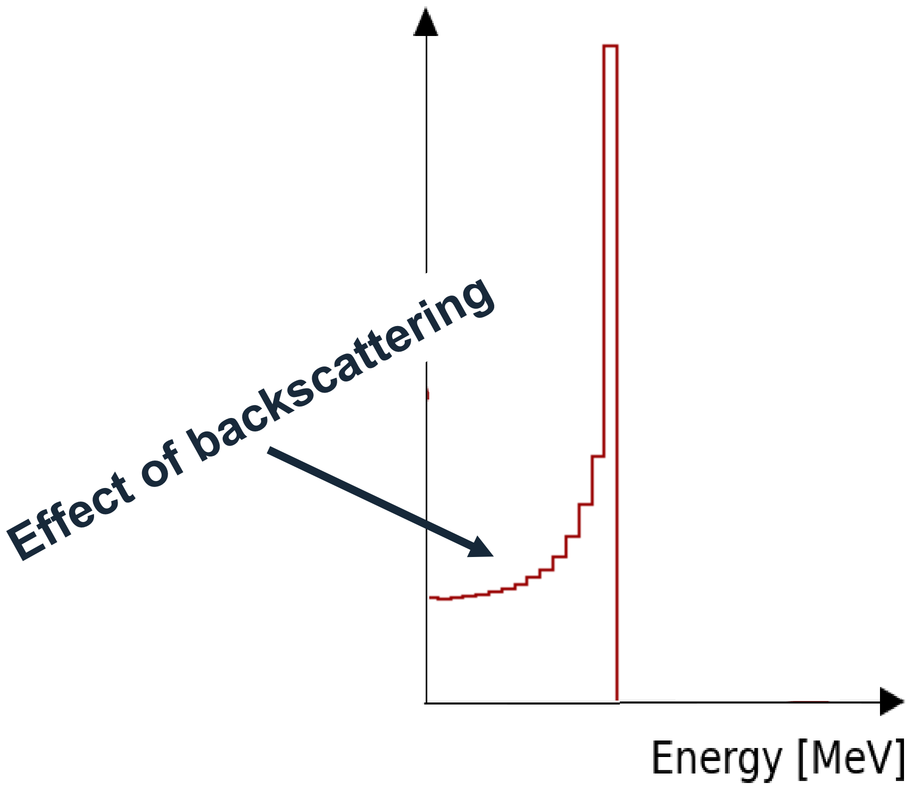
Measure as precise as possible the energy distribution of the electron emerging from beta decay

Intrinsic problem:

Backscattering:



Partial energy deposition…



PRECISION SPECTRUM MEASUREMENT

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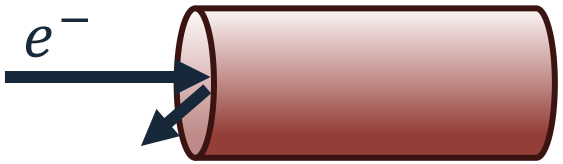


Partial energy deposition…

Possible solutions?

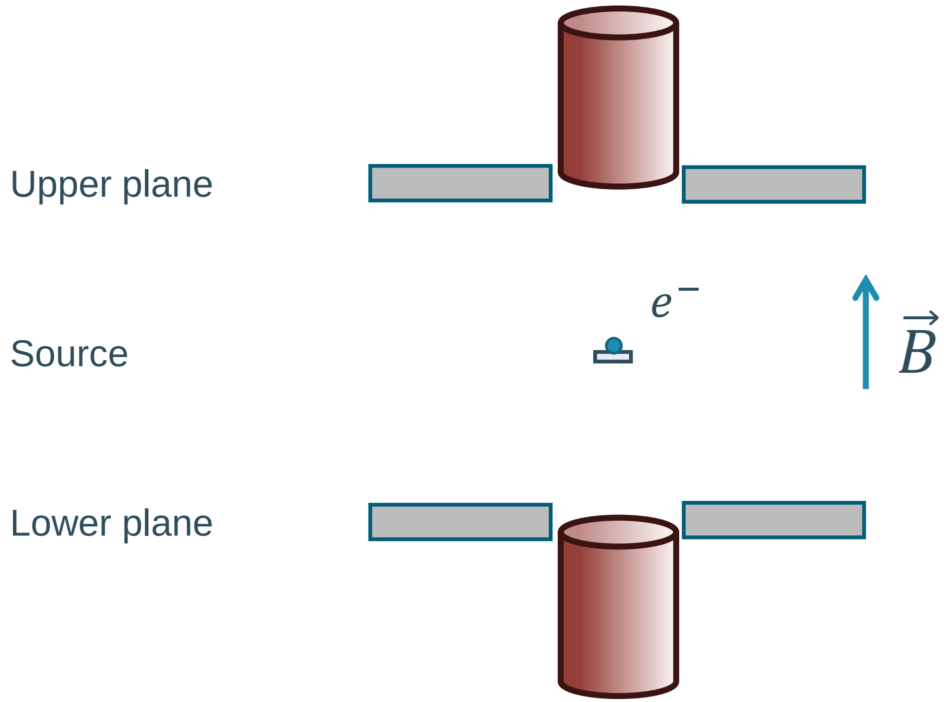
Count at a given energy (spectrometers)

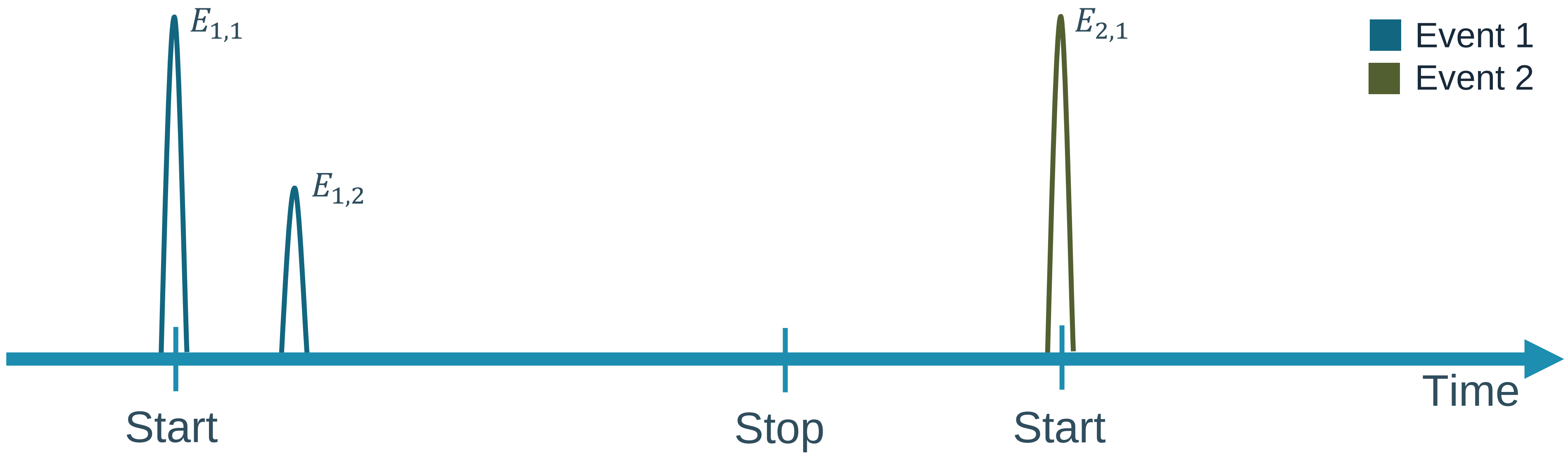
Encapsulate the electrons (bSTILDED)

Use a magnetic field (WISArD)

