WISArD

24/09/2026 Colloque GANIL

Lecanuet Samuel

LP2iB
3rd year PhD student

Weak Interaction Studies with ^{32}Ar Decay

- Introduction
- Experimental Setup
- Measurement
- Data taking
- Systematics
- Conclusion

Weak interaction with β-decay

For a pure Fermi transition and an unpolarized nucleus:

Standard Model Lagrangian

$$\begin{aligned}\mathcal{L}_{Lee-Yang} = &+ \overline{p}\gamma^{\mu}n\overline{e}\gamma_{\mu}(C_V + C'_V\gamma_5)\nu \\ &+ \overline{p}n\overline{e}(C_S + C'_S\gamma_5)\nu \\ &+ h.c\end{aligned}$$

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β decay rate function

$$N(\theta_{\beta\nu}, W_\beta)\mathrm{d}W_\beta \propto \left(1 + a\frac{p_\beta p_\nu}{W_\beta W_\nu}\cos(\theta_{\beta\nu}) + b\gamma\frac{m_e}{W_\beta}\right)\mathrm{d}W_\beta$$

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angular correlation coefficient

$$a = \frac{-C_S^2 - C_S'^2 + C_V^2 + C_V'^2}{C_S^2 + C_S'^2 + C_V^2 + C_V'^2}$$

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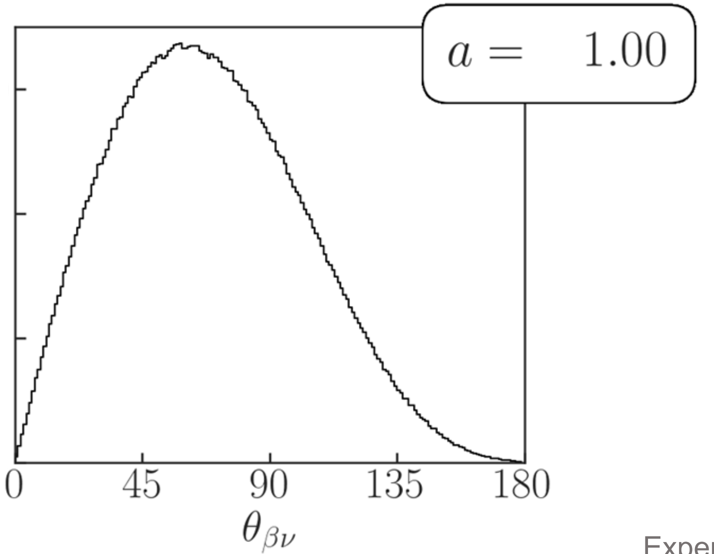

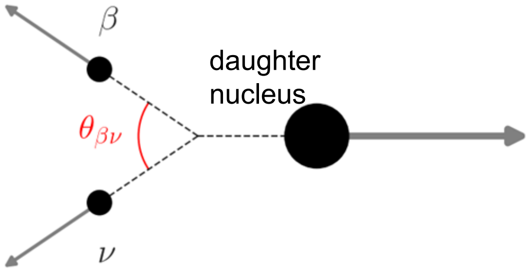

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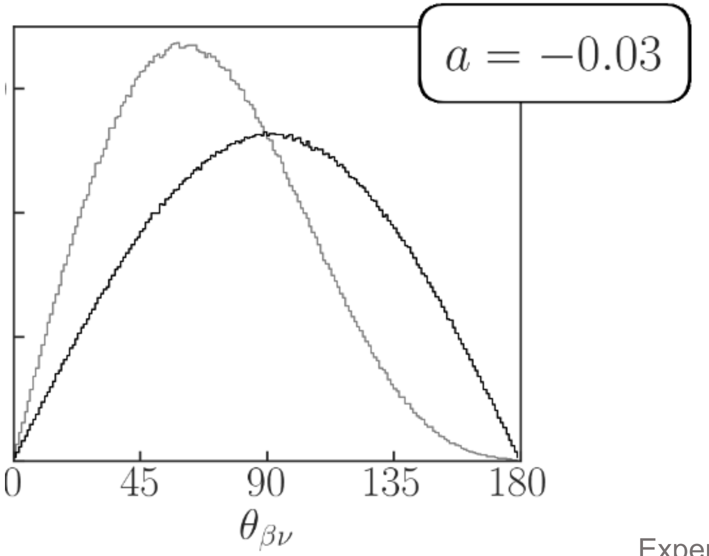
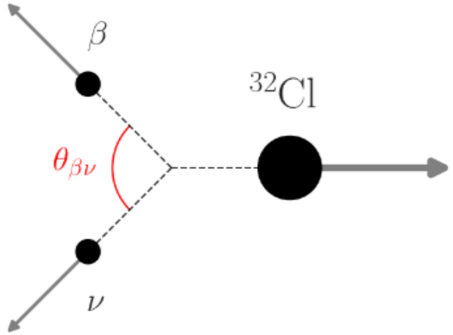
Beyond Standard Model





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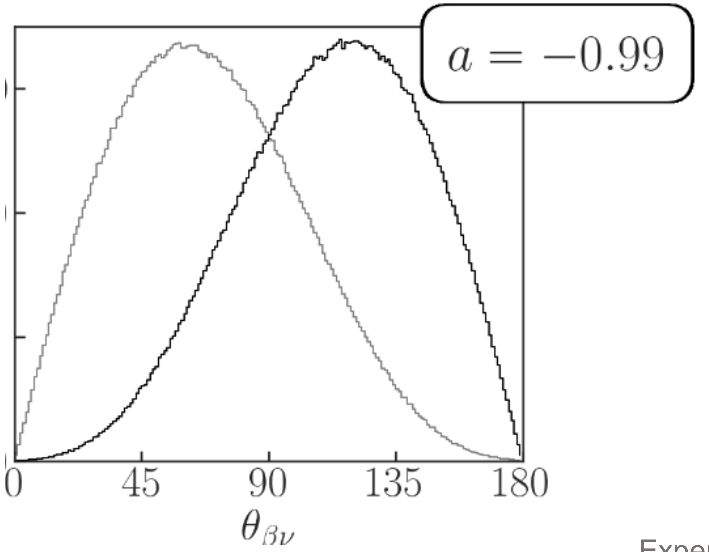
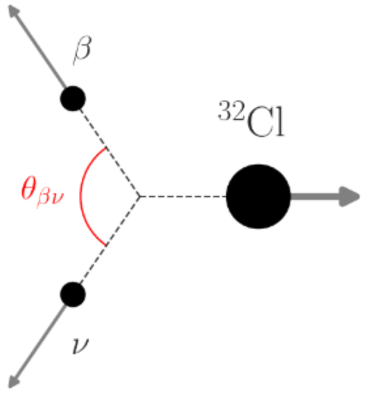




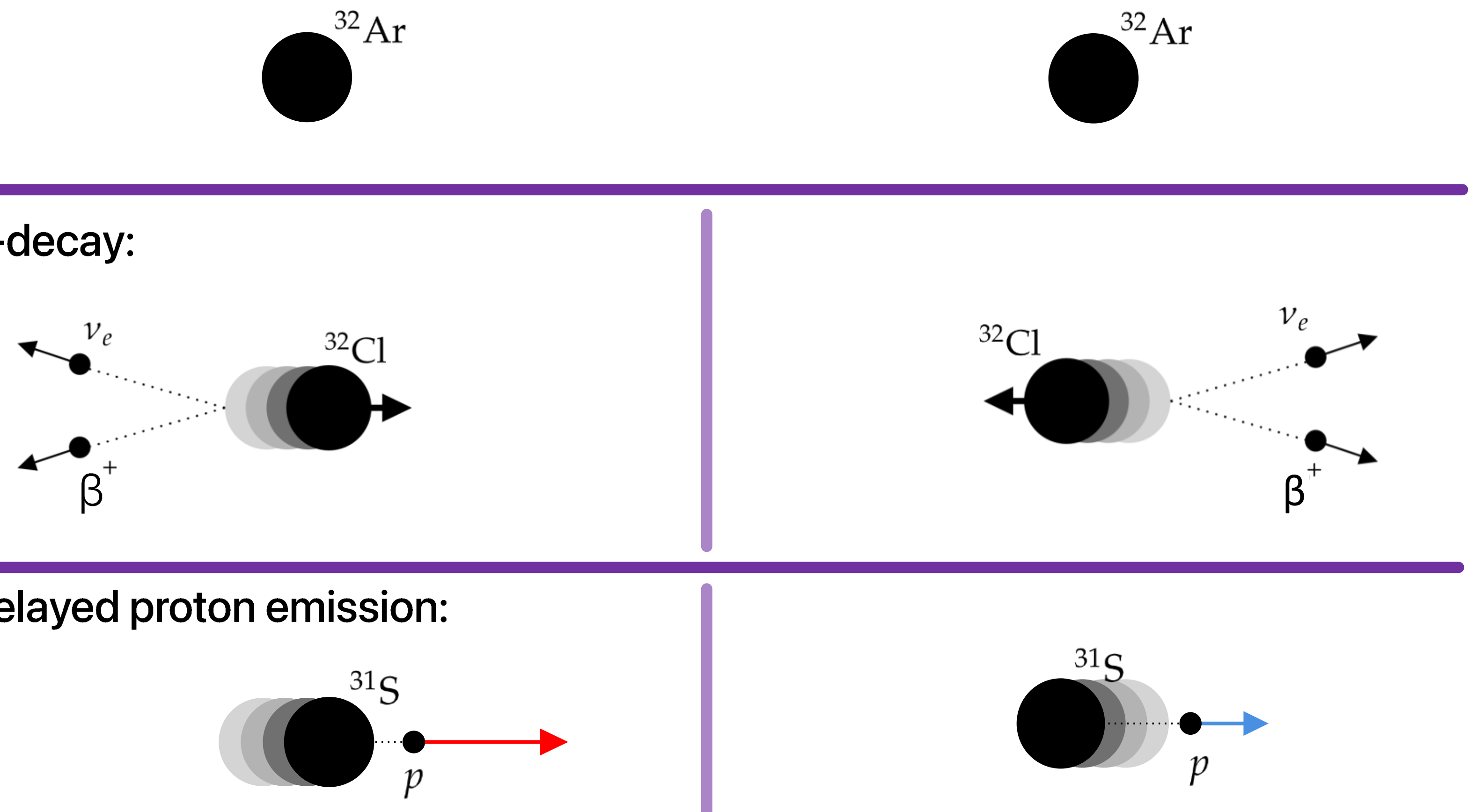
Experimentally a is measured (contribution of a and b)

β-delayed proton emission

At rest:

β-decay:

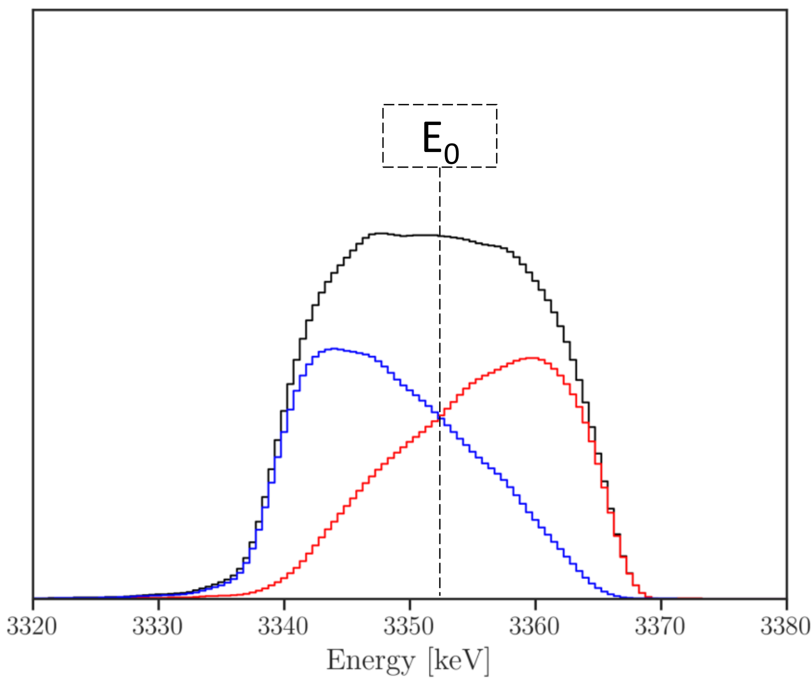
Delayed proton emission:



Energy increasing

Energy decreasing

Proton peak



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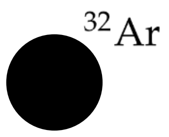
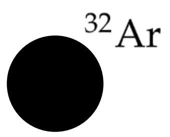
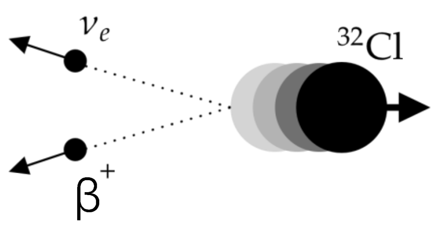
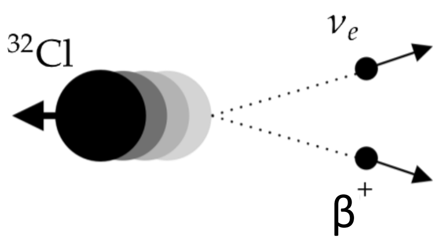




β-decay:





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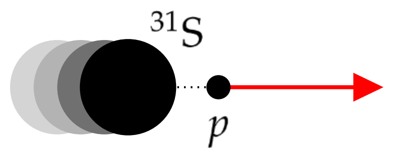
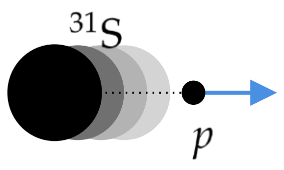


Energy increasing



Energy decreasing

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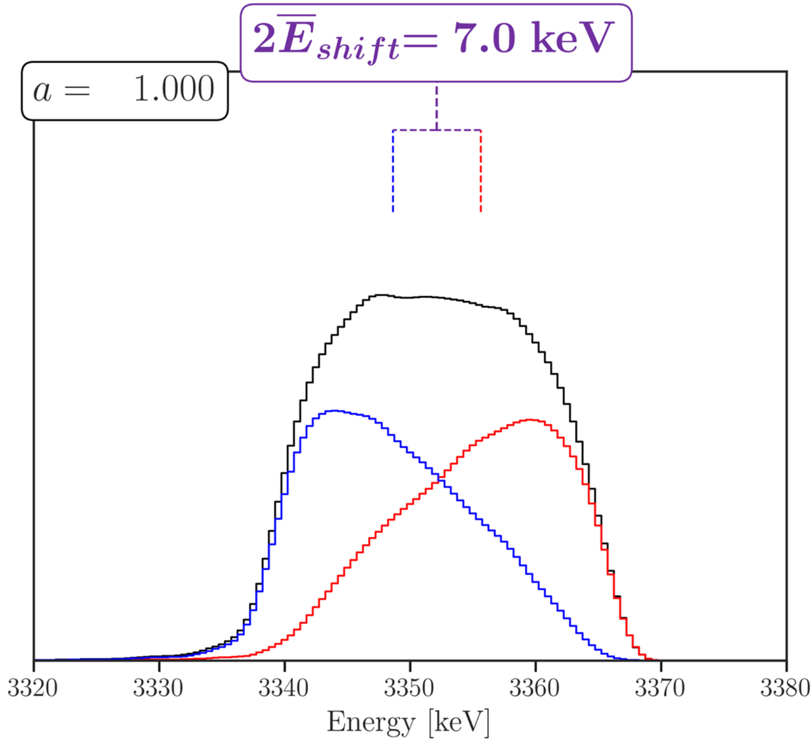

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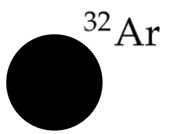

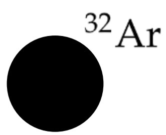

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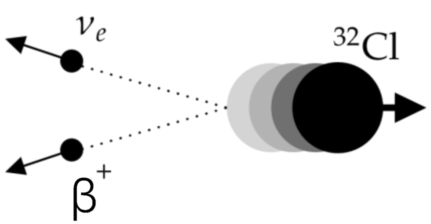

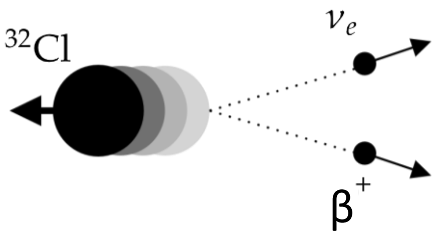

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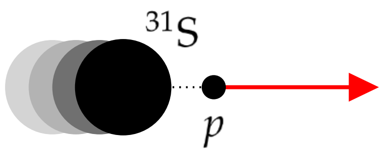

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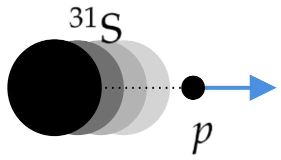