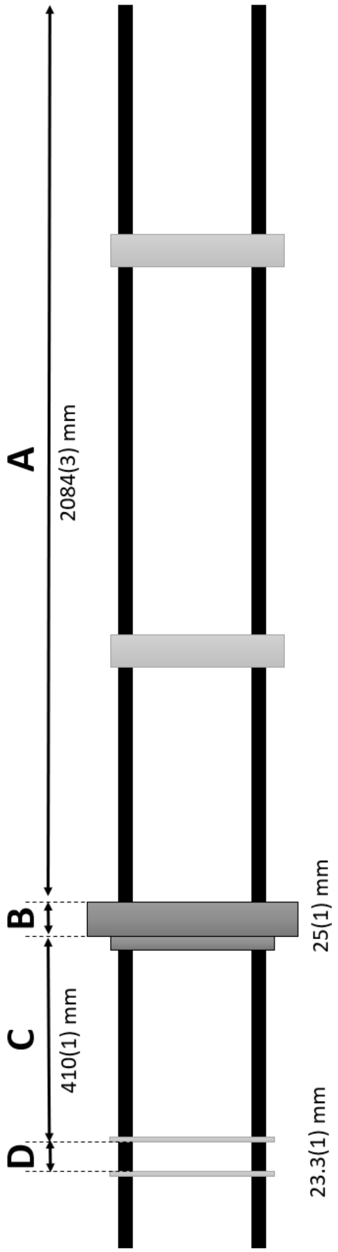
…

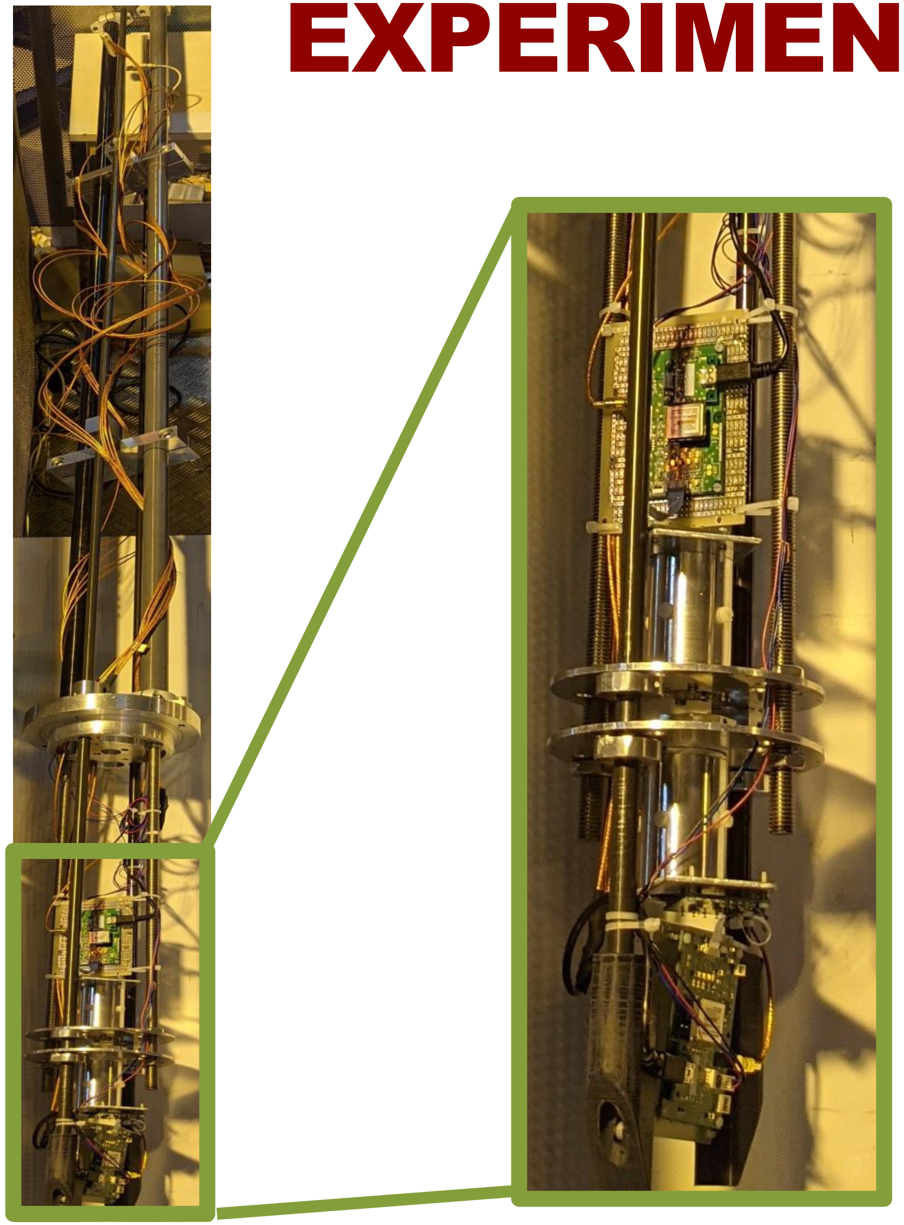
INTEGRATION TIME

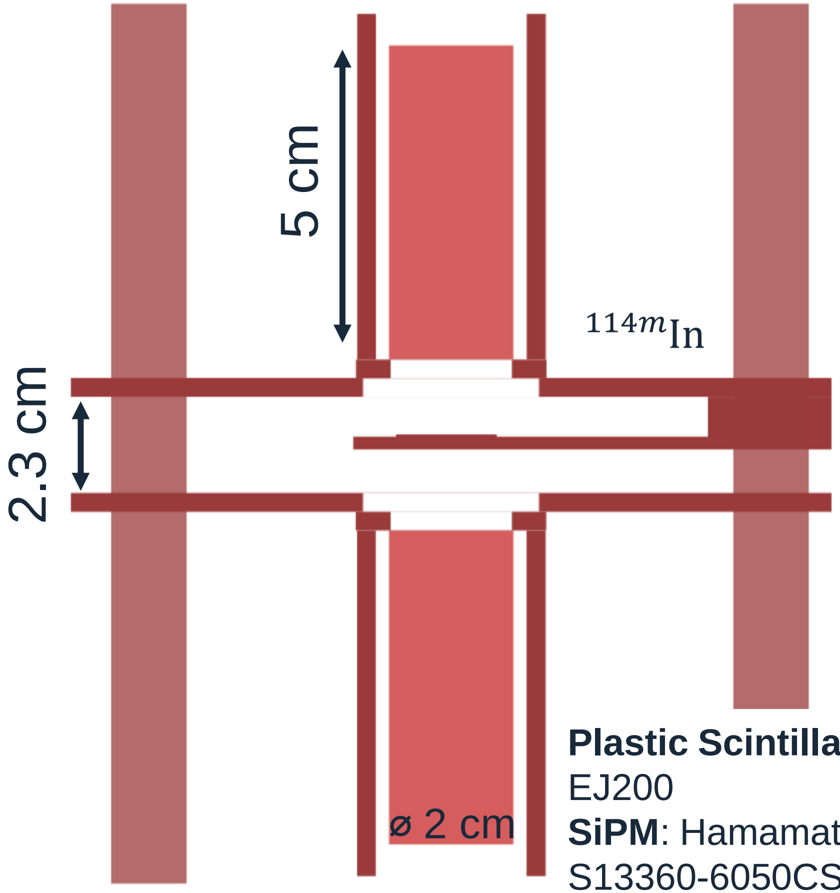




EXPERIMENTAL SET-UP



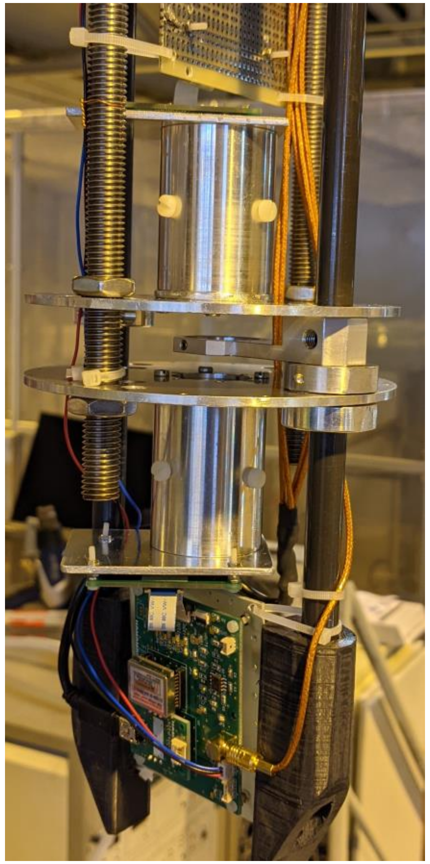


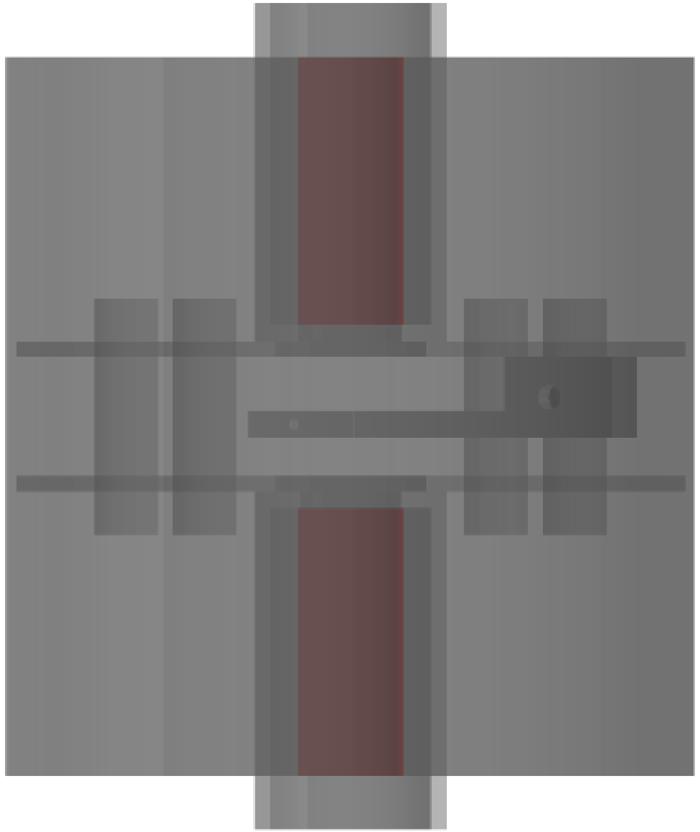


Plastic Scintillator: EJ200
SiPM: Hamamatsu S13360-6050CS

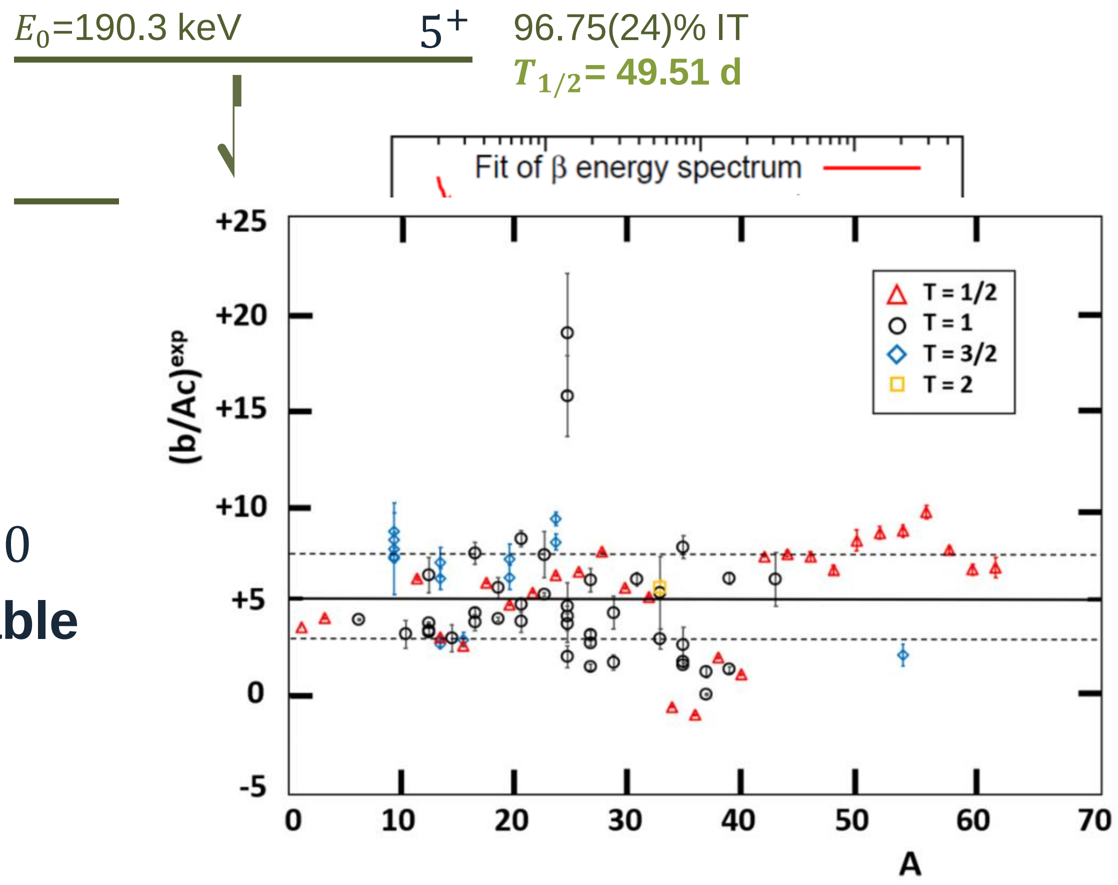
SIMULATIONS

Make a digital twin of the set-up





WHICH ISOTOPE?