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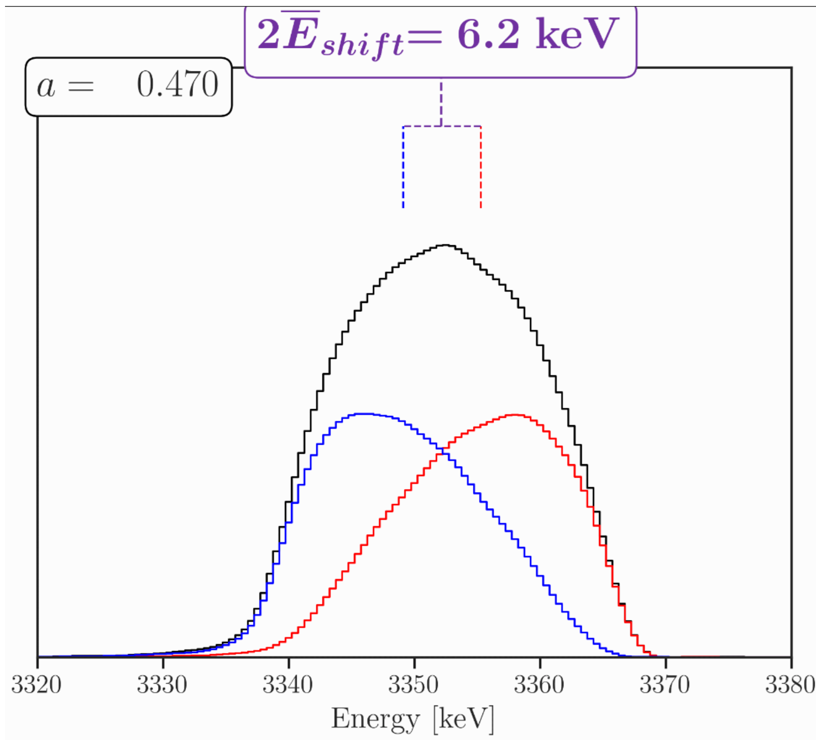

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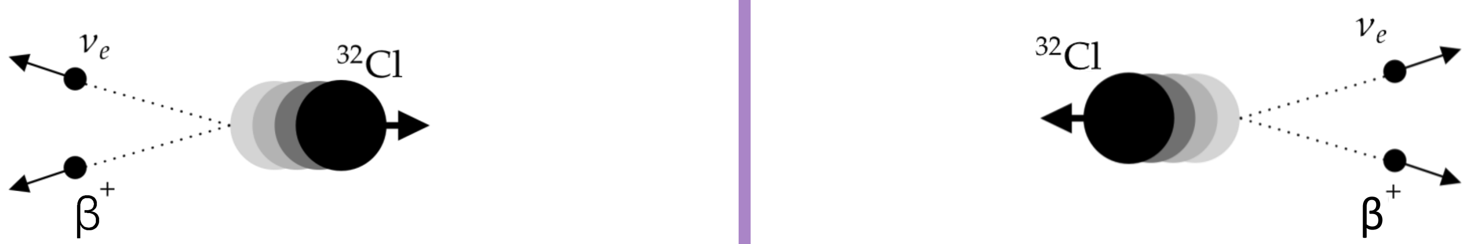

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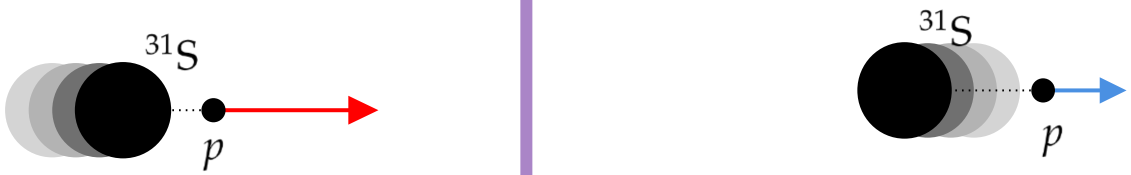

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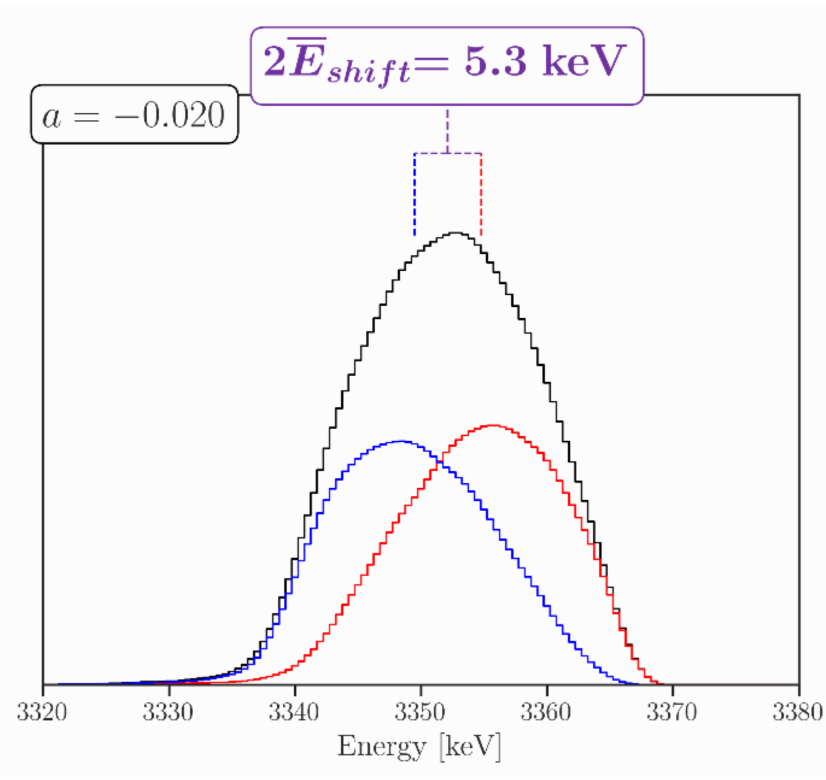

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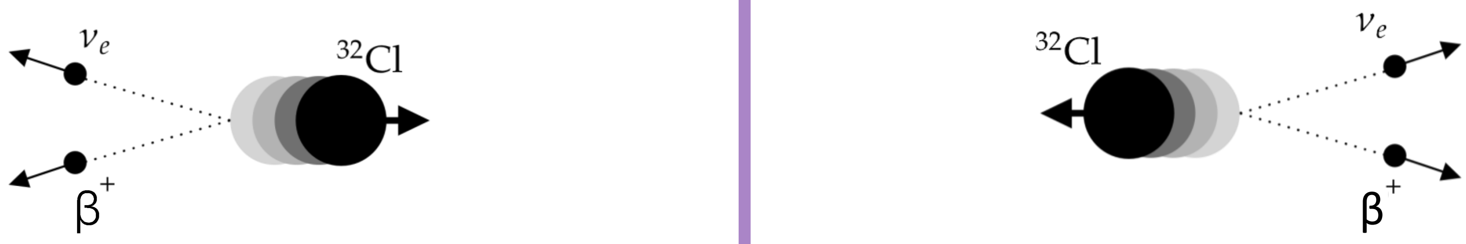

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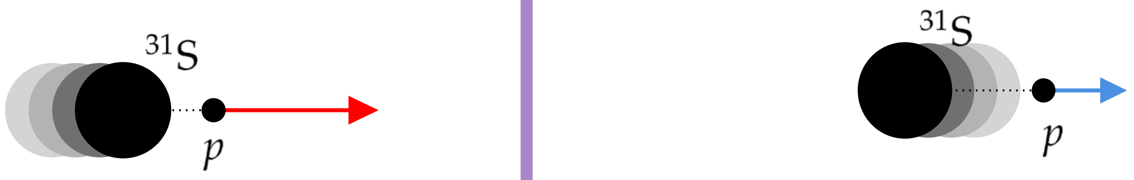

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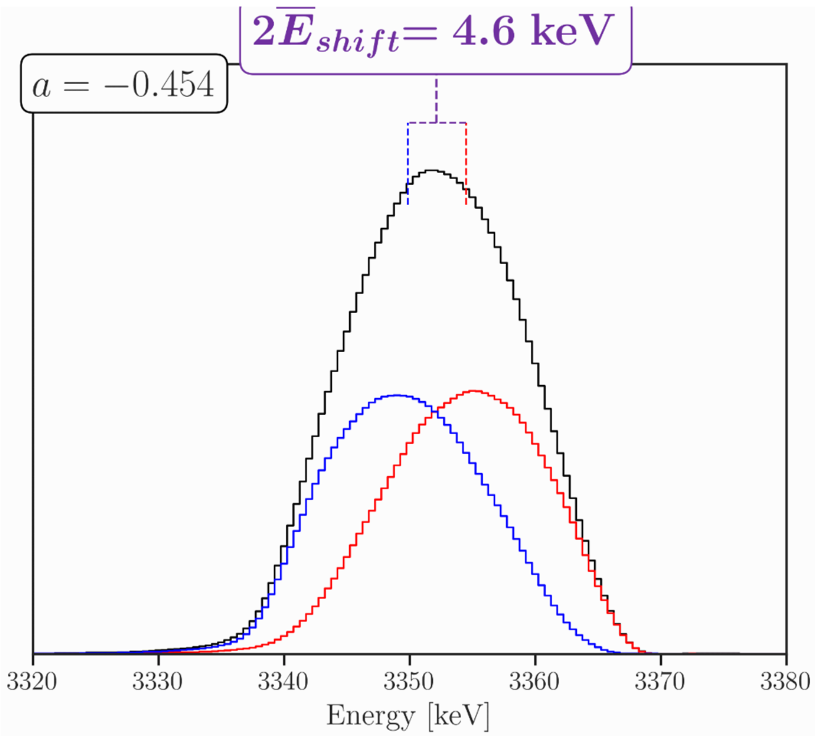

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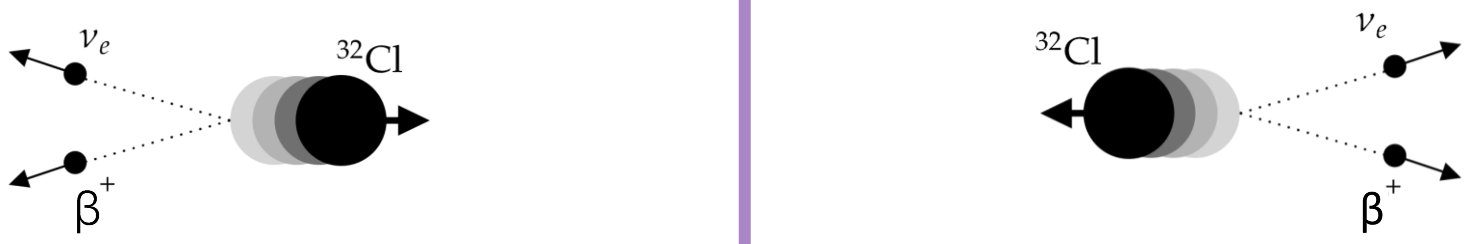

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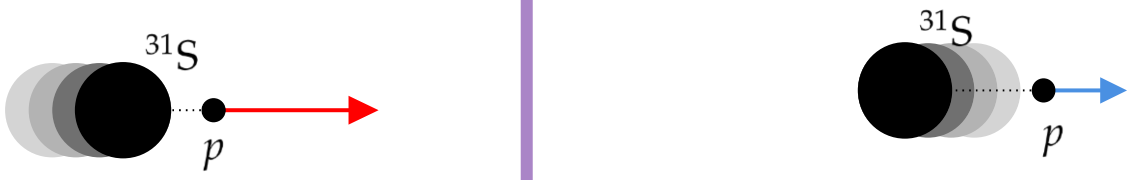

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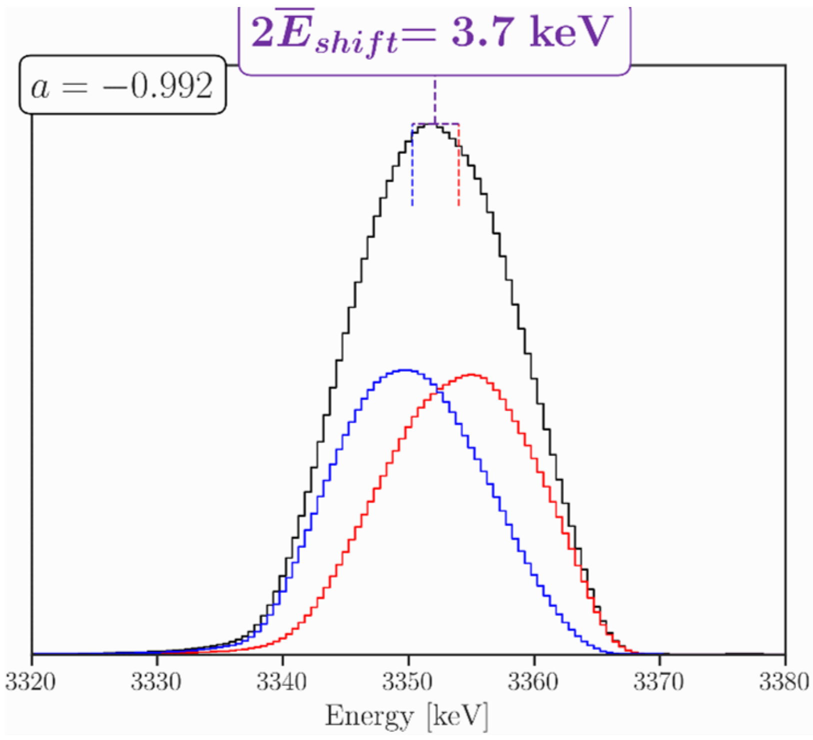
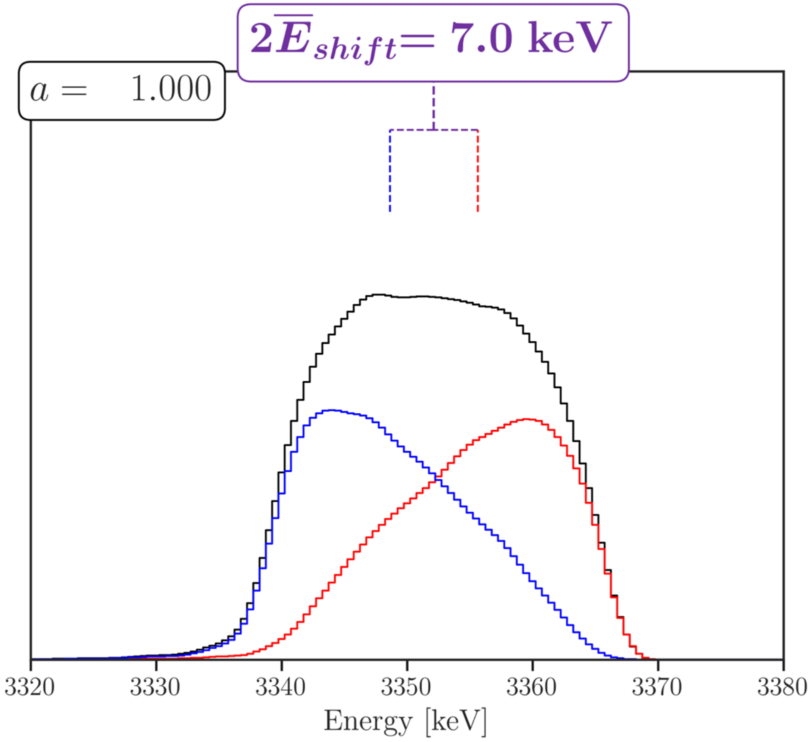


β-delayed proton emission

0.1% precision on a ⟶ ~5 eV precision on $\overline{E}_{shift}$

Proton peak



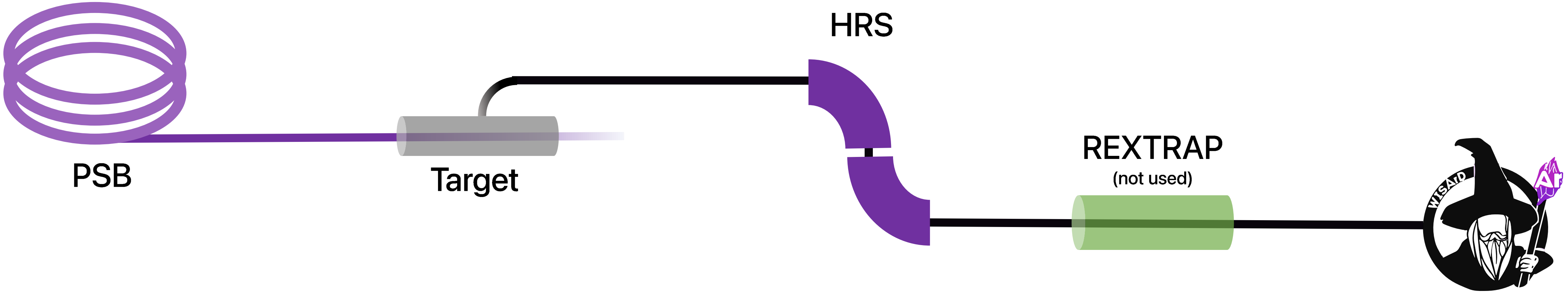
WISArD at ISOLDE

^{32}Ar production: $$p + CaO \rightarrow Ar$$

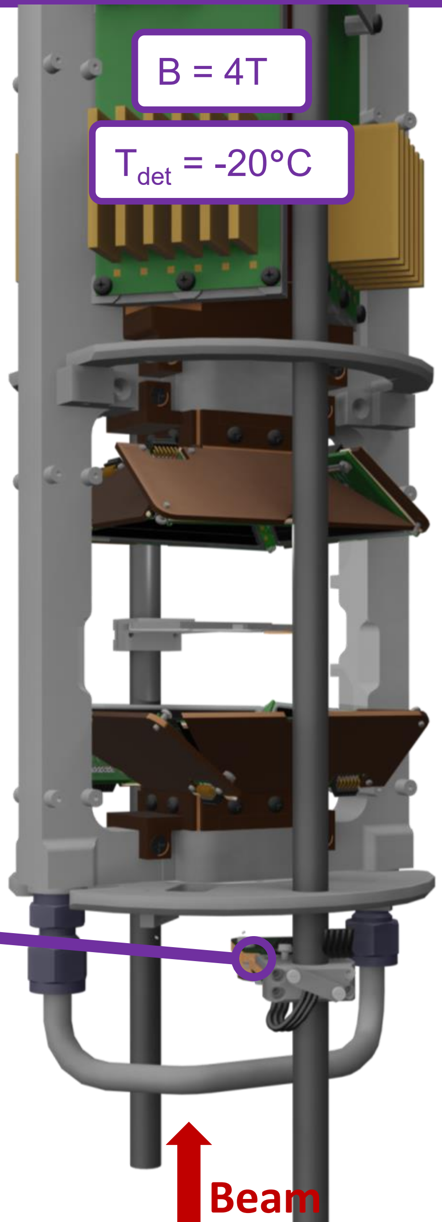
- From Proton Synchrotron Booster
- 2.5 µA at 1.4 GeV

- CaO target
- Nanostructured powder

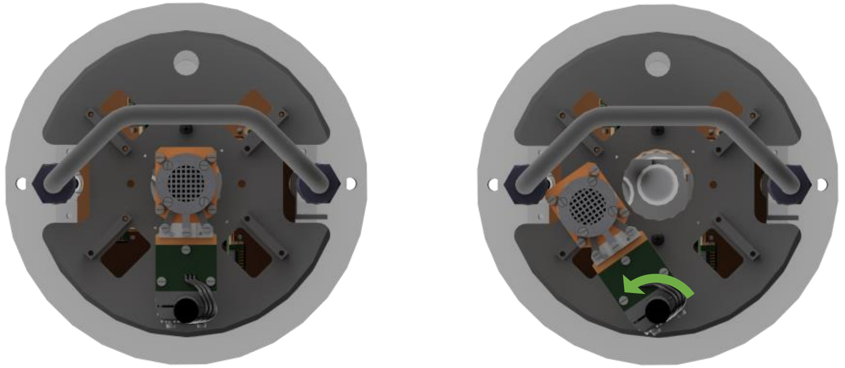
- ISOLDE HRS
- A/Q selection
- 30 keV



WISArD: detection tower



2 mechanical positions: bottom view



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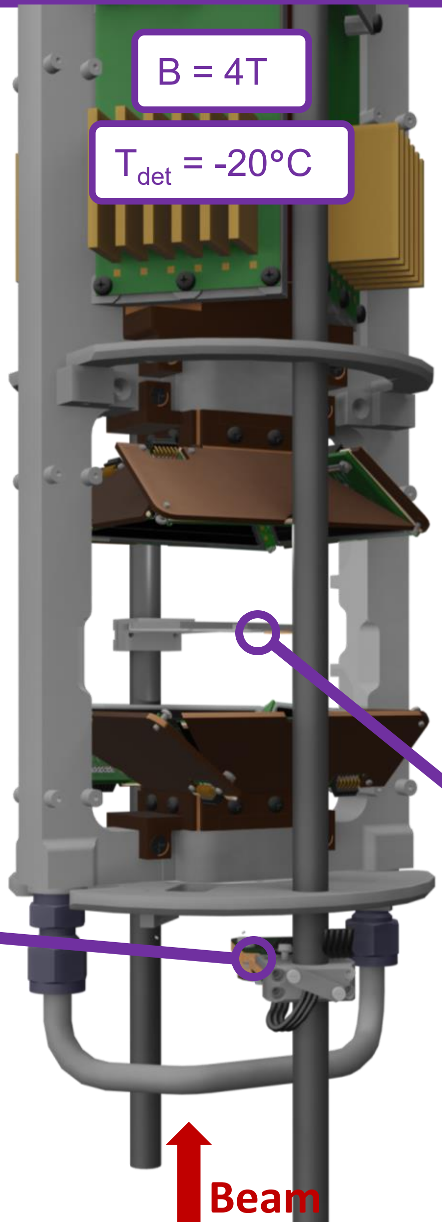

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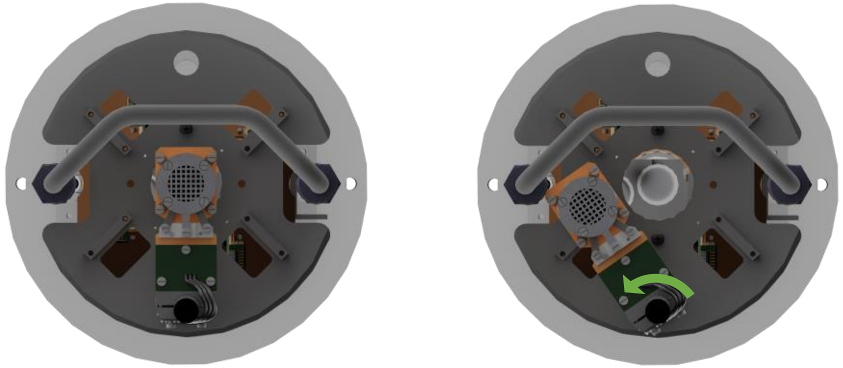
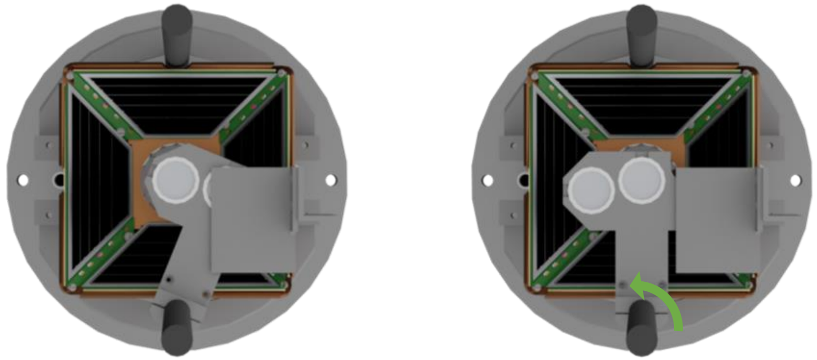
MCP measurement | Decay measurement



2 catcher positions: bottom view

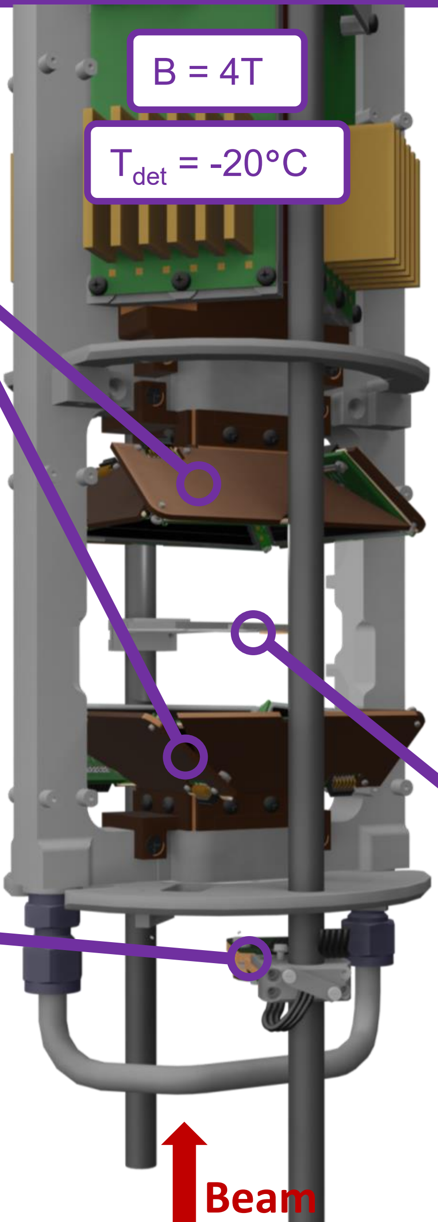
Thin catcher | Thick catcher



WISArD: detection tower

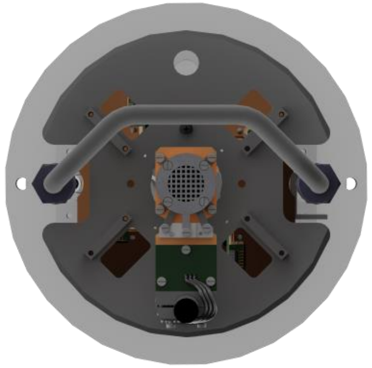
40 Silicon detectors channels:

- Thickness: 300 µm
- Dead-Layer: 92(20) nm
- Proton resolution: ~10keV FWHM
- Total solid angle: ~40%
- Interstrip geometry (RBS + AFM @ LOMA)



2 mechanical positions: bottom view

MCP measurement



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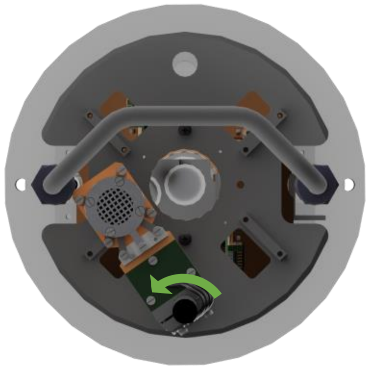

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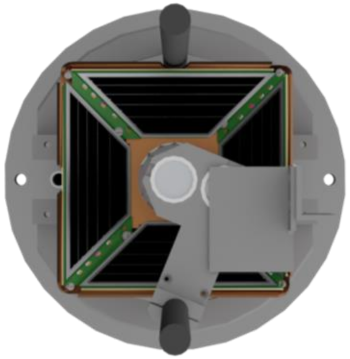
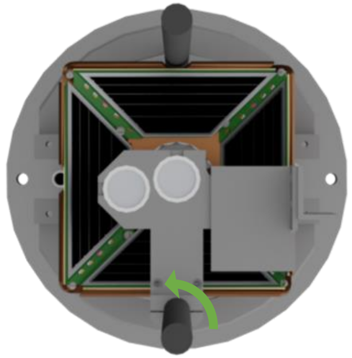


Thick catcher



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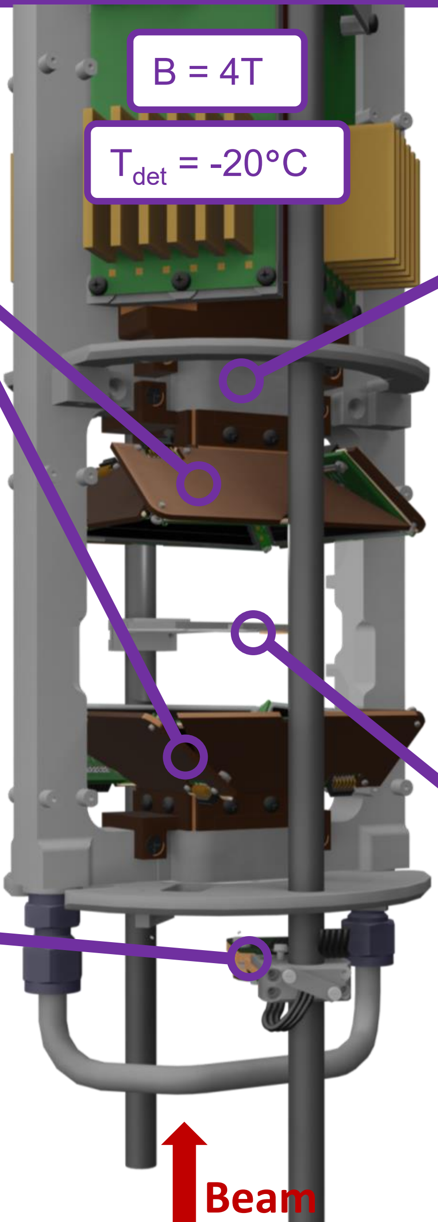
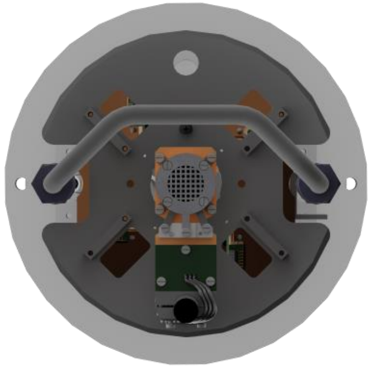


9 SiPMs:

- 2 gain regimes (x10 factor)
- Coupled with a plastic scintillator (EJ212)
- Removing dark counts using SiPMs correlations

2 mechanical positions: bottom view

MCP measurement



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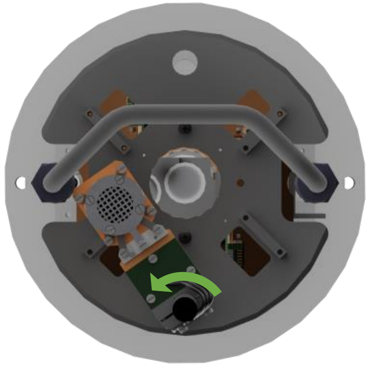

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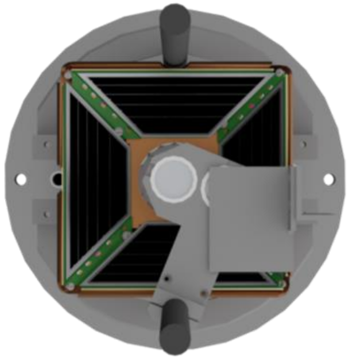

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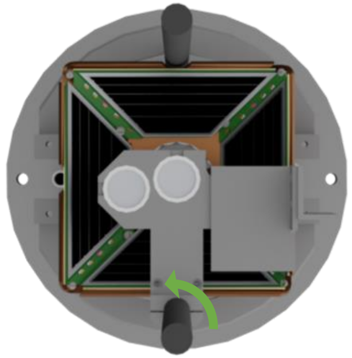
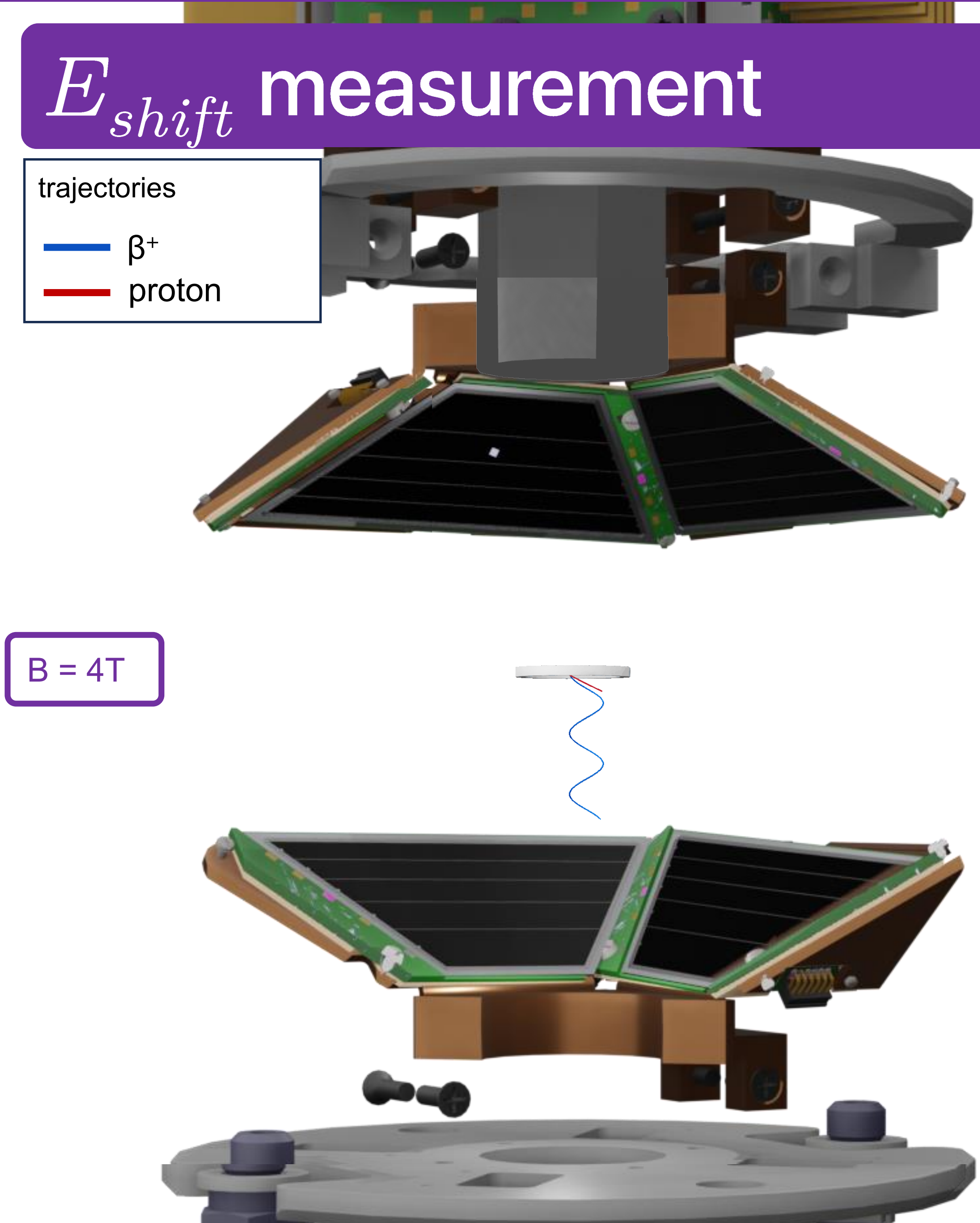
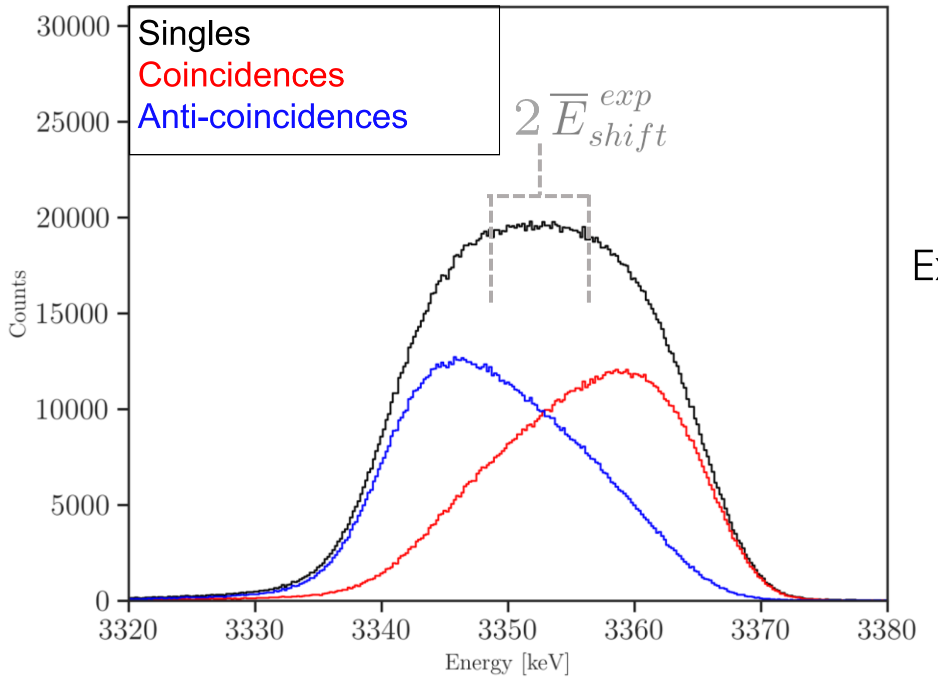