Measure the beta-spectrum shape of $^{114}\mathrm{In}$

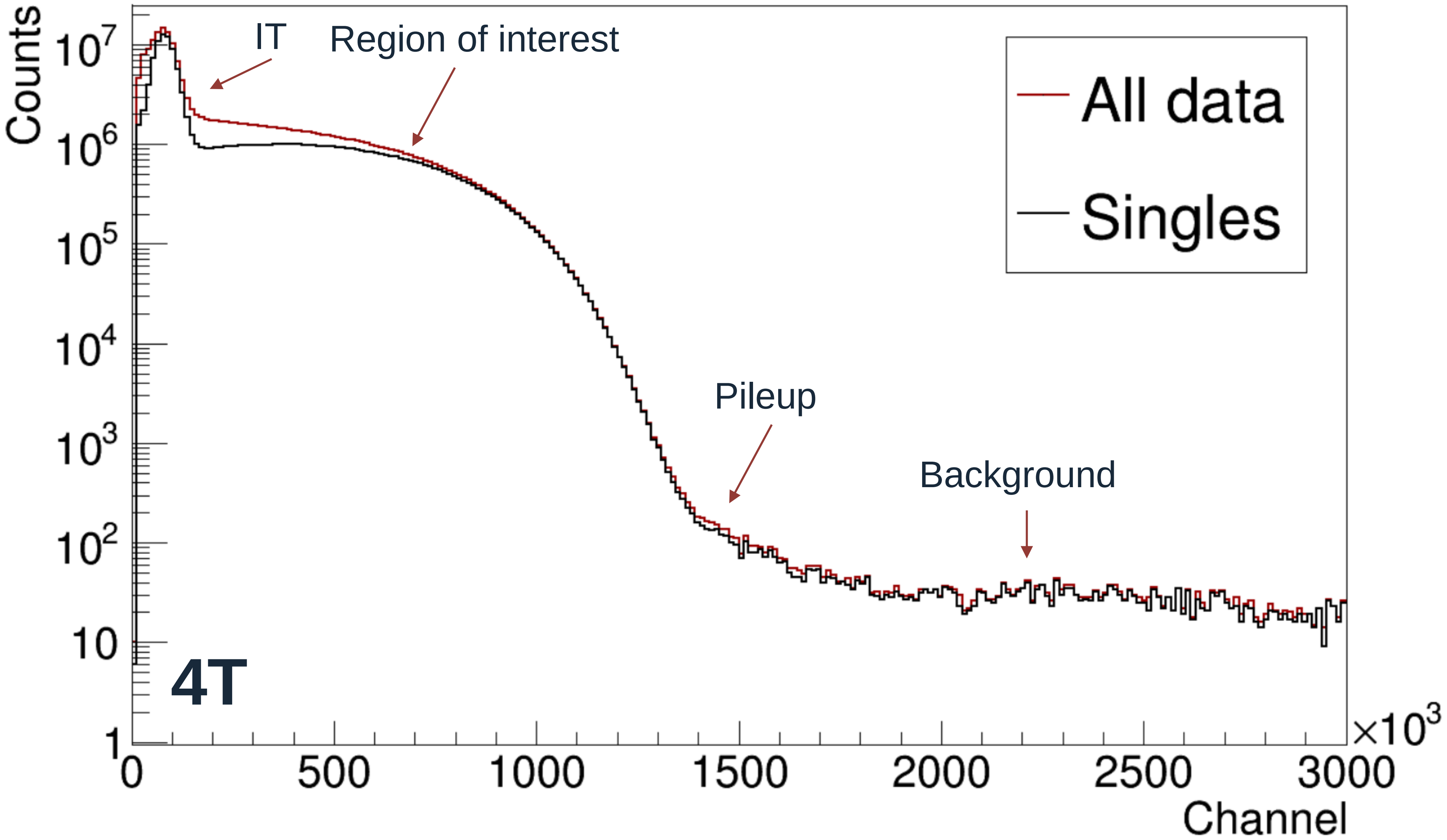
- Pure Gamow-Teller decay
- Favorable endpoint for BSM
- Weak-Magnetism (b_{WM}) not known for $A > 70$

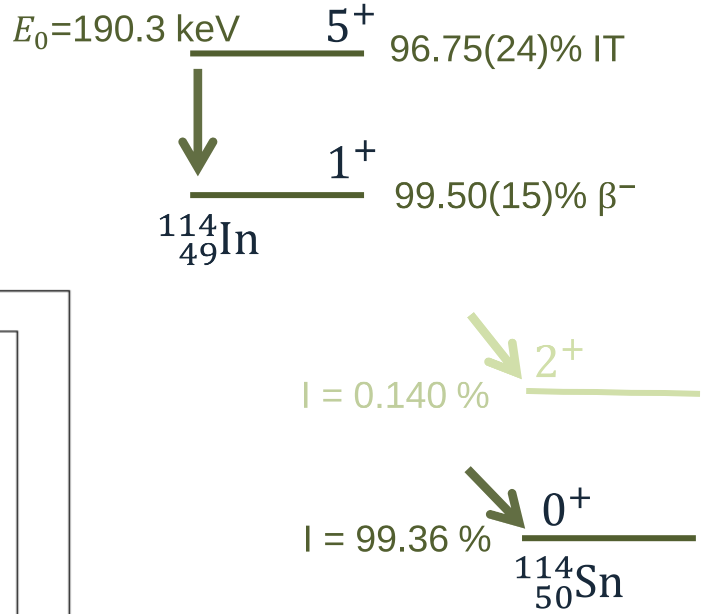
Long half-life of isomer and commercially available

- Off-line measurements
- High radionuclidic purity
- Use IT for energy calibration

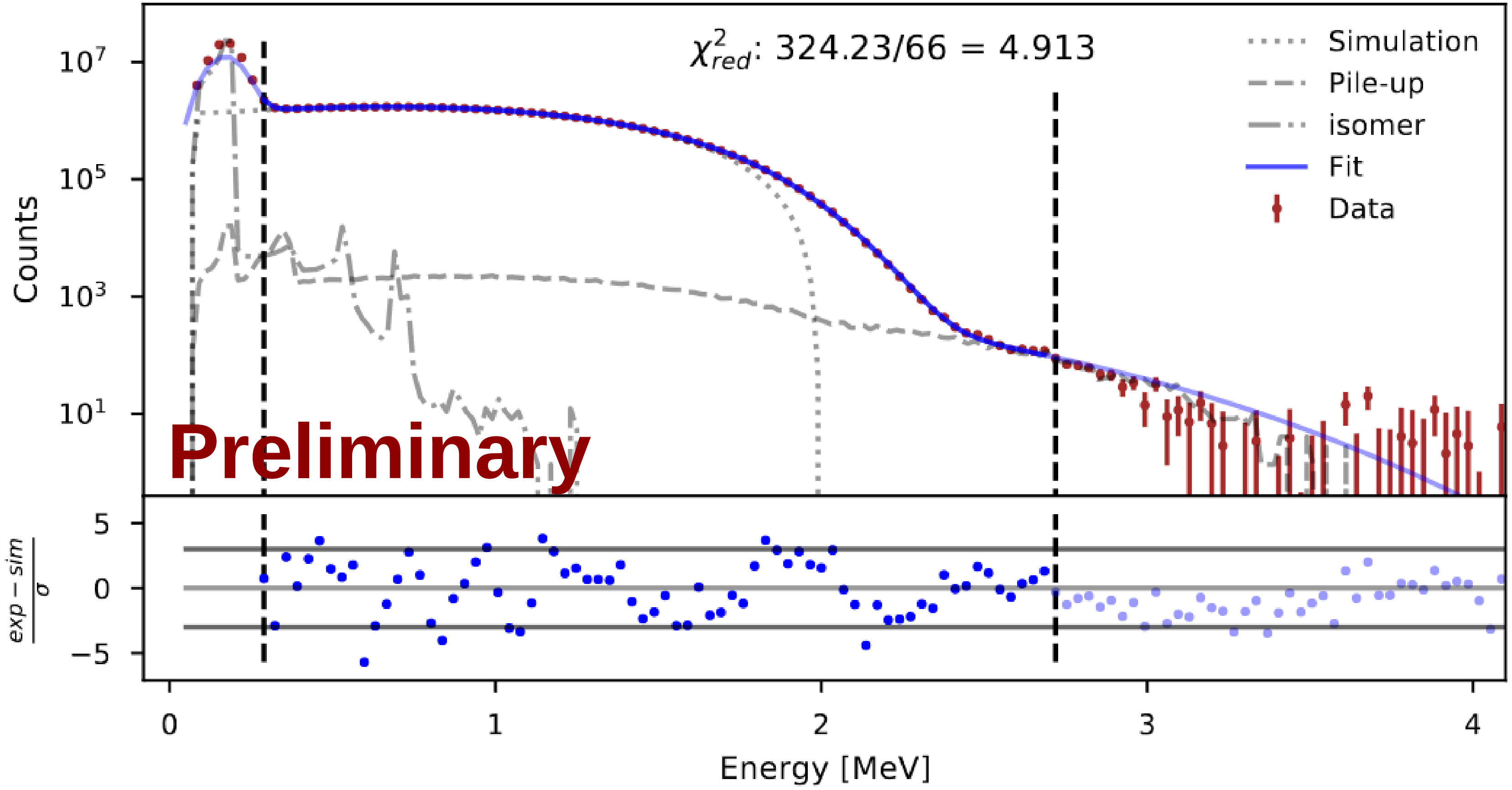
Ft values of mirror *β transitions and weak magnetism induced current in allowed nuclear β decay* N. Severijns *et al*., Physical Review C 107, 015502 (2023)
The AME 2020 atomic mass evaluation (II). Tables, graphs and references. M. Wang *et al.* Chinese Physics C 45, 3 (2021), 030003.
Brookhaven National Nuclear Data Center. https://www.nndc.bnl.gov/nudat3/.

EXPERIMENTAL RESULTS





DATA ANALYSIS: ONGOING



S. Vanlangendonck, *The effect of weak magnetism on the shape of the ^{114}In beta energy,* PhD thesis, KU Leuven (2023).