E_{shift} measurement



B = 4T

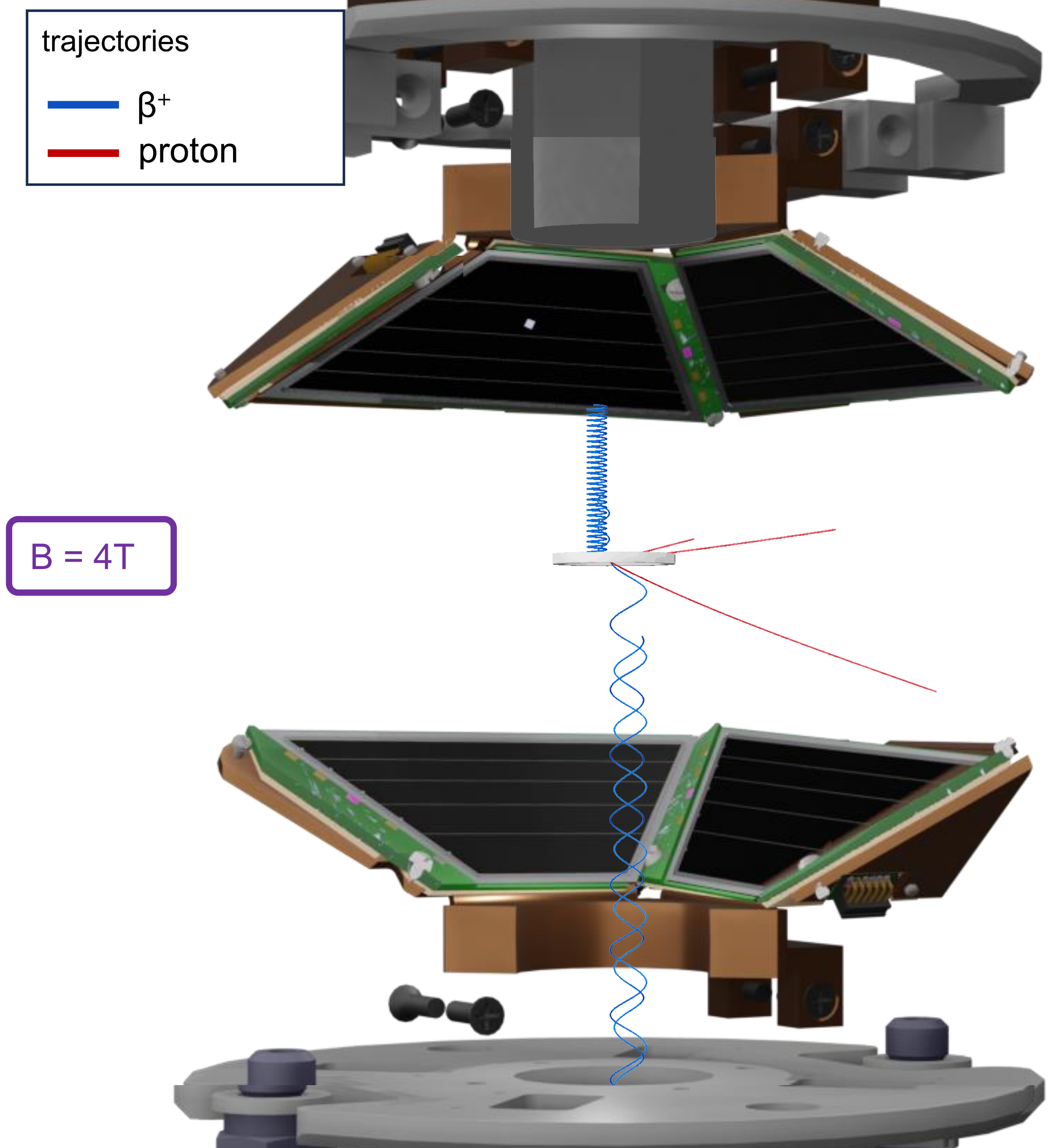


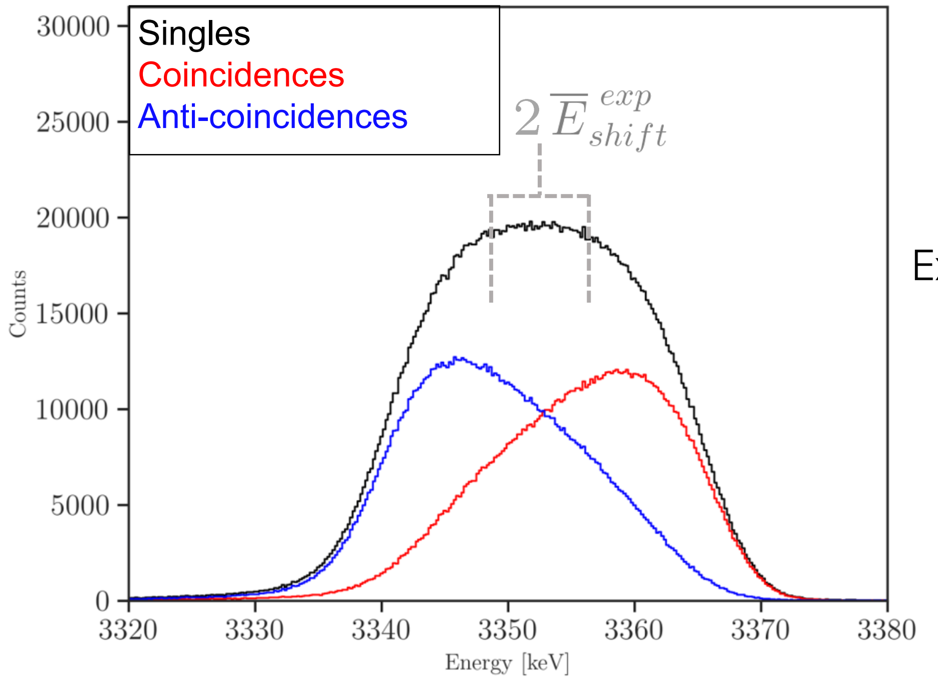
Experimental data (2025)

$$\overline{E}_{shift} = \left|\overline{E}_{singles} - \overline{E}_{coinc}\right|$$

→ Simulations

E_{shift} measurement





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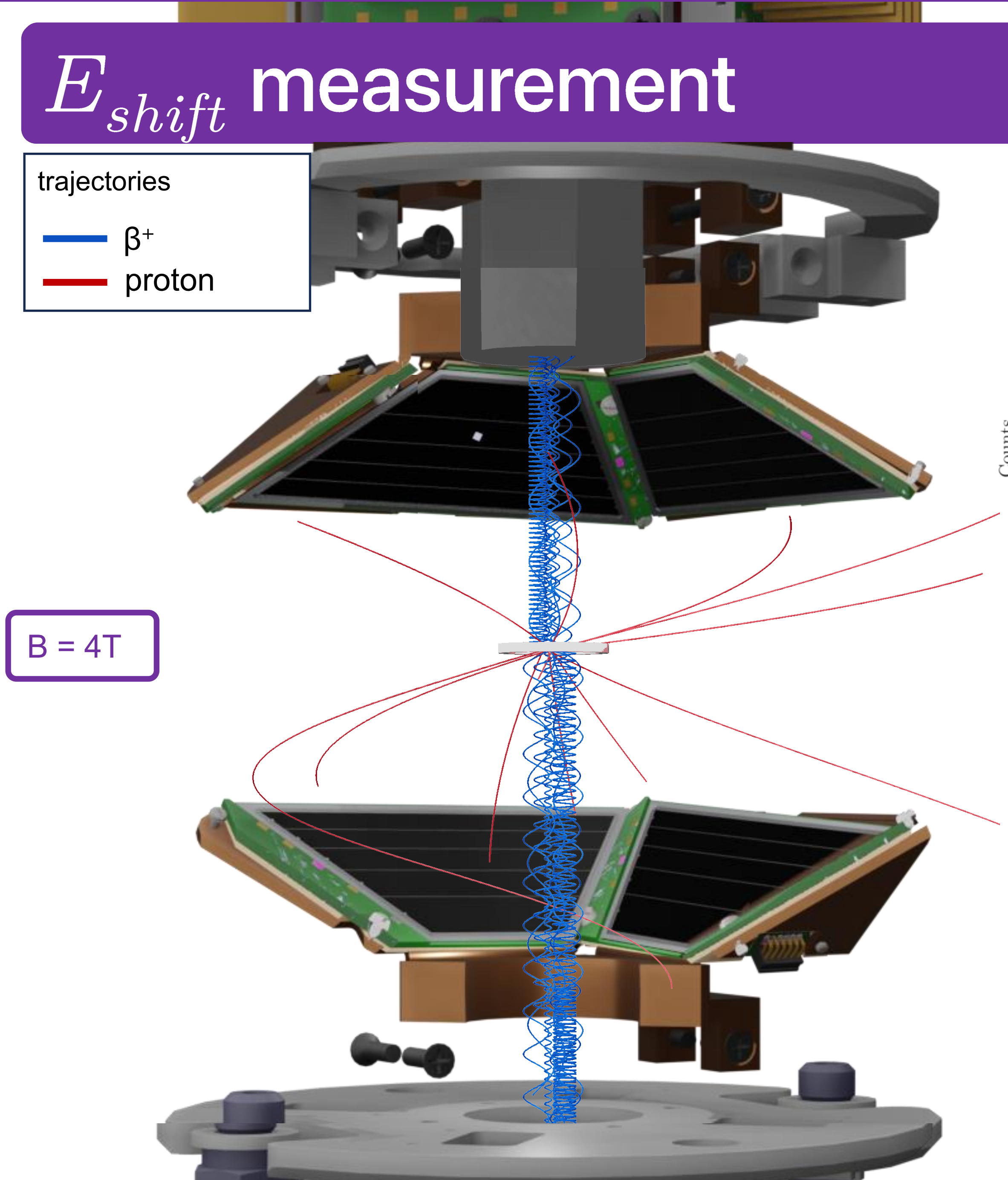

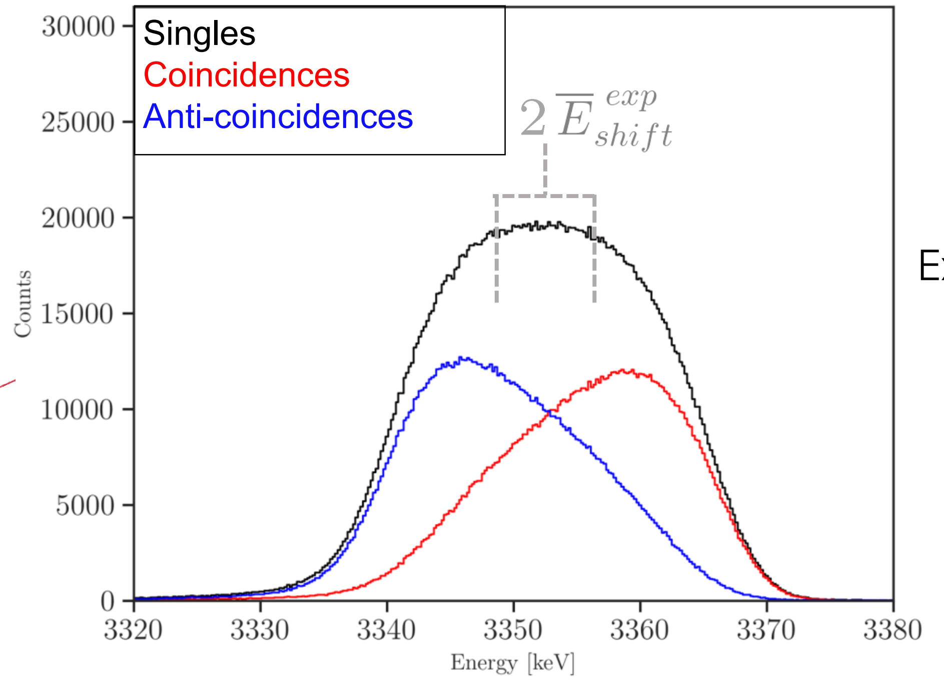

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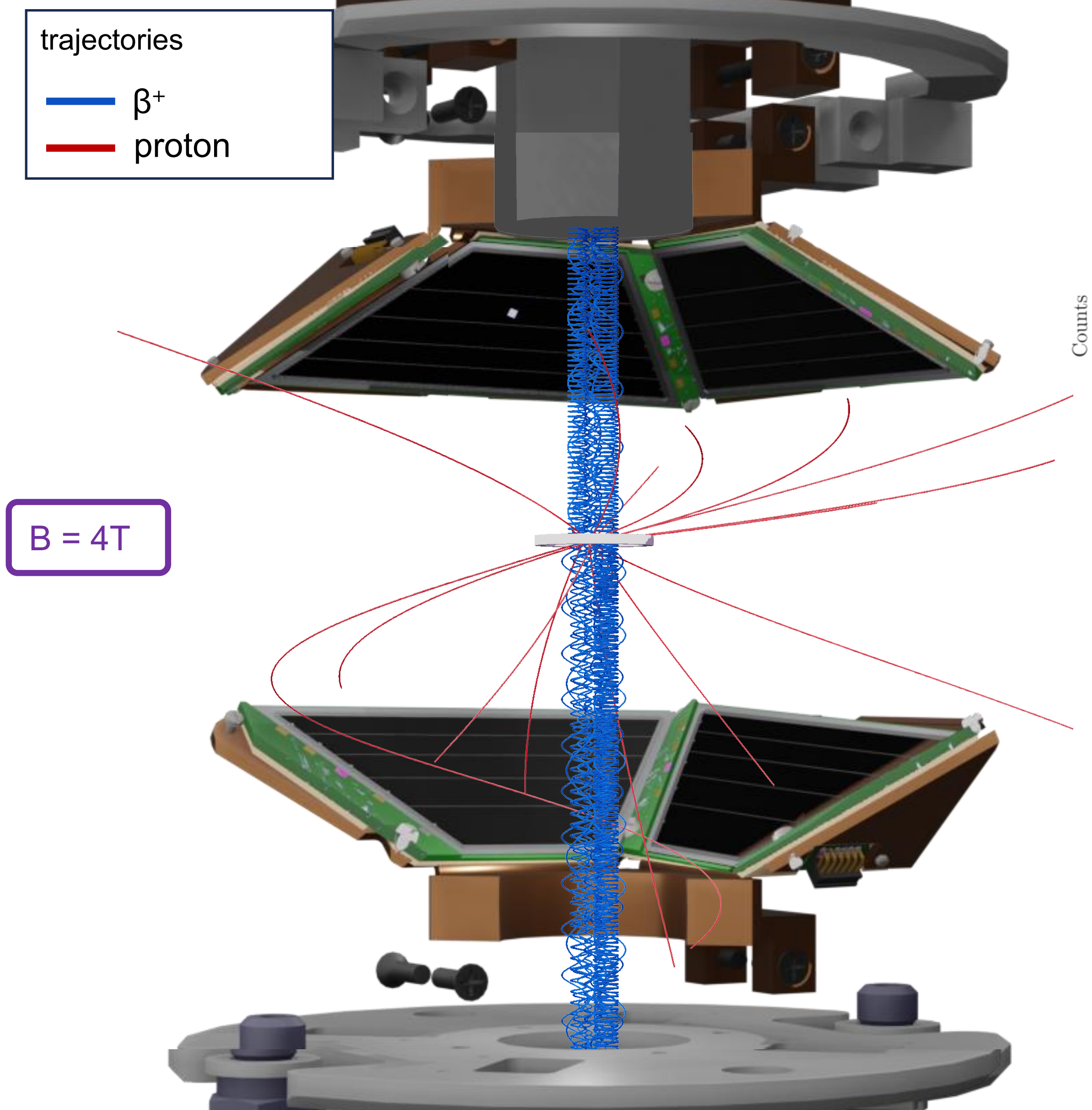
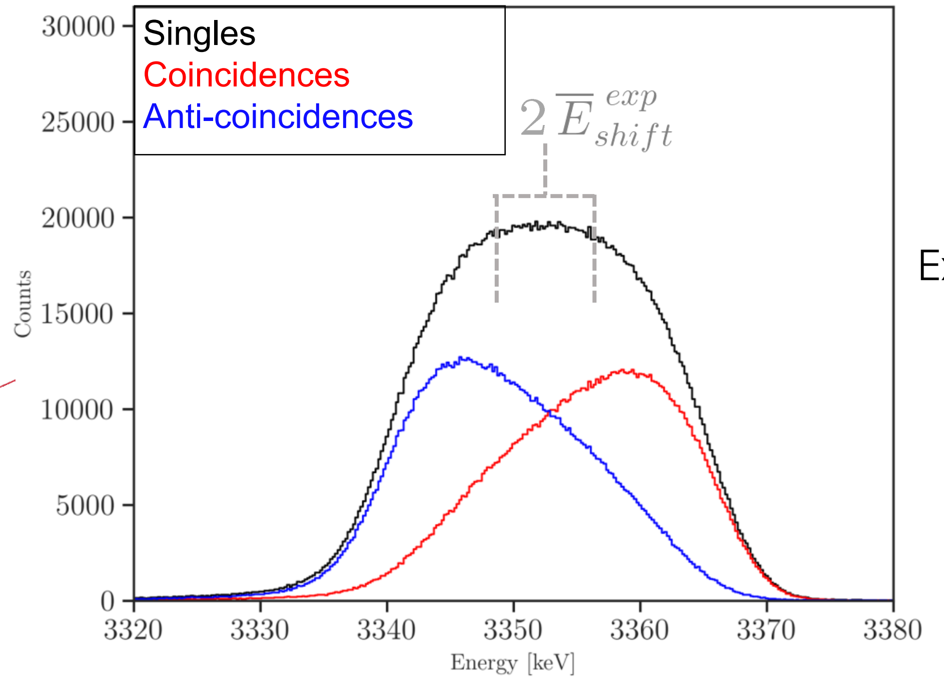
$$\boxed{\overline{E}_{shift} = \left|\overline{E}_{singles} - \overline{E}_{coinc}\right|} \longrightarrow \text{Simulations}$$