SYSTEMATIC UNCERTAINTIES ON WM

	Effect	Uncertainty	Δb_{WM}
Theory	Endpoint energy	0.3 keV	0.1
	ρ, R and d/Ac		None
Geant4	Detector threshold	3.75 keV	1.2
	Source position		
	Rotation	1°	0.1
	Source diameter	1 mm	0.3
	QDC time window	50 ns	None
	Foil thickness	±10%	None
Energy resolution	σ_1	σ_{fit}	< 0.1
	σ_2	σ_{fit}	< 0.1
SiPM non-linearity	E/pixel	0.16 keV	1.1
	$P_{crosstalk}$	Unknown	
(Auto-)calibration	a_0	σ_{fit}	< 0.1
	a_1	σ_{fit}	0.3
Total			1.7

PRELIMINARY

Detector characterization = limiting factor

➔ To be improved (SiLi)

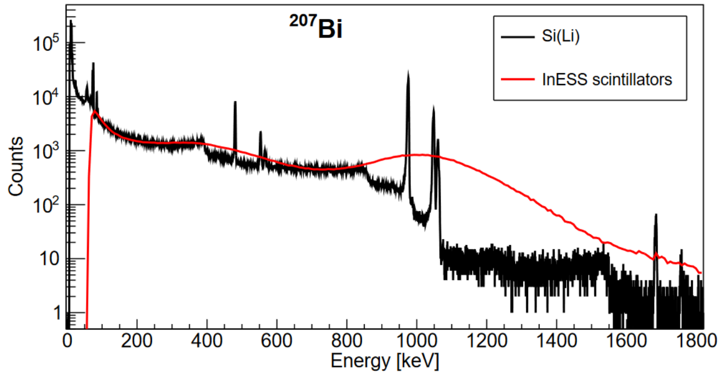


Figure by C. Knapen

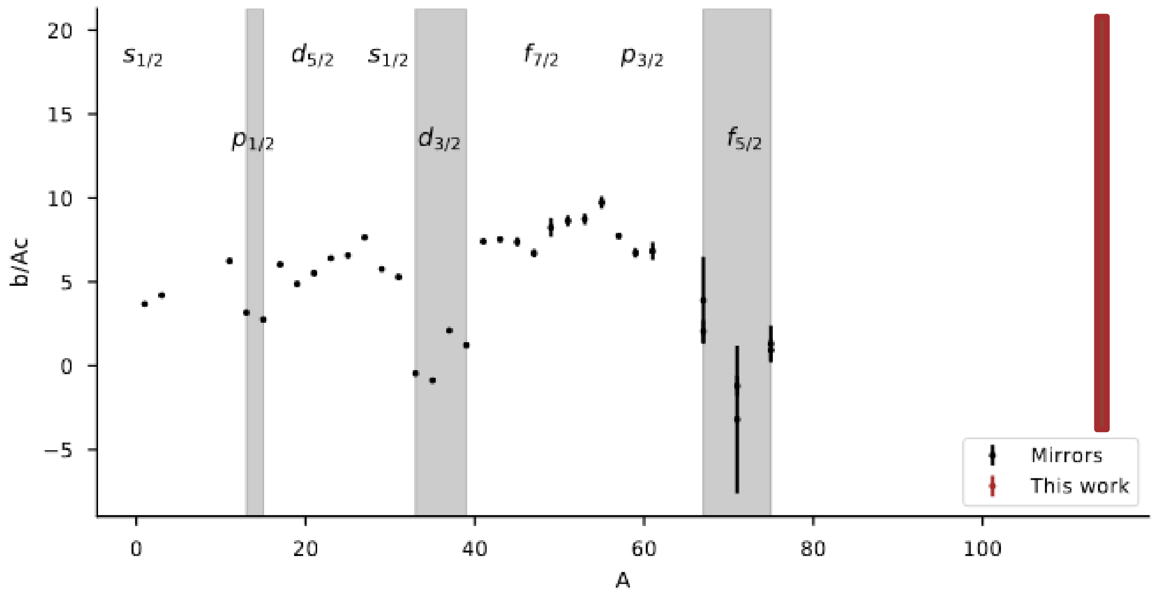
S. Vanlangendonck, *The effect of weak magnetism on the shape of the* ^{114}*In beta energy,* PhD thesis, KU Leuven (2023).

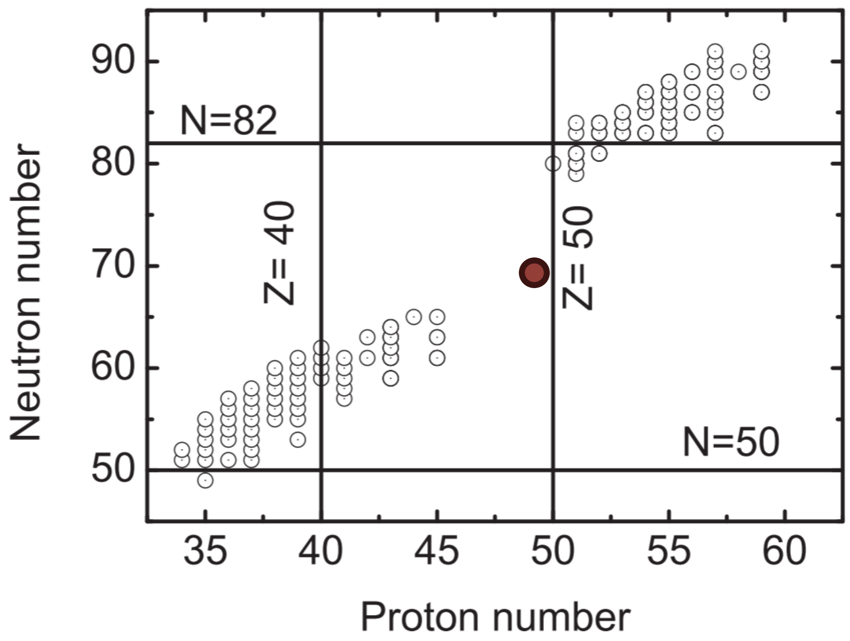
IMPORTANCE OF THIS RESULT?

This proof-of-principle experiment provided the first measurement of the beta energy spectrum shape with WISArD.

^{114}In is the first isotope in this mass range with the weak magnetism form factor determined:

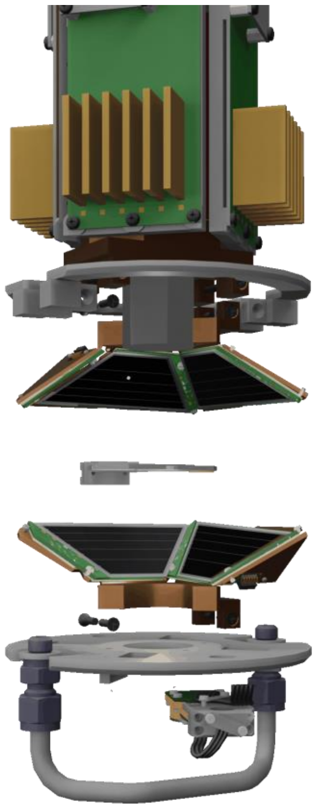
➔ see also miniBETA (*ArXiv:2404.0314*)

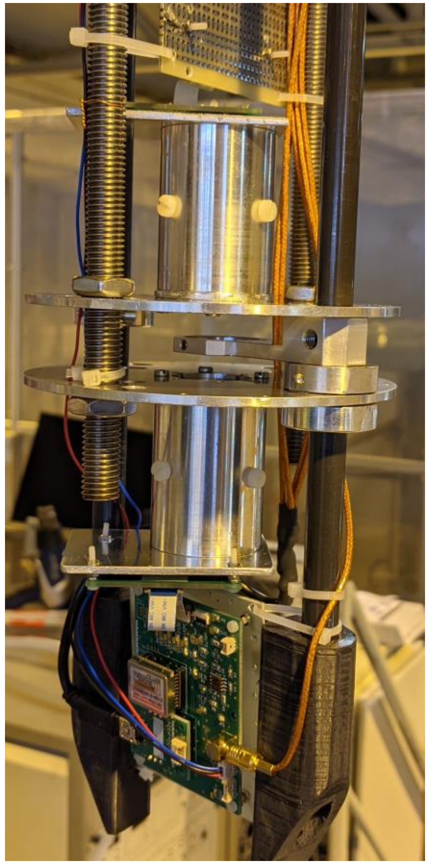


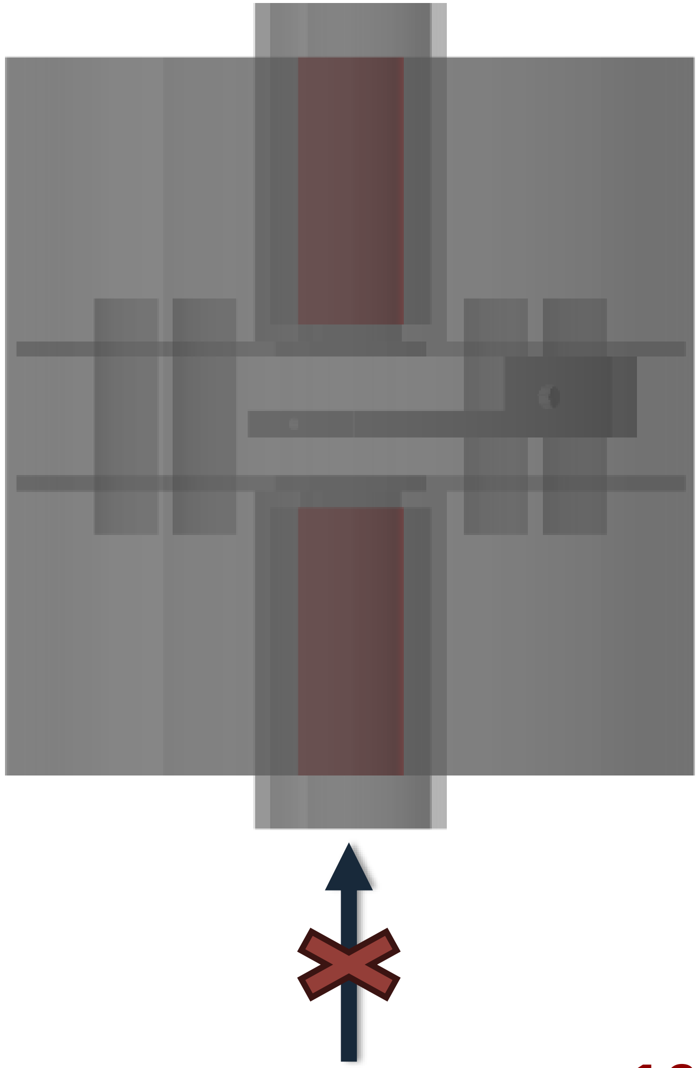


Ft values of mirror *β transitions and weak magnetism induced current in allowed nuclear β decay* N. Severijns *et al*., Physical Review C 107, 015502 (2023)
Weak magnetism correction to allowed β decay for reactor antineutrino spectra X. Wang and A. Hayes, Physical Review C 95, 064313 (2017)