E_{shift} measurement



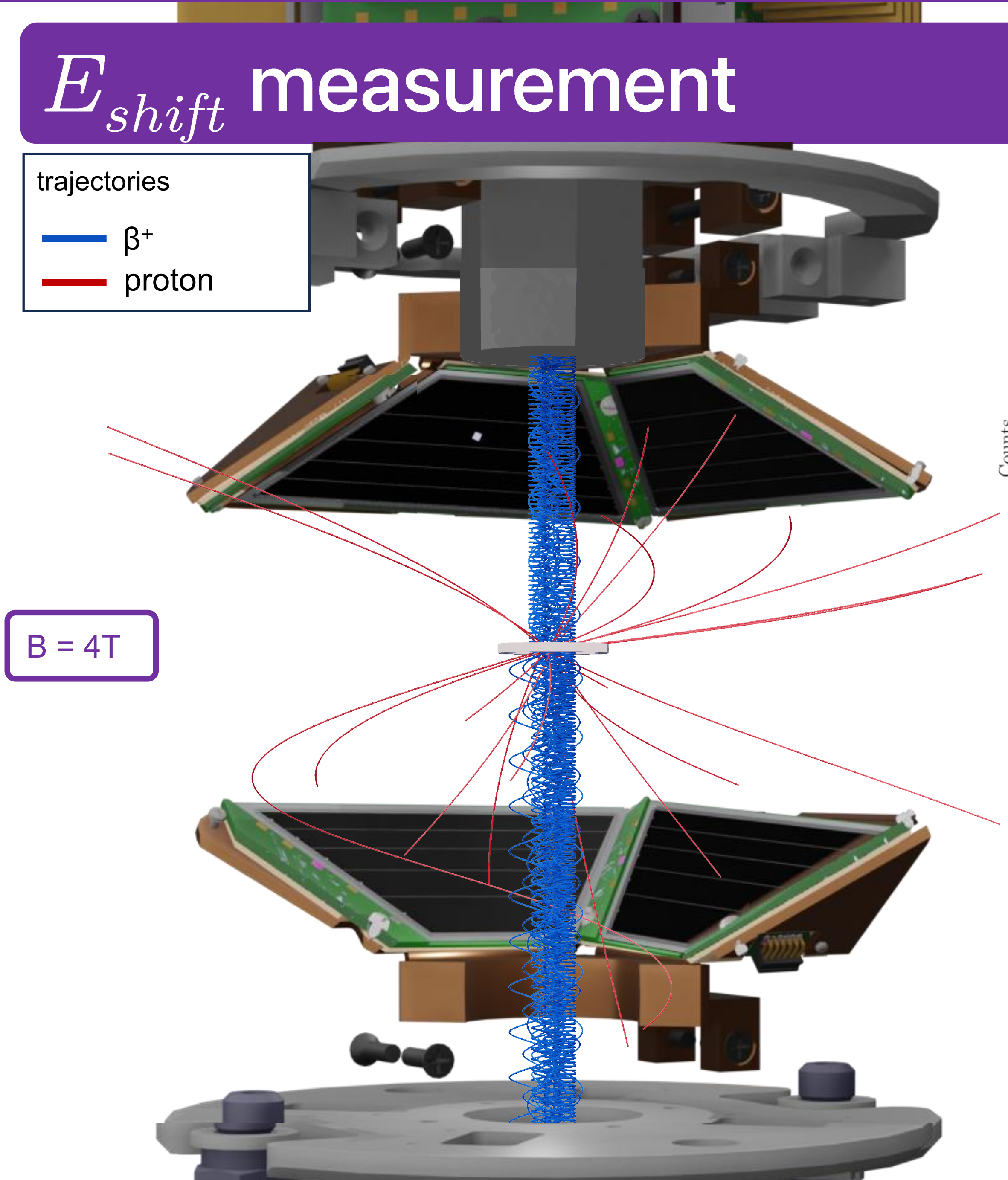


Experimental data (2025)

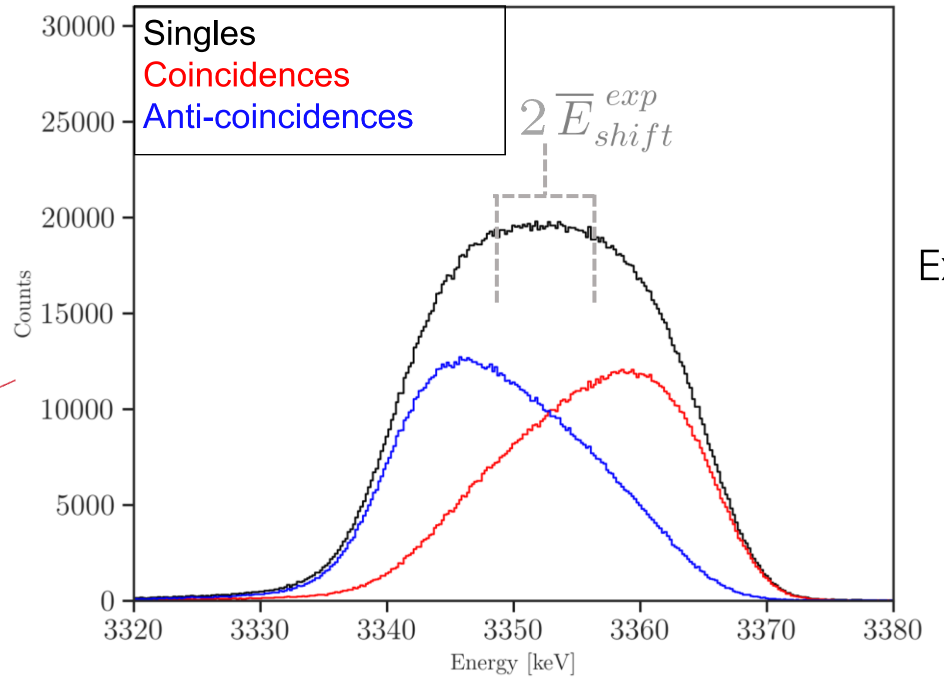
$$\overline{E}_{shift} = \left|\overline{E}_{singles} - \overline{E}_{coinc}\right|$$

→ Simulations

E_{shift} measurement



B = 4T



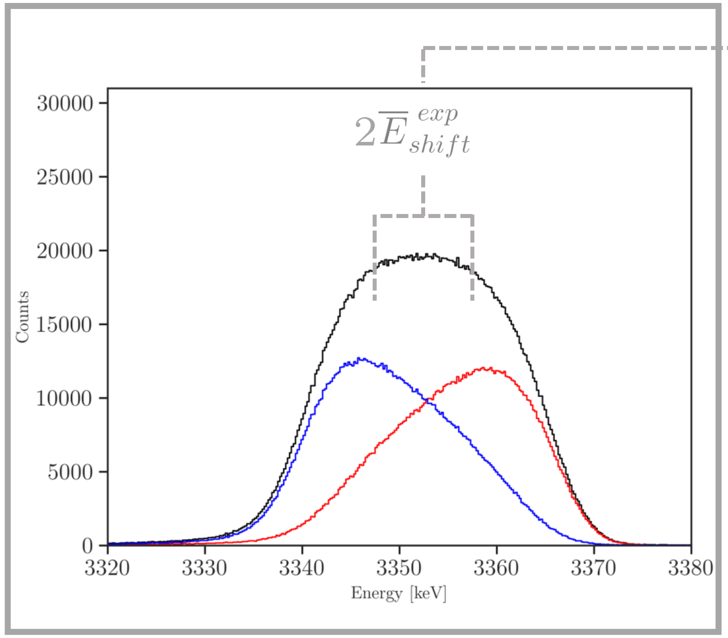
Experimental data (2025)

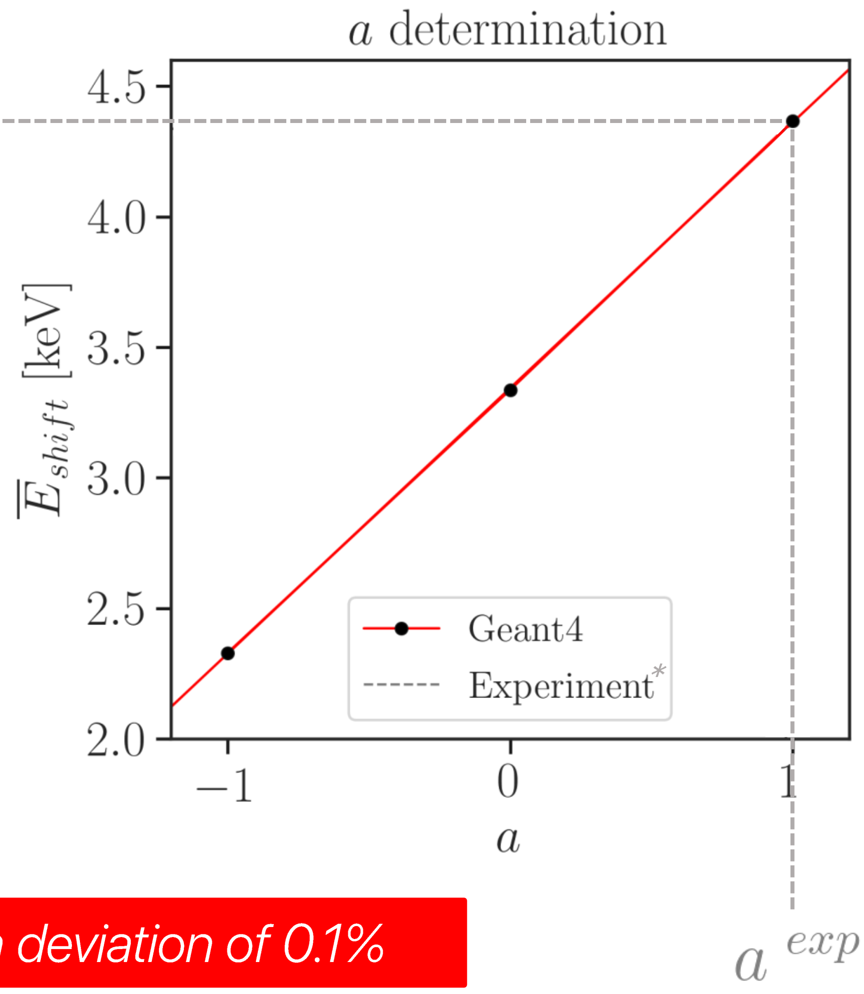
$$\overline{E}_{shift} = \left|\overline{E}_{singles} - \overline{E}_{coinc}\right|$$

→ Simulations

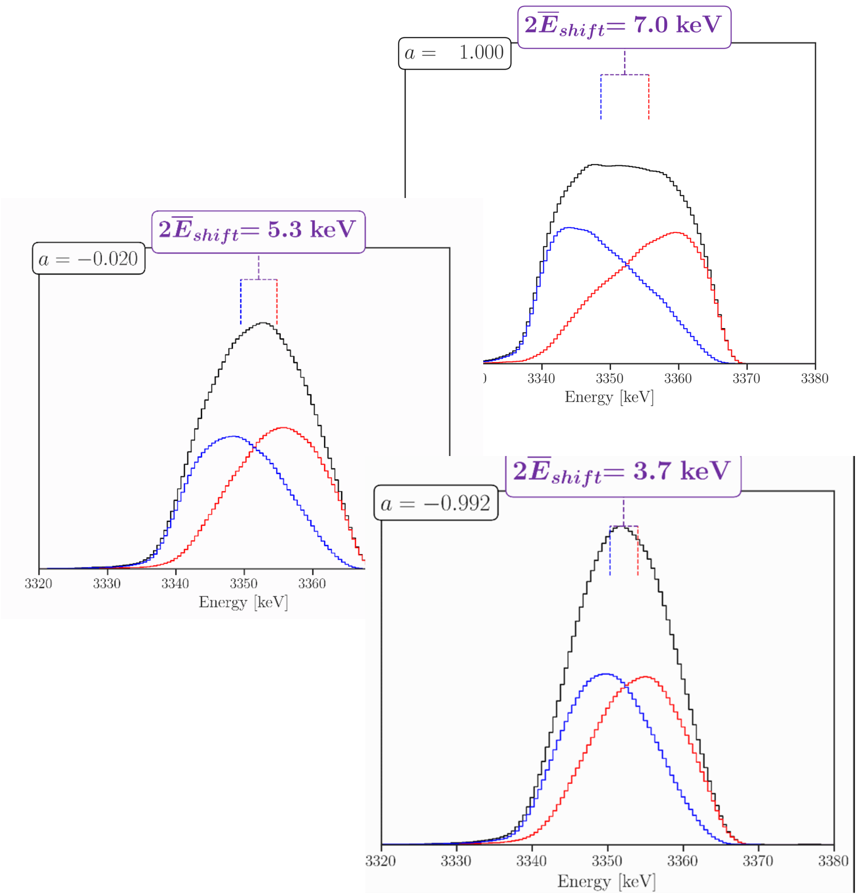
Extraction of a

Experiment
(2025)





Simulation



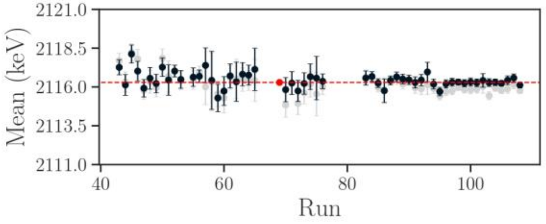
Keeping in mind that we look for a deviation of 0.1%

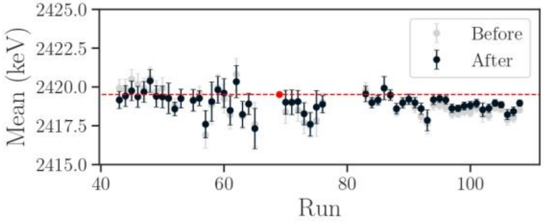
*illustrative data

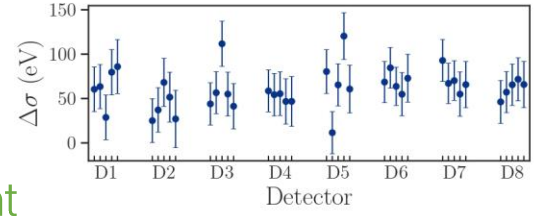
Current analysis status

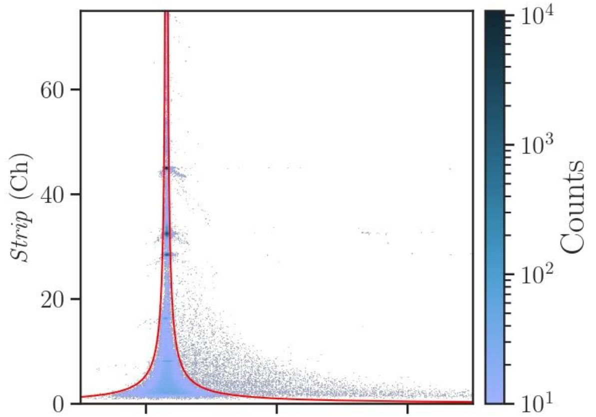
2024 / 2025:

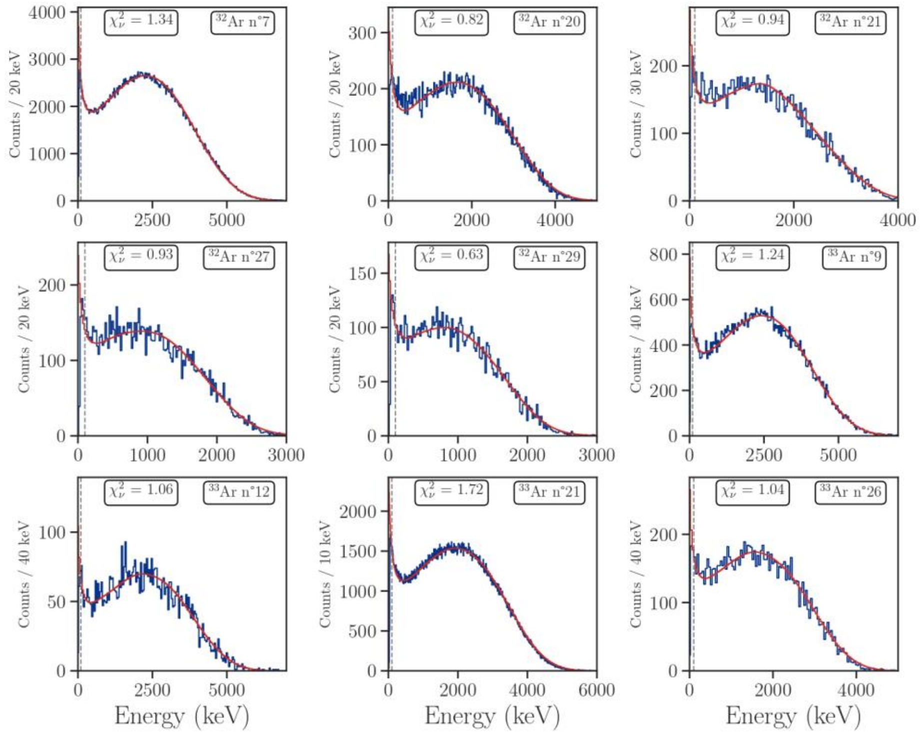
- Data cleaning and selection
- Walk effect corrected
- Gain matching along the experiment (silicon detectors + SiPM)
- x40 precise silicon detectors calibration
- Geant4 simulation adapted to both datasets with year dependent parameters + optimized for high-performance computing
- x9 SiPM calibration (on proton gated β-spectrum without sources)
- Absolute position of the catcher foil
- 4-body decay correction