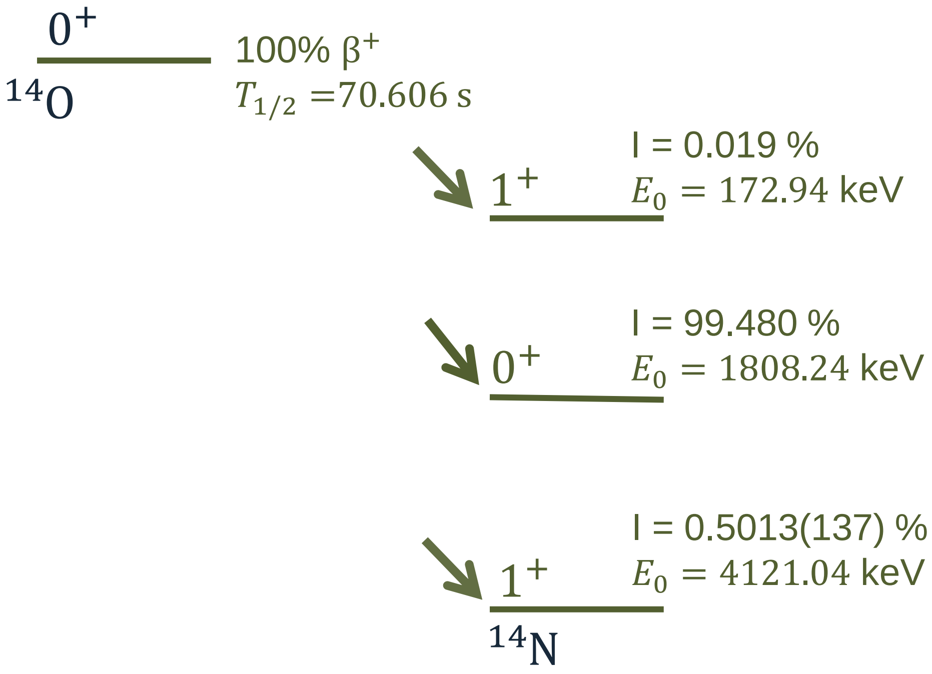
ISOL?

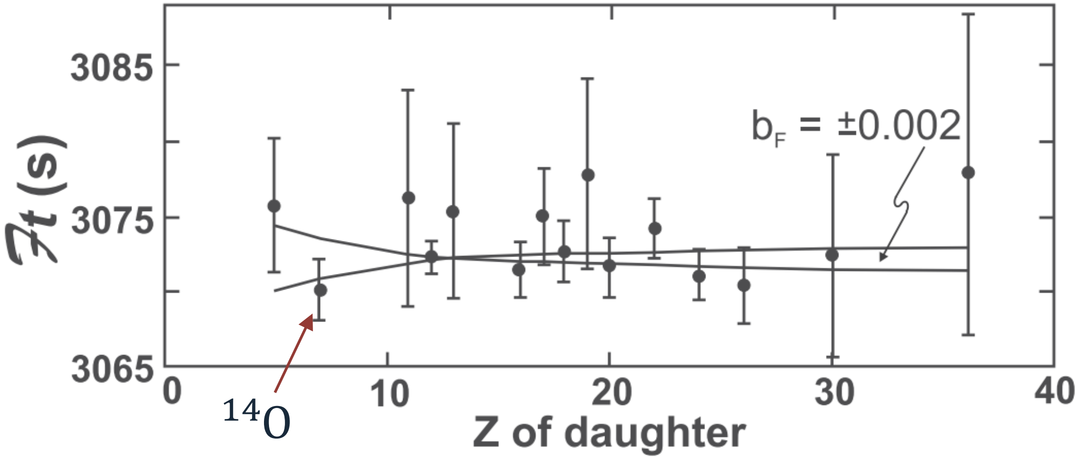






ISOL EXAMPLE: ^{14}O





Superallowed $0^+ \rightarrow 0^+$ nuclear β decays: 2020 critical survey, with implications for V_{ud} and CKM unitarity, J. Hardy and I. Towner, Physical Review C 102(4), 1-29 (2020)

CONCLUSION & OUTLOOK

This proof-of-principle experiment provided the first measurement of the beta energy spectrum shape with WISArD.

$^{114}\mathrm{In}$ is the first isotope where the weak magnetism form factor is determined in a previously uncharted mass range.

We are currently upgrading the detection set-up and plan to make ISOL experiments possible.

THANK YOU FOR YOUR ATTENTION!

And thanks to all collaborators for their support during this project:

ISOLDE

lpc caen
Laboratoire de physique corpusculaire

LP2i Bordeaux

KU LEUVEN

simon.vanlangendonck@kuleuven.be

Instituut voor Kern- en Stralingsfysica, KU Leuven

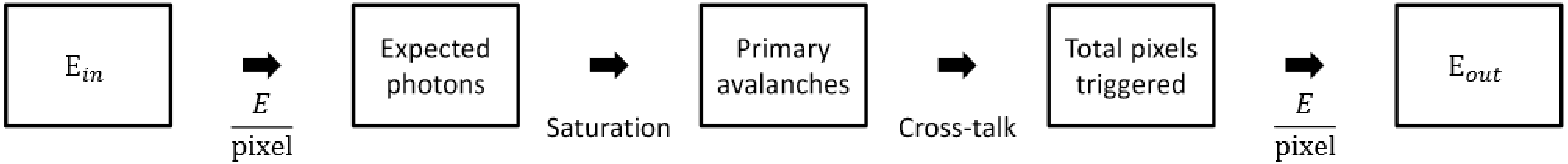
EXPERIMENTAL CAMPAIGN

November-December 2020

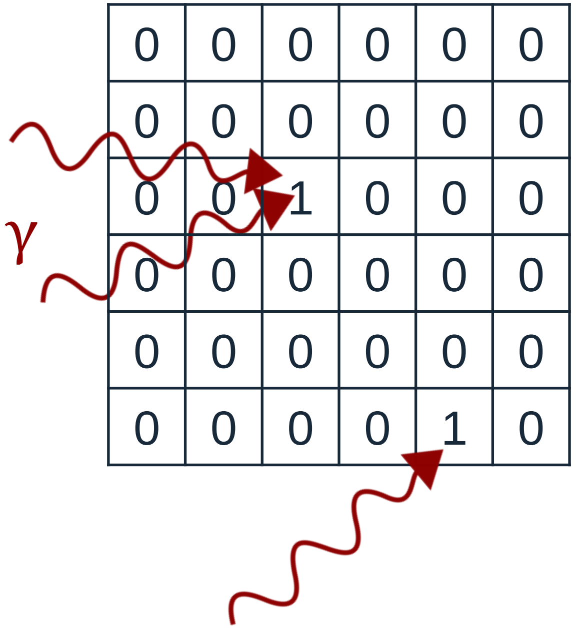
Set-up characterization + actual measurements

- $^{207}\mathrm{Bi}$
- $^{137}\mathrm{Cs}$
- $^{90}\mathrm{Sr}$
- $^{114}\mathrm{In}$ (1 kBq + 5 kBq)
- Background

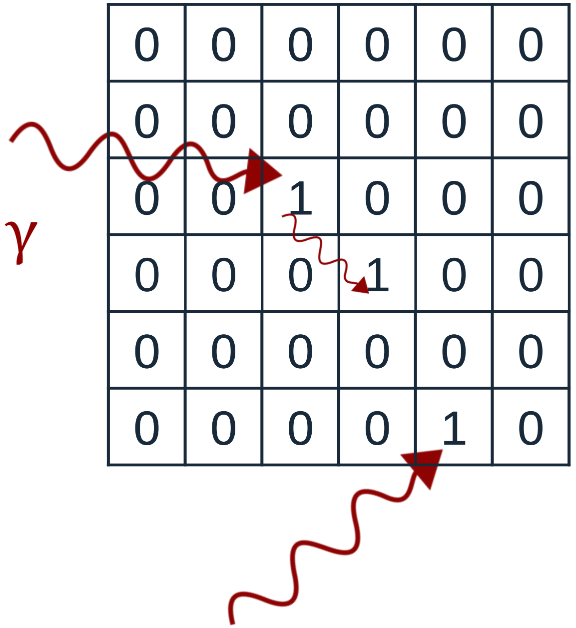
SIPM NON-LINEARITY



Saturation:

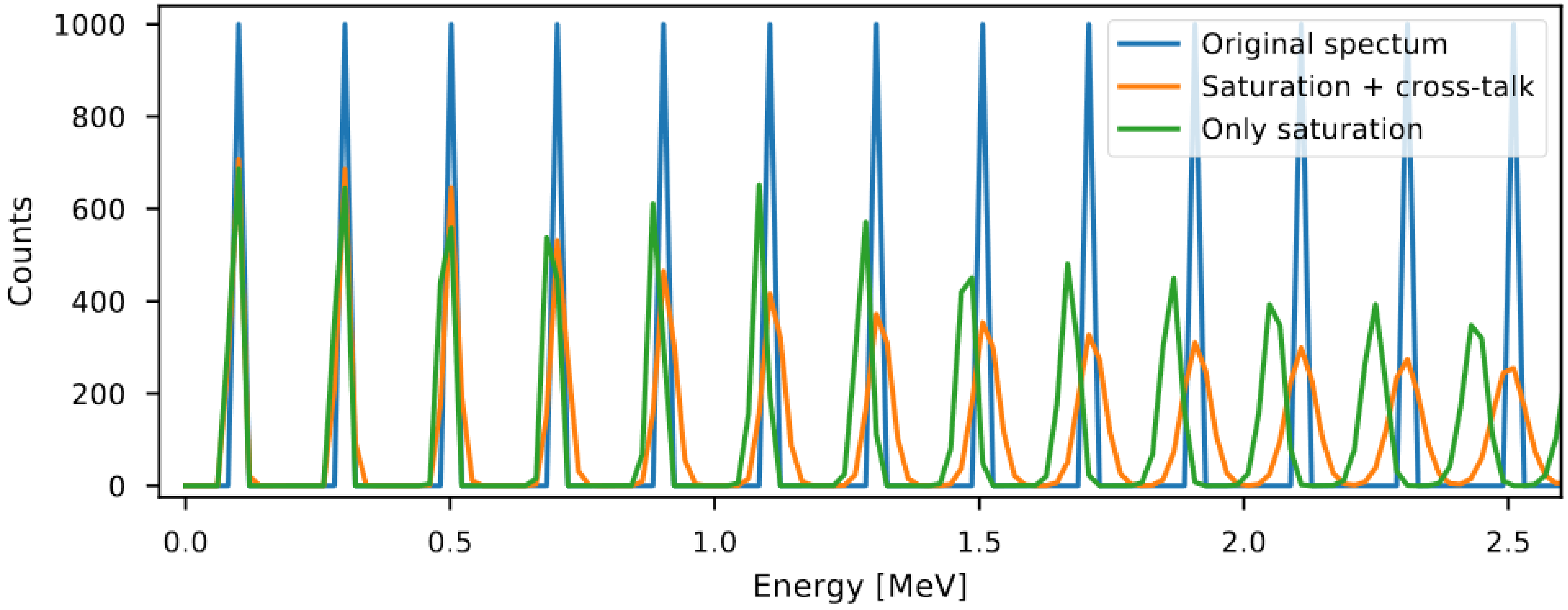


Crosstalk:



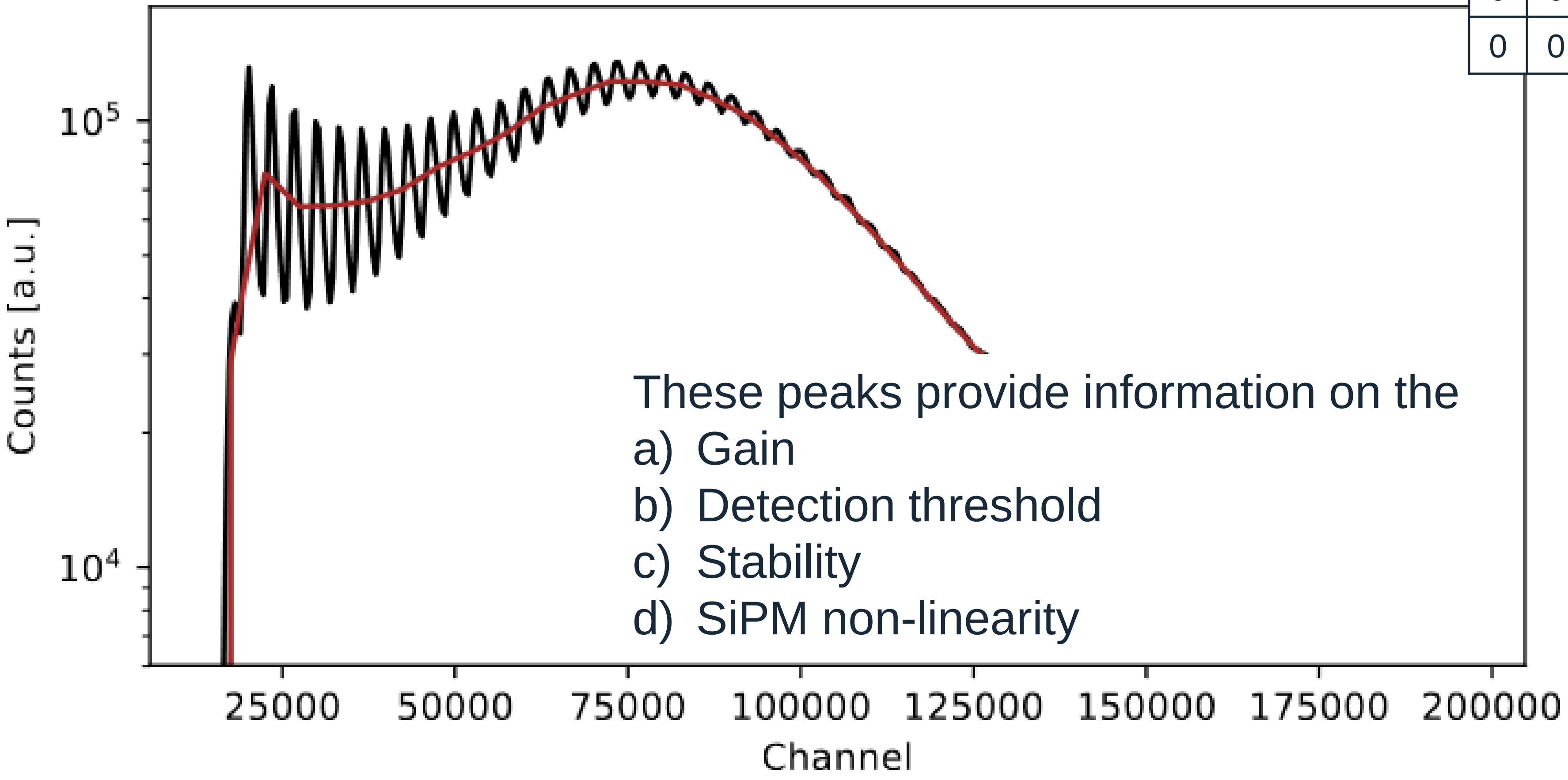
SIPM NON-LINEARITY

E_{in} → ($\frac{E}{\text{pixel}}$) → Expected photons → (Saturation) → Primary avalanches → (Cross-talk) → Total pixels triggered → ($\frac{E}{\text{pixel}}$) → E_{out}



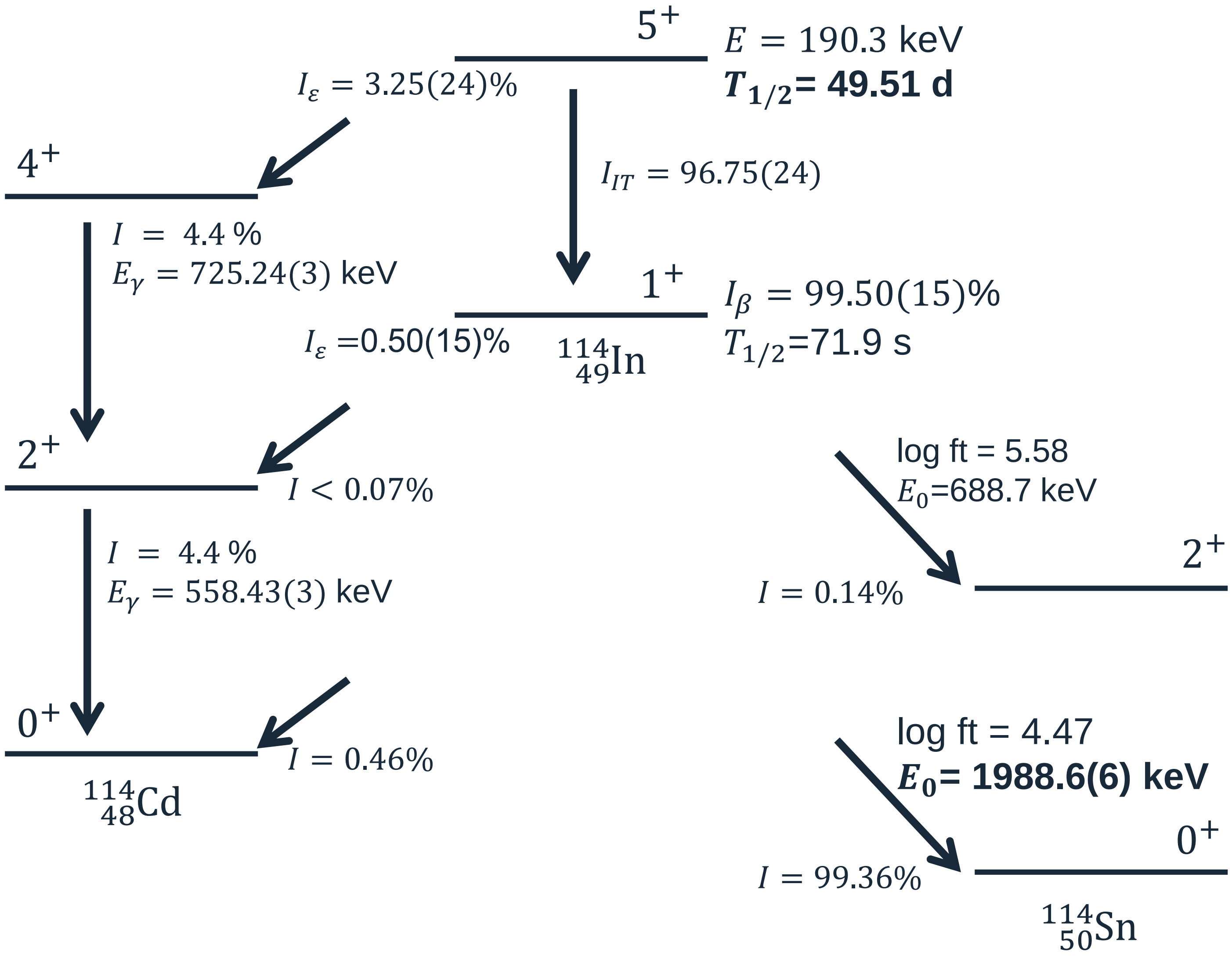
SIPM MULTIPLICITY

0	0	0	0	0	0
0	0	0	0	0	0
0	0	1	0	0	0
0	0	0	1	0	0
0	0	0	0	0	0
0	0	0	0	1	0



These peaks provide information on the

a) Gain
b) Detection threshold
c) Stability
d) SiPM non-linearity


5^+
$E = 190.3$ keV
$T_{1/2}$= 49.51 d
$I_\varepsilon = 3.25(24)\%$
$I_{IT} = 96.75(24)$
4^+
$I = 4.4\%$
$E_\gamma = 725.24(3)$ keV
1^+
$I_\beta = 99.50(15)\%$
$T_{1/2}$=71.9 s
I_ε =0.50(15)%
$^{114}_{49}\mathrm{In}$
2^+
$I < 0.07\%$
$I = 4.4\%$
$E_\gamma = 558.43(3)$ keV
0^+
$I = 0.46\%$
$^{114}_{48}\mathrm{Cd}$
log ft = 5.58
E_0=688.7 keV
2^+
$I = 0.14\%$
log ft = 4.47
E_0= 1988.6(6) keV
0^+
$I = 99.36\%$
$^{114}_{50}\mathrm{Sn}$