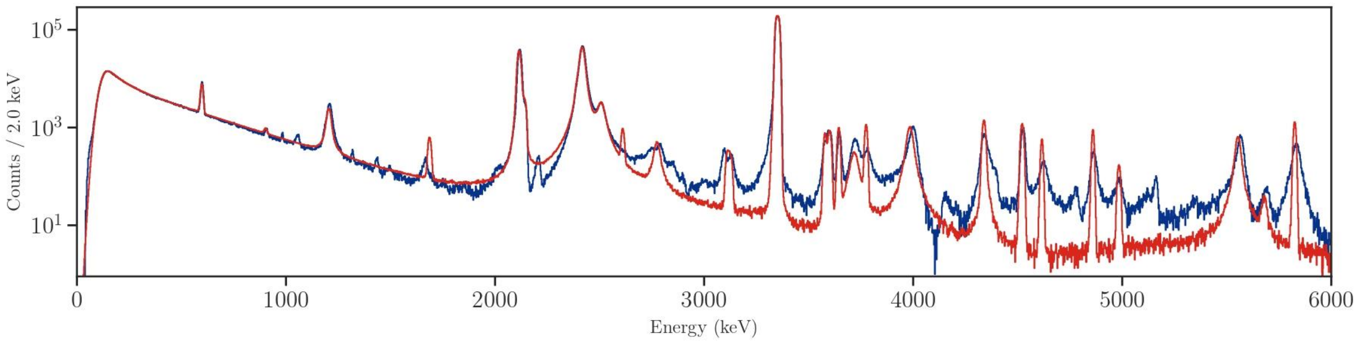






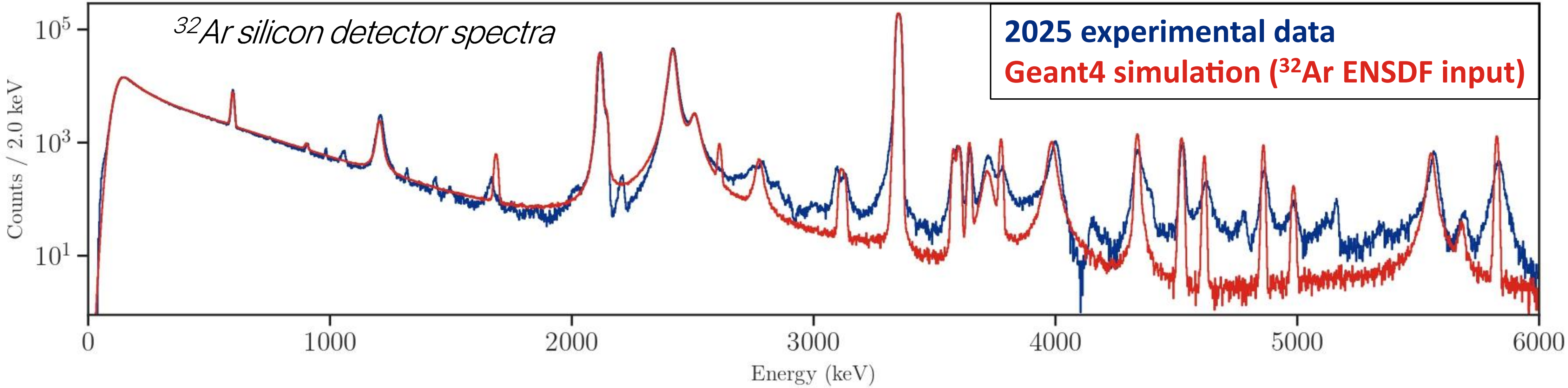






^{32,33}Ar spectroscopy

- Missing data in the literature: BR, proton channels, nuclear level width …



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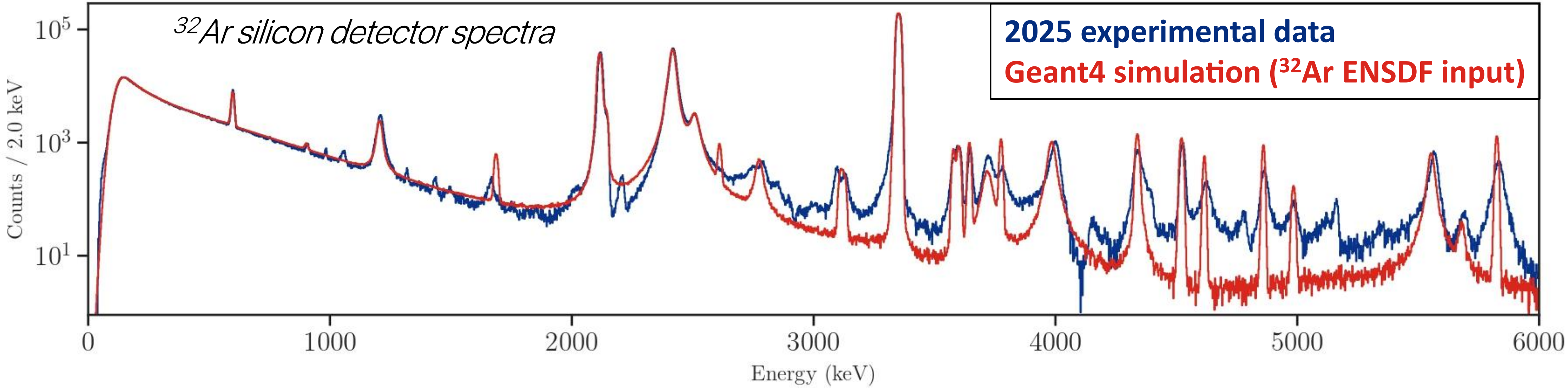

- **WISArD is a powerful tool for spectroscopy**
  - ΔE-E detector for decay product
  - ISOLDE t_0 send to the DAQ
  - High-resolution silicon detectors
  - β detector
  - High efficiency

- **Observables**
  - Particle identification
  - Precise proton/alpha energy $\mathbf{E_0}$
  - Nuclear level width $\mathbf{\Gamma_p}$
  - β spectrum $\mathbf{Q_\beta}$
  - Relative branching ratio **BR**
  - Half-life $\mathbf{T_{1/2}}$

Already new protons groups identified for ^{32}Ar and ^{33}Ar

On going analysis with B.Blank

Data taking

Statistical error

*V. Araujo-Escalona PhysRevC.101.055501 (2020)

2018*	200 000 events	$\Delta a = 0.037$
2021	700 000 events	$\Delta a = 0.017$
2024	12 000 000 events	$\Delta a = 0.004$
2025	6 000 000 events	$\Delta a = 0.005$

Systematic error

Main sources	Uncertainty				Improvement
	2018*	Δa x10^{-3}	2024/2025	Δa x10^{-3}	
β-backscattering	±15%	17	±3.5%	2.7	Thinner catcher, lower threshold
Dead layer thickness	430 ± 300 nm	12	92 ± 20 nm	0.4	New detectors
Catcher thickness	6.70 ± 0.15 μm	5	525 ± 30 nm	1.3	RBS measurement @ LP2IB
Source size/position	± 3 mm	1	± 0.1 mm	0.7	MCP beam profile
Detector position	± 1 mm	0.3	± 0.2 mm	0.3	CERN photogrammetry
Silicon calibration slope	0.3%	10	0.1%	2.0	^{33}Ar runs, new detectors
Lit. masses and energies	*Not estimated*		1σ	1.2	
β calibration	12 keV	15	< 5 keV	1.5	SiPM matrix & response function
GT peak contamination	*Not estimated*		1σ	1.2	

Published paper:
S. Lecanuet et al., NIMA, 2026, 11582

Data taking

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Systematic

Best measurement of $\tilde{a}_{\beta\upsilon}$ using ^{37m}K *(A.Gorelov and al. PRL 94 (2005) 142501)*:
$\tilde{a}_{\beta\upsilon}$ = 0.998(3)(4)

Preliminary precision of WISArD (2025):
$\tilde{a}_{\beta\upsilon}$ = x.xxx(5)(5)

Main sources					
β-backscattering					
Dead layer thickness					
Catcher thickness					
Source size/position	[illegible]	[illegible]	± 0.1 mm	0.7	MCP beam profile
Detector position	± 1 mm	0.3	± 0.2 mm	0.3	CERN photogrammetry
Silicon calibration slope	0.3%	10	0.1%	2.0	^{33}Ar runs, new detectors
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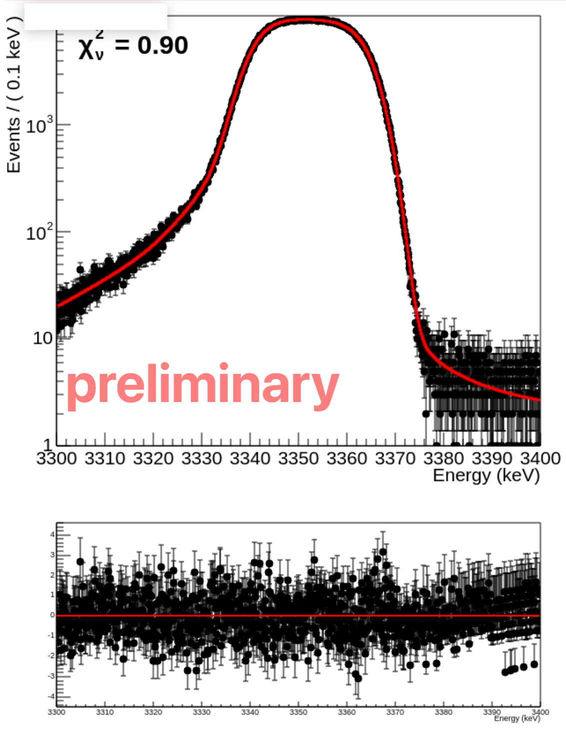
Next step for WISArD

Present status

- Ending the analysis of 2024/2025 data taking using βp
- Preliminary result using only protons:

Fitted proton peak shape on 2025 data

$$a = 1.0019(47)_{\text{stat}}(?)_{\text{sys}}$$



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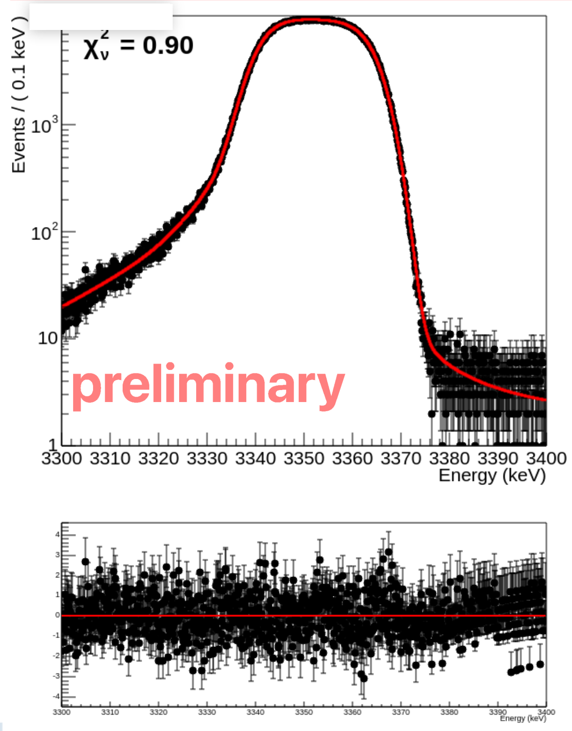
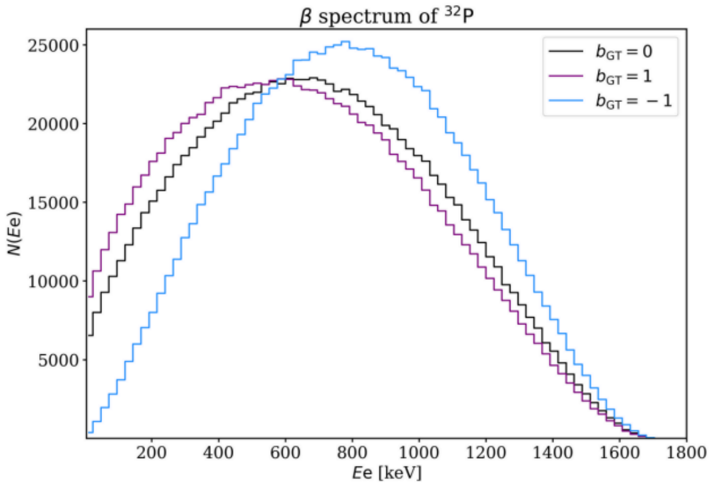


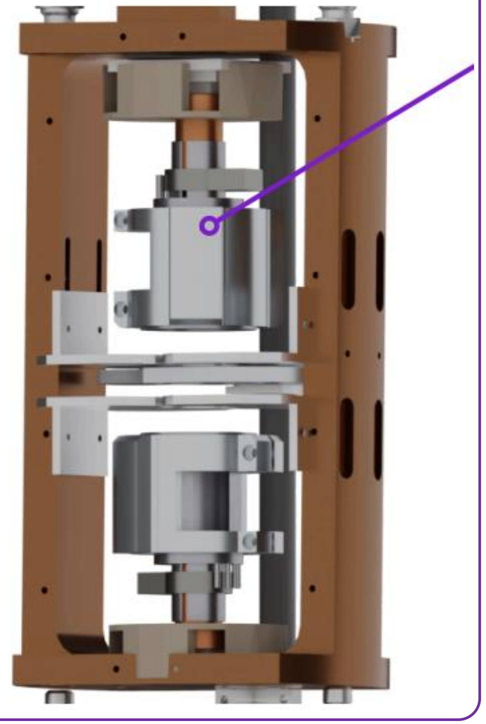
Next steps:

- New measurement with ^{32}Ar
- Other candidate for SM tests:
  - Pure Fermi β decay: ^{20}Mg
  - Pure Gamow-Teller β decay: ^{8}Li
- Spectroscopy on β-delayed α or p emitters

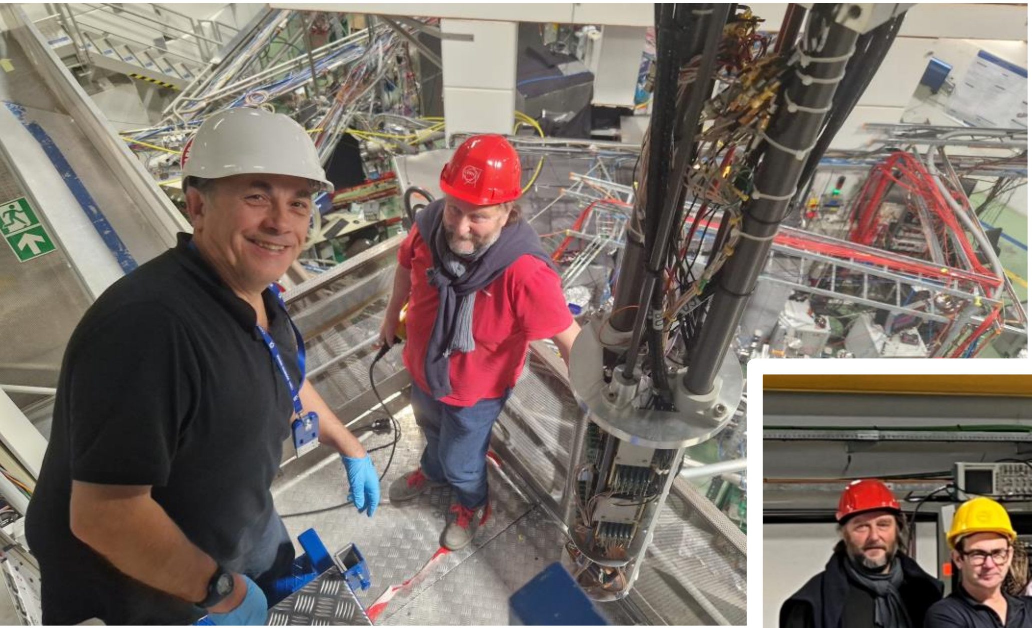
SPELS/InESS @ WISArD

- Spectrum shape measurement
- ^{114}In and ^{32}P
- SiLi detector at -70°C





Thanks for your attention!