WM & FIERZ IN THE SPECTRUM

When taking both the Beyond Standard Model Fierz term and the Standard Model WM term into account, the β spectrum shape for an allowed Gamow-Teller decay can be written as:

$$W(E_e)dE_e = \frac{F(\pm Z, E_e)}{2\pi^3} p_e E_e (E_0 - E_e)^2 dE_e \, \xi \left(1 + b_{\mathrm{Fierz}} \frac{m_e}{E_e} \pm \frac{4}{3} \frac{E_e}{M_n} \frac{b_{\mathrm{WM}}}{Ac}\right), \quad (1)$$

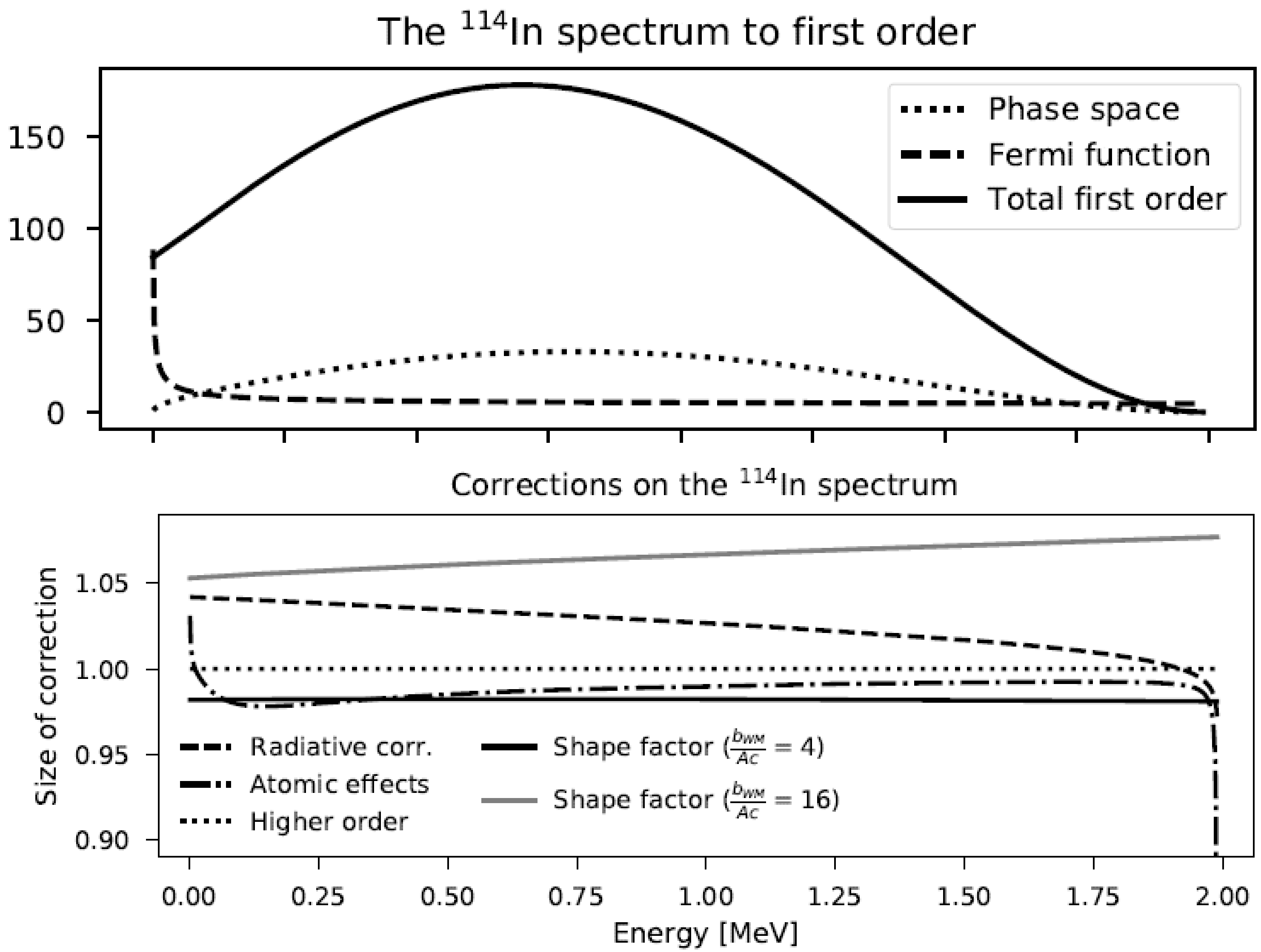
THEORETICAL DESCRIPTION: SPECTRUM SHAPE

Table 4.1: An overview of the different terms in the analytical description of the beta spectrum shape and their corresponding size. All terms are grouped in the categories described in the text. The relative importance of some terms can change depending on the atomic number or the endpoint energy. This table is adapted from Refs. [102, 103].

Category	Effect	Formula	Magnitude
Phase space		$pW(W_0 - W)^2$	Unity or larger
Electrostatic	Fermi function	F_0	
	Finite size nucleus	L_0	
Radiative corr.		R	
Recoil-order	Shape factor	C	
	Isovector correction	C_I	
Atomic	Atomic exchange	X	$10^{-1} - 10^{-2}$
	Atomic mismatch	r	
	Atomic screening	S	
	Shake-up & Shake-off	included in r	
Higher order	Diffuse nucl. surface	U	
	Nuclear deformation	D_{FS} & D_C	
	Recoil Coulomb corr.	Q	$10^{-3} - 10^{-4}$
	Recoiling nucleus	R_N	
	Molecular screening	ΔS_{Mol}	
	Molecular decay	Case by case	
	Bound state β decay	Γ_b/Γ_c	$< 1 \times 10^{-4}$
	Neutrino mass	negligible	

High precision analytical description of the allowed β spectrum shape L. Hayen et al. 2018 Reviews of Modern Physics

THEORETICAL SPECTRUM SHAPE ^{114}In



SHAPE FACTOR

$$^{A}C(Z,W) \approx 1 + ^{A}C_0 + ^{A}C_1 W + ^{A}C_{-1}/W + ^{A}C_2 W^2$$

$$^{A}C_0 = -\frac{1}{5}(W_0R)^2 + \frac{4}{9}R^2\left(1 - \frac{1}{10}\Lambda\right)$$

$$+ \frac{1}{3}\frac{W_0}{M_N}\left(\mp 2\frac{b}{Ac_1} + \frac{d}{Ac_1}\right) \pm \frac{\alpha Z}{M_N R}\left(\pm 2\frac{b}{Ac_1} + \frac{d}{Ac_1}\right) \tag{4.3}$$

$$+ \frac{2}{35}\alpha Z W_0 R(1 - \Lambda) - \frac{233}{630}(\alpha Z)^2,$$

$$^{A}C_1 = \pm\frac{4}{3M_N}\frac{b}{Ac_1} + \frac{4}{9}W_0R^2\left(1 - \frac{1}{10}\Lambda\right) \mp \frac{3}{5}\alpha Z R\left(1 - \frac{2}{21}\Lambda\right), \tag{4.4}$$

$$^{A}C_{-1} = -\frac{1}{3M_N}\left(\pm 2\frac{b}{Ac_1} + \frac{d}{Ac_1}\right) - \frac{2}{45}W_0R^2(1 - \Lambda) \mp \frac{\alpha Z R}{70}, \tag{4.5}$$

$$^{A}C_2 = -\frac{4}{9}R^2(1 - \frac{1}{10}\Lambda) \tag{4.6}$$

High precision analytical description of the allowed β spectrum shape L. Hayen et al. 2018 Reviews of Modern Physics

ENERGY RESOLUTION

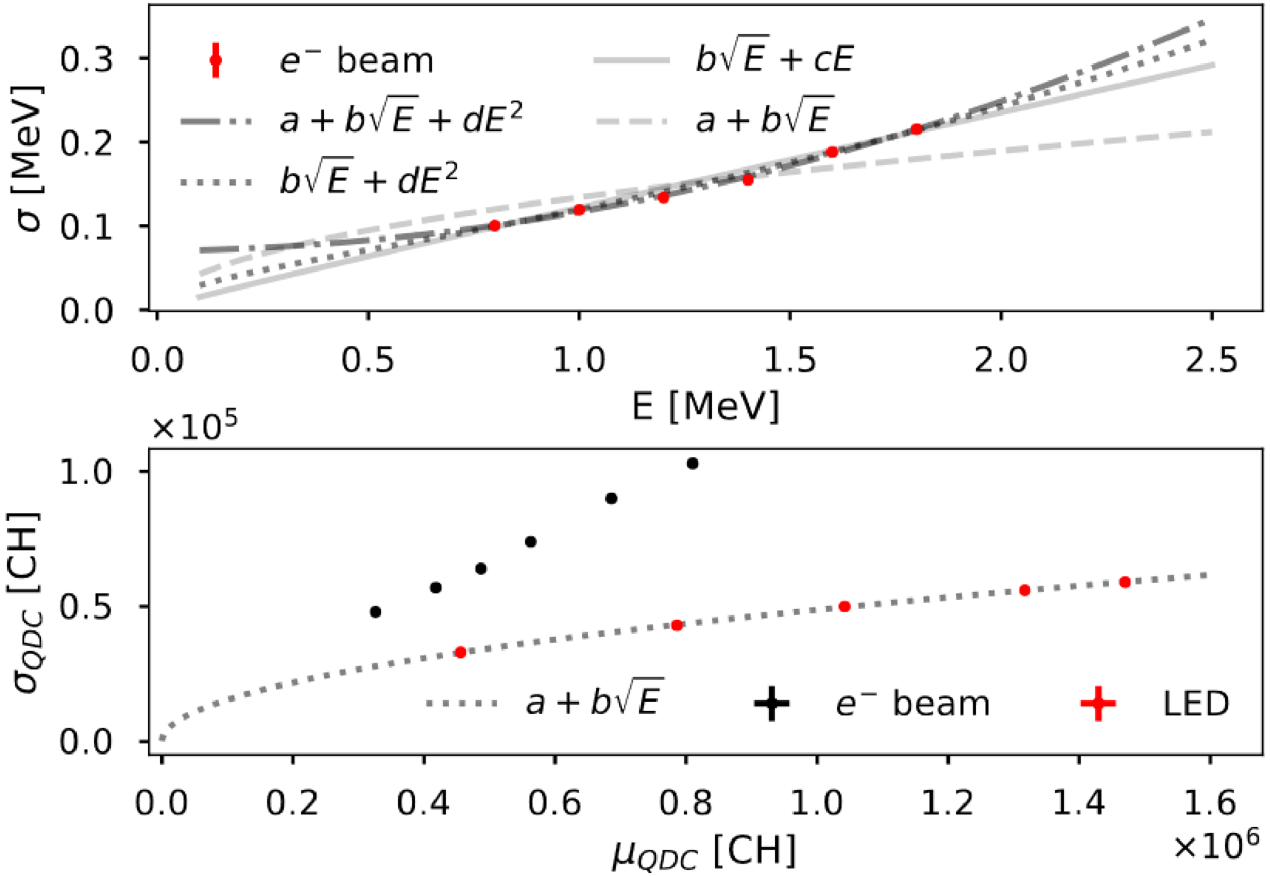
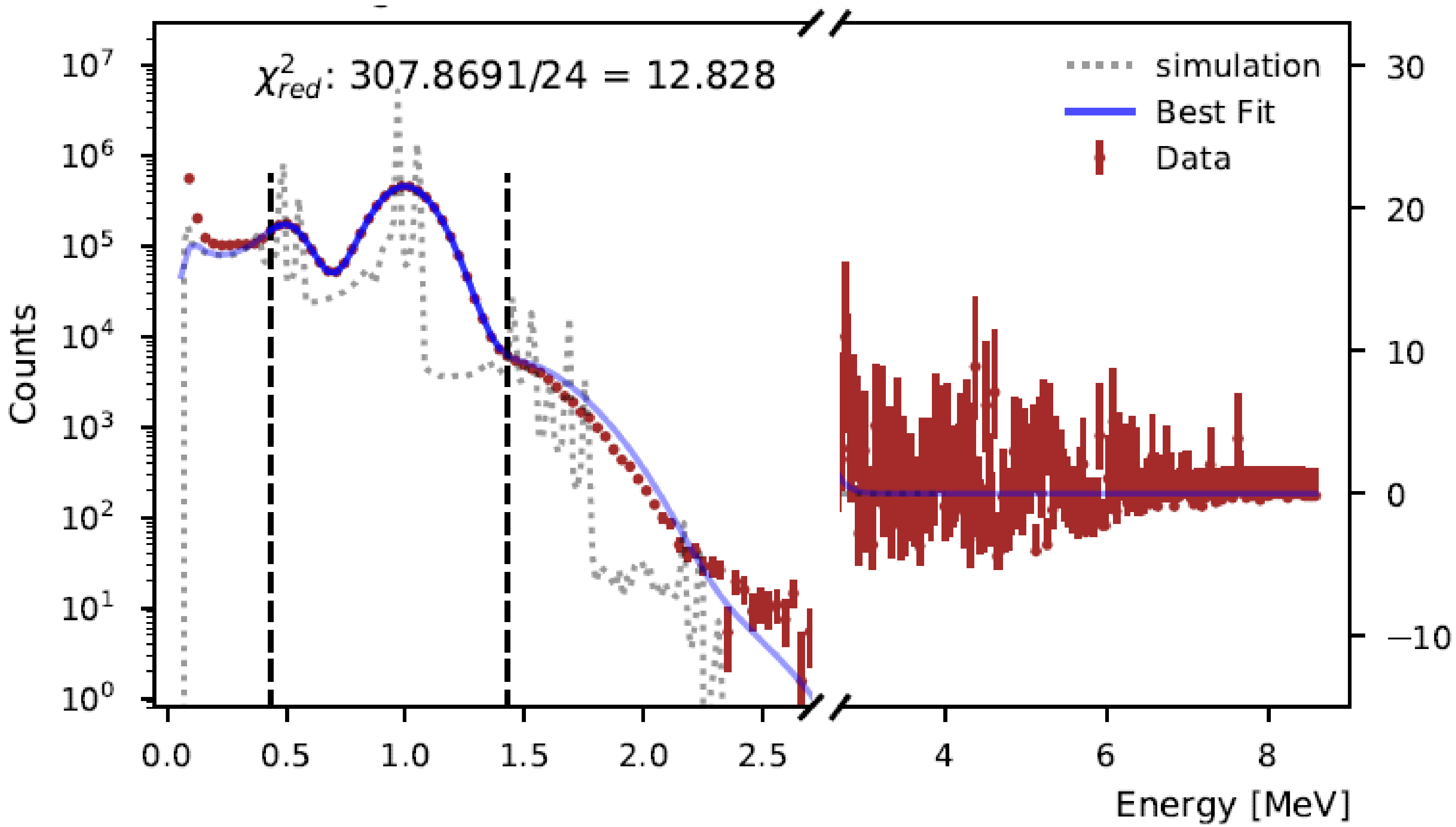


Figure 7.3: Results for the energy resolution during the detector characterisation using an electron spectrometer and LED at LP2i. The fits are explained in the text and in Table 7.3.

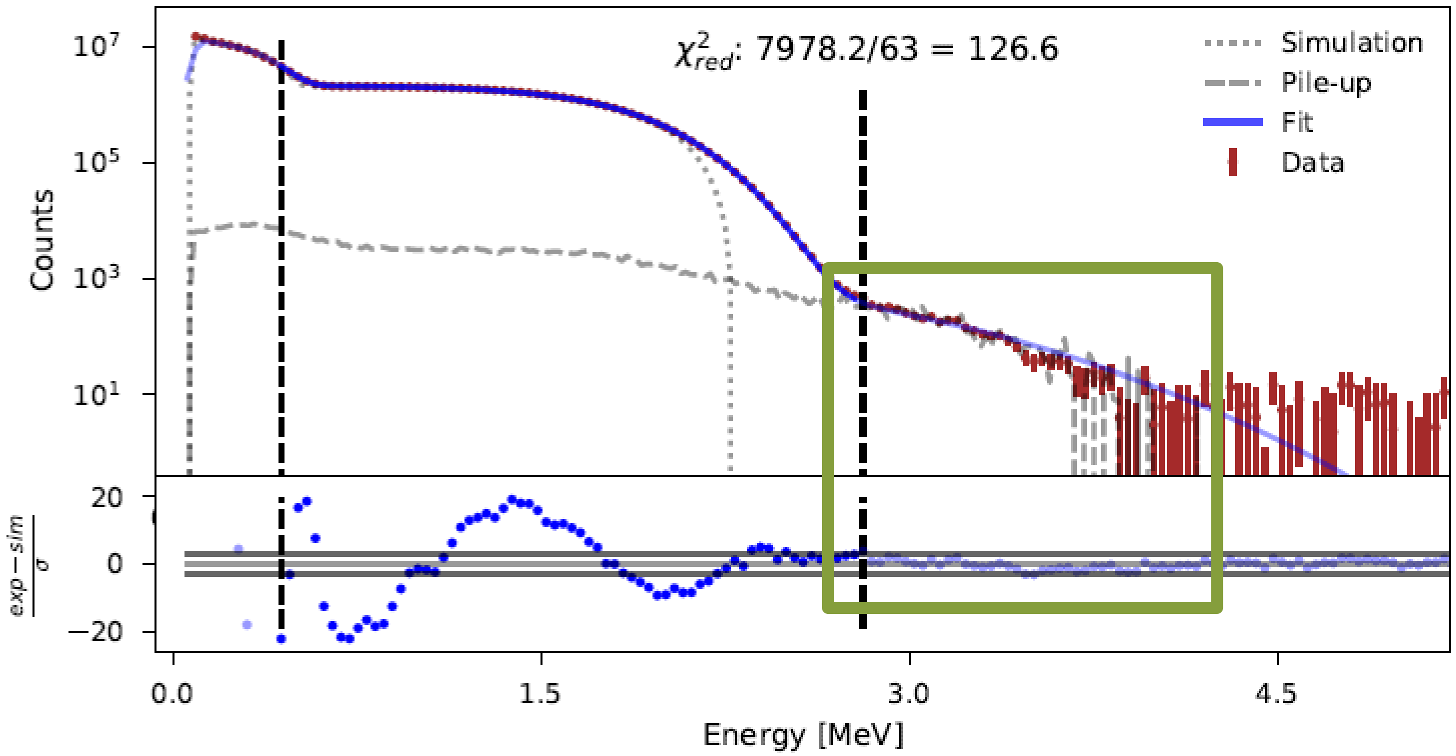
	a	b	c	d	χ^2_{red}
I	0.0000(17)	0.134(2)			1479
II	0.069(11)	0.004(14)		0.043(2)	7.8
III		0.0908(6)		0.0285(4)	15.9
IV		0.0138(16)	0.1080(14)		43.4
	σ'_0	σ'_1	σ'_E	σ'_2	
II	0.029(13)	0.101(5)		0.0507(10)	6.7
III		0.1065(5)		0.0497(3)	5.3
IV		0.043(3)	0.1136(8)		43.9

BACKGROUND



The background subtraction behaves as expected

PILE-UP - ^{90}Sr



χ^2_{red}: 7978.2/63 = 126.6
Simulation
Pile-up
Fit
Data
Counts
10^7
10^5
10^3
10^1
$\frac{exp-sim}{\sigma}$
20
0
−20
0.0
1.5
3.0
4.5
Energy [MeV]

SOURCE PREPARATION

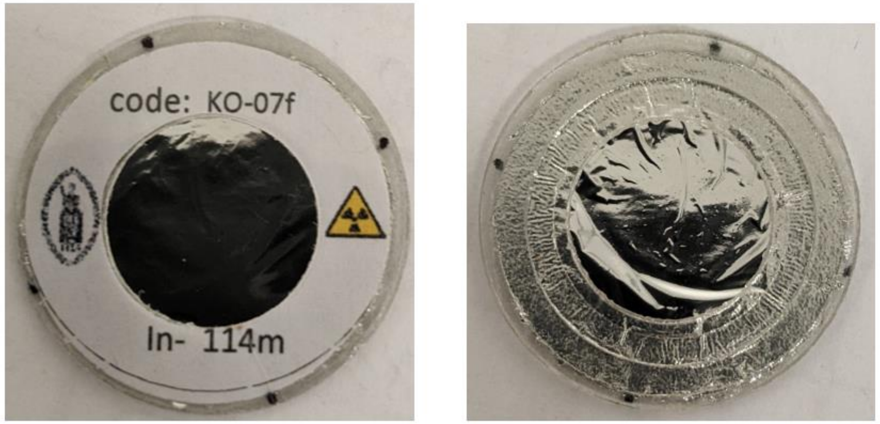


Figure B.5: Front and backside of a ^{114m}In source prepared at KU Leuven.