P. Alfaurt, P. Ascher, D. Atanasov, B. Blank, L. Daudin, X. Fléchard, G. Frémont, M. Gerbaux, J. Giovinazzo, S. Grévy, J. Ha, C. Knapen, A. Lépine, R. Lica, M. Pomorski, M. Roche, N. Severijns, S. Vanlangendonck, M. Versteegen, D. Zakoucky

We acknowledge the support of the ISOLDE technical team

Weak interaction

Example of the β^+ decay : $u \longrightarrow d + e^+ + \nu_e$ $\quad {}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{X} \longrightarrow {}^{\mathrm{A}}_{\mathrm{Z-1}}\mathrm{X}' + e^+ + \nu_e$

$$\begin{aligned} \mathcal{L}_{Lee-Yang} = &+ \bar{p}\gamma^\mu n \bar{e}\gamma_\mu (C_V + C'_V\gamma_5)\nu \\ &- \bar{p}\gamma^\mu\gamma_5 n\bar{e}\gamma_\mu(C_A\gamma_5 + C'_A)\nu \\ &+ \bar{p}n\bar{e}(C_S + C'_S\gamma_5)\nu \\ &+ \frac{1}{2}\bar{p}\sigma^{\mu\nu}n\bar{e}\sigma_{\mu\nu}(C_T + C'_T\gamma_5)\nu \\ &- \bar{p}\gamma_5 n\bar{e}(C_P\gamma_5 + C'_P)\nu \\ &+ h.c \end{aligned}$$

→ Vector

→ Axial-Vector

→ Scalar

→ Tensor

→ Pseudo-Scalar (HEP)

Beyond Standard Model : $C_V = C'_V = 1 \quad C_A = C'_A \simeq 1.27 \qquad C_S = ? \quad C_T = ?$

Formulas back-up

$$a\xi = |M_F|^2(-C_S^2 - C_S'^2 + C_V^2 + C_V'^2) - \frac{|M_{GT}|^2}{3}(-C_T^2 - C_T'^2 + C_A^2 + C_A'^2)$$

$$b\xi = 2|M_F|^2(C_S C_V + C_S' C_V') + 2|M_{GT}|^2(C_T C_A + C_T' C_A')$$

$$\xi = |M_F|^2(C_S^2 + C_S'^2 + C_V^2 + C_V'^2) + |M_{GT}|^2(C_T^2 + C_T'^2 + C_A^2 + C_A'^2)$$

$$\frac{d\Gamma_i}{dE_e d\Omega_e d\Omega_\nu} = \hat{\xi}_i \frac{M_F^2}{64\pi^5} F_i(\Delta_i - E_e)^2 p_e E_e \left\{1 + b_i \frac{m_e}{E_e} + a_i \frac{\vec{p}_e}{E_e}\cdot\frac{\vec{p}_\nu}{E_\nu} + A_i \frac{\vec{p}_e}{E_e}\cdot\frac{\langle\vec{J}\rangle}{J} + B_i \frac{\vec{p}_\nu}{E_\nu}\cdot\frac{\langle\vec{J}\rangle}{J} \right.$$
$$\left. + c_i\left[\frac{\vec{p}_e\cdot\vec{p}_\nu}{3E_e E_\nu} - \frac{(\vec{p}_e\cdot\vec{j})(\vec{p}_\nu\cdot\vec{j})}{E_e E_\nu}\right]\left[\frac{J(J+1) - 3(\langle\vec{J}\rangle\cdot\vec{j})^2}{J(2J-1)}\right]\right\}$$

High precision measurement

Some previous measurements:

Delayed gamma of ^{18}Ne (1997): $a = 1.06(19)$ *V.Egorov and al. Nucl. Phys. A, 621 (1997), 745*

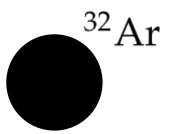
Delayed proton of ^{32}Ar (1999): $\tilde{a} = 0.9989(52)_{stat}(39)_{sys}$ *Adelberger and al. PRL 83 (1999) 1299*

Recoil of ^{38m}K (2005): $\tilde{a} = 0.9981(30)_{stat}(37)_{sys}$ *A.Gorelov and al. PRL 94 (2005) 142501*

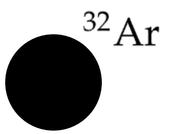
WISArD (2018): $\tilde{a} = 1.01(3)_{stat}(2)_{sys}$ *V.Araujo-Escalona and al. PRC 101 (2020) 5, 055501*

Perfect case vs reality

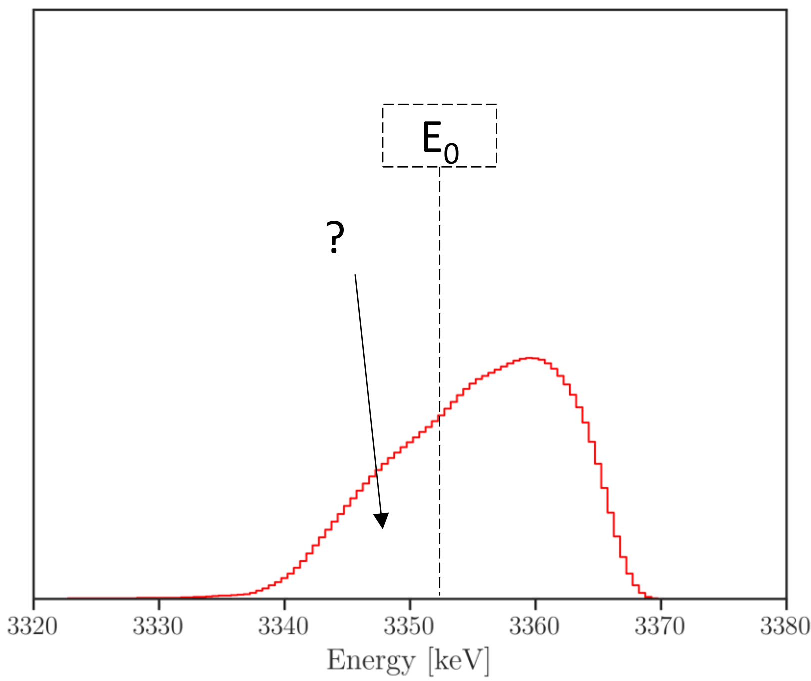
At rest:



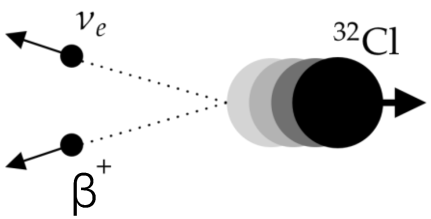
At rest:



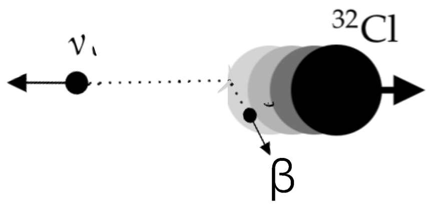
Proton peak



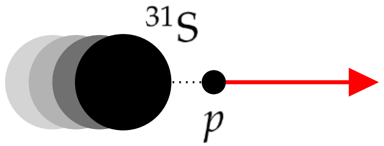
β-decay:



β-decay: Asymmetric energy repartition

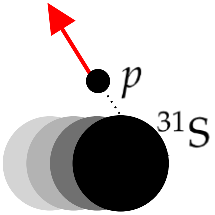


Delayed proton emission:



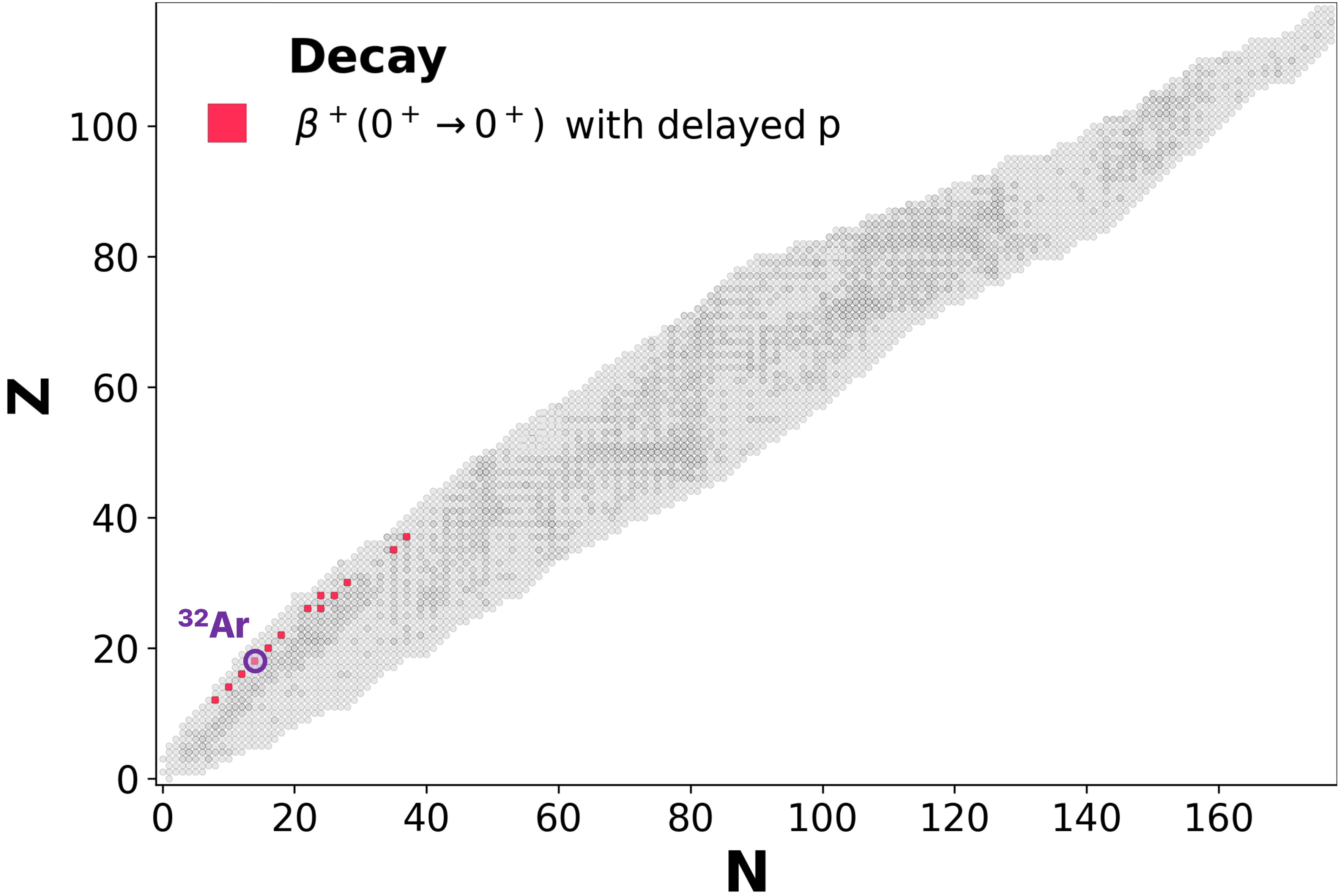
Energy increasing

Delayed proton emission:



Energy decreasing

Why ^{32}Ar?



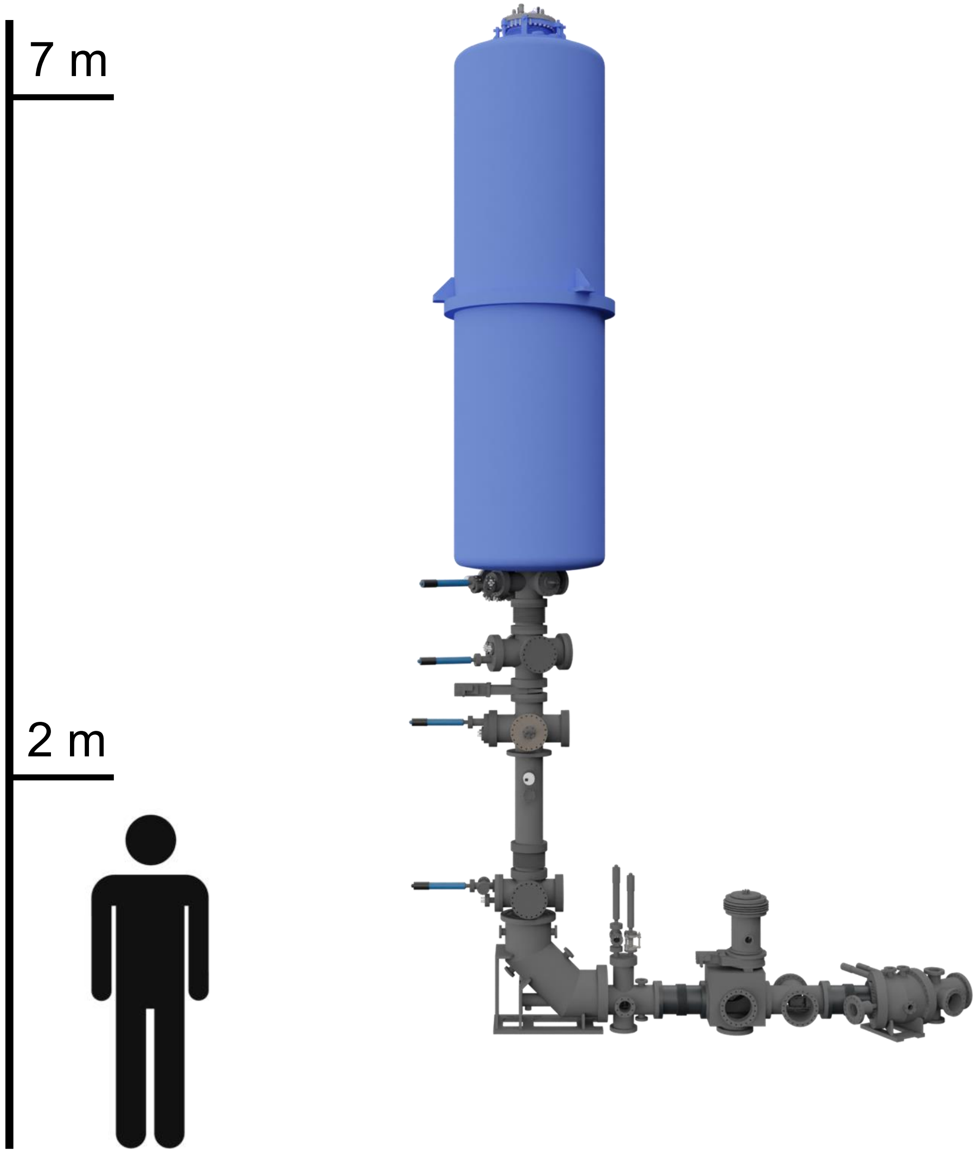
Requirement:

- β – decay
- $0^+ \rightarrow 0^+$
- delayed emission
- High production rate in facilities

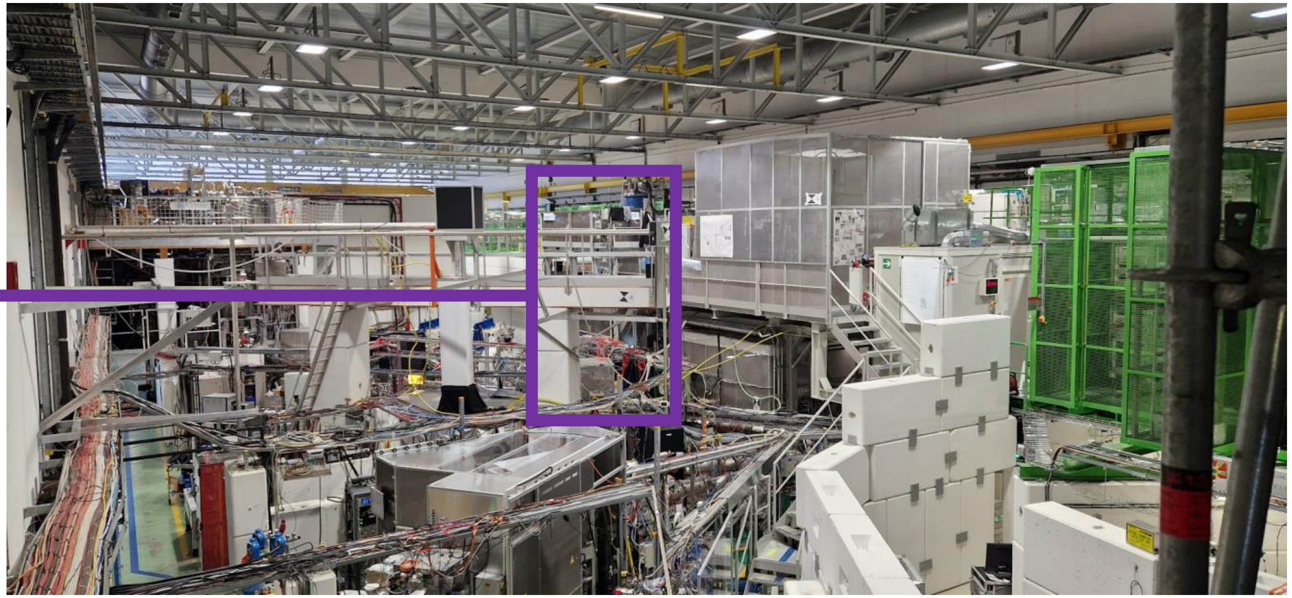
Sensitivity:

- 1 / Mass
- Q_β
- $\sqrt{E_0}$ delayed

WISArD beam line

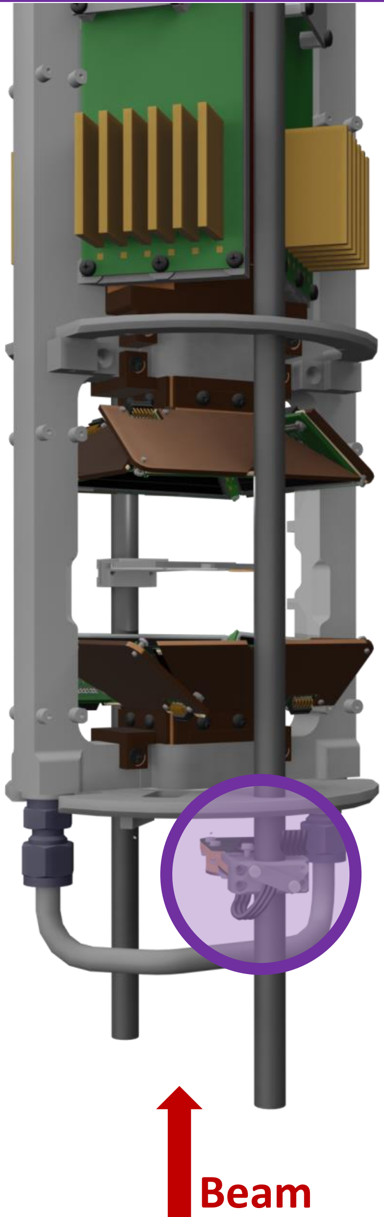


ISOLDE hall



^{32}Ar beam from ISOLDE

WISArD: MCP

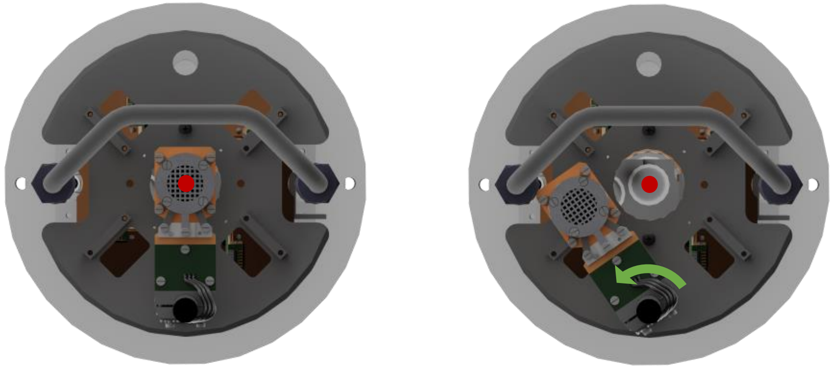


B = 4T

2 mechanical positions: bottom view

MCP measurement

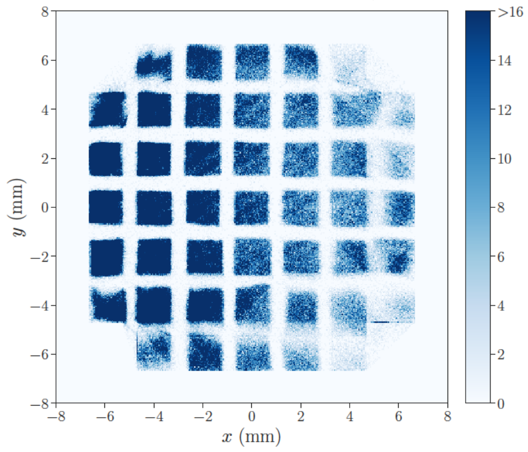
Decay measurement



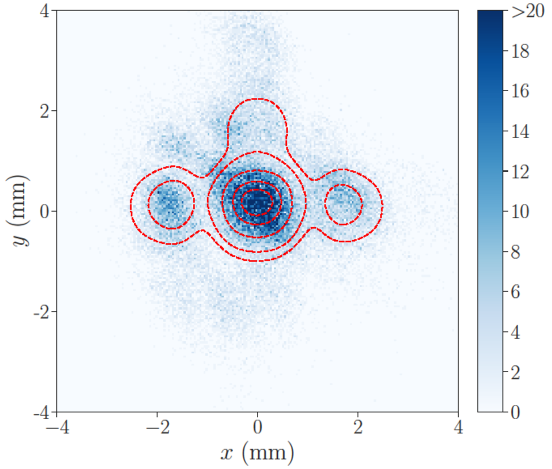
● Beam

Beam scan at 0T

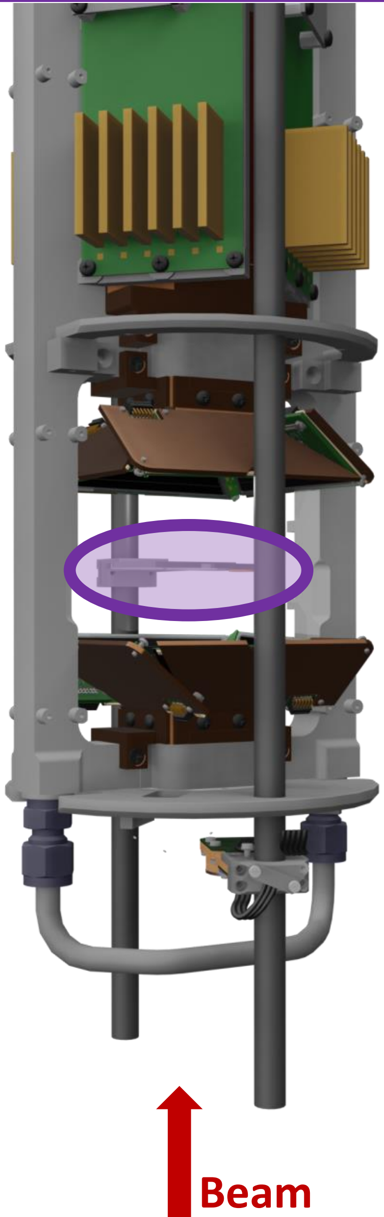
Reconstructed image



^{32}Ar Beam at 4T

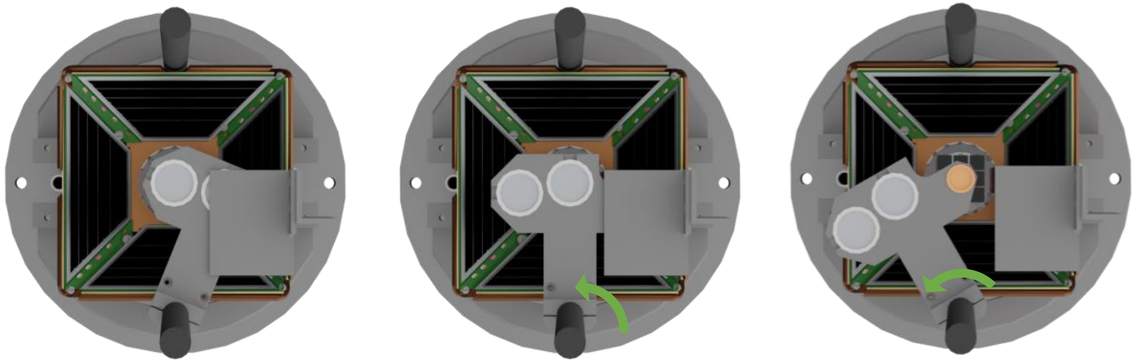


WISArD: Catcher



B = 4T

3 mechanical positions: bottom view



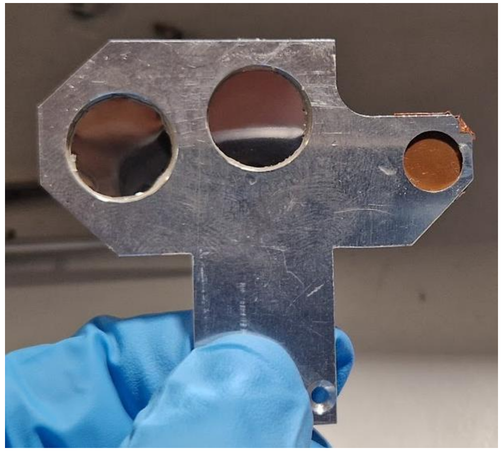
Catcher support:

- Thin catcher 0.6 µm
- Thick catcher 6 µm

Foil: Al - Mylar - Al

- α source (^{208}Po)

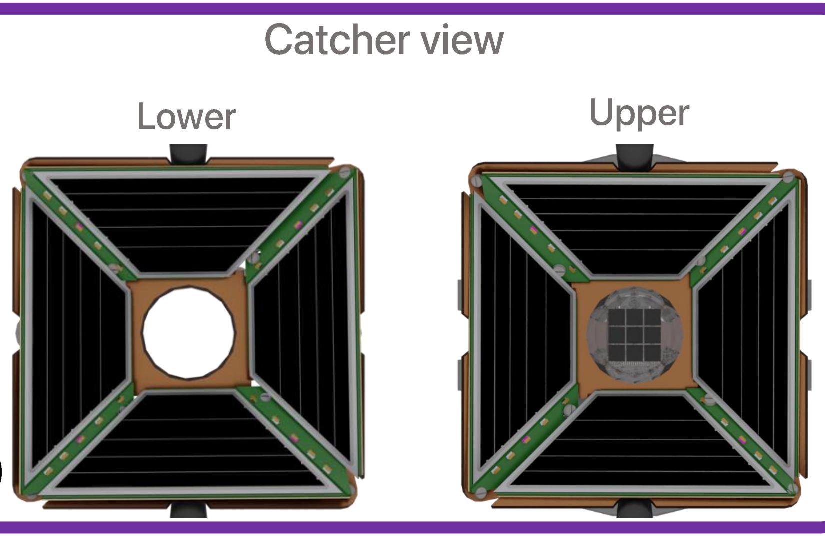
Catchers made by GANIL

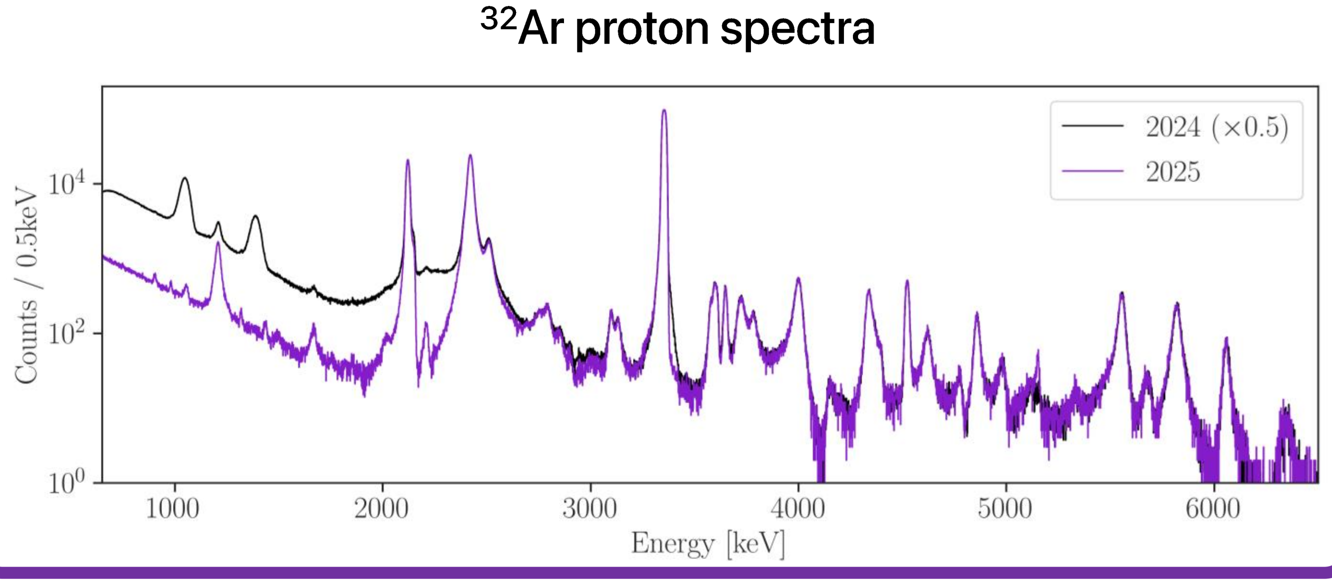


WISArD: proton detection

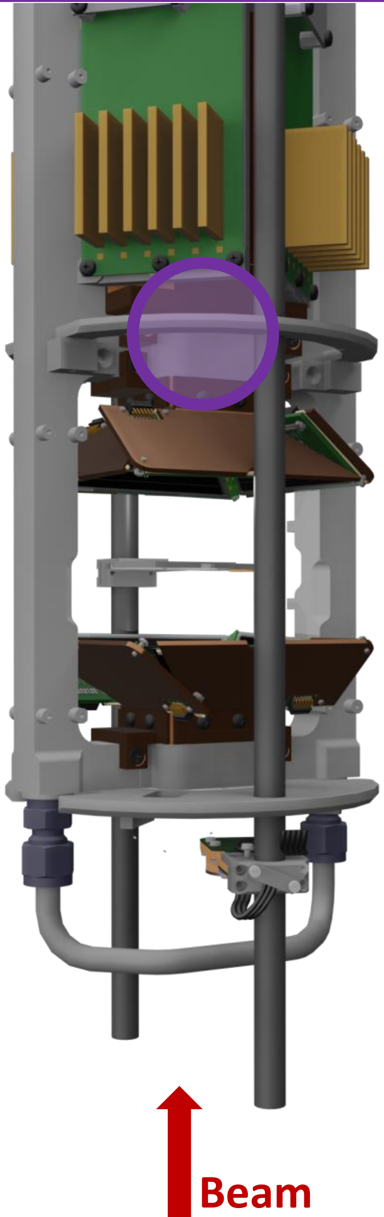
8 Silicon detectors:

- Thickness: 300 µm
- Dead-Layer: 92(20) nm
- Strips: 5
- Proton resolution: ~10keV FWHM
- Total solid angle: ~40%
- Interstrip geometry (RBS + AFM @ LOMA)





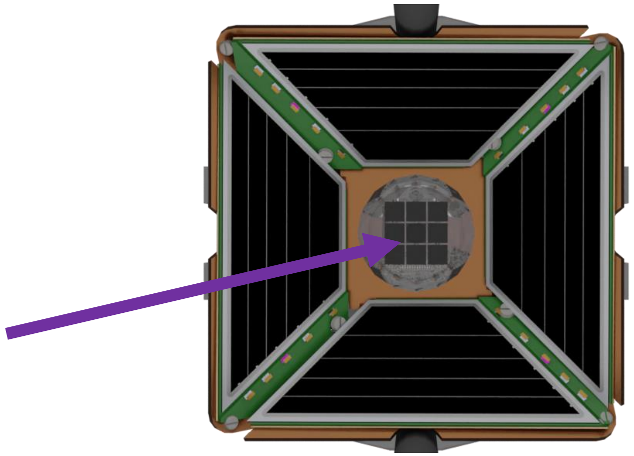
WISArD: β detection



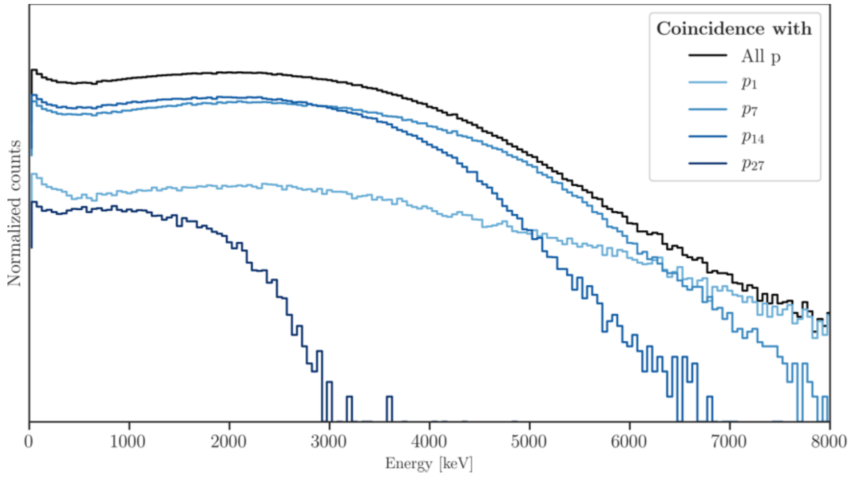
T_{det} = -20°C

B = 4T

SiPMs + plastic scintillator



^{32}Ar SiPM β-spectra



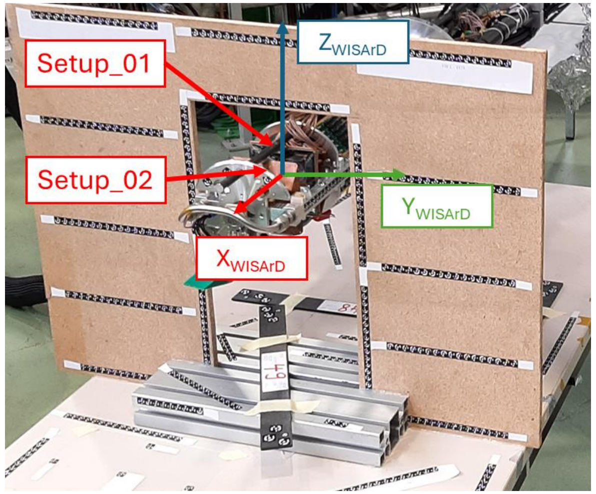
Silicon detectors position

Will change:
- Solid angle
- Energy loss

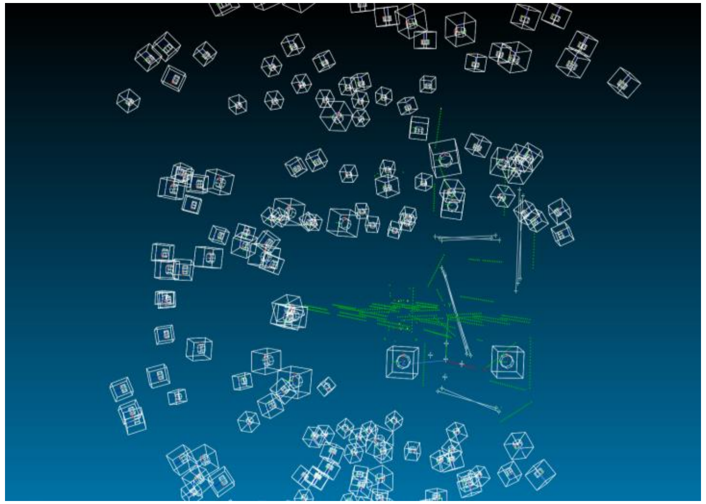
Impact on:
- E_{shift}
- Branching ratio (spectroscopy purpose)

Position measurement made by a CERN team
- Precision requested: < 0.5 mm
- Photogrammetry
- Measurement in an arbitrary reference frame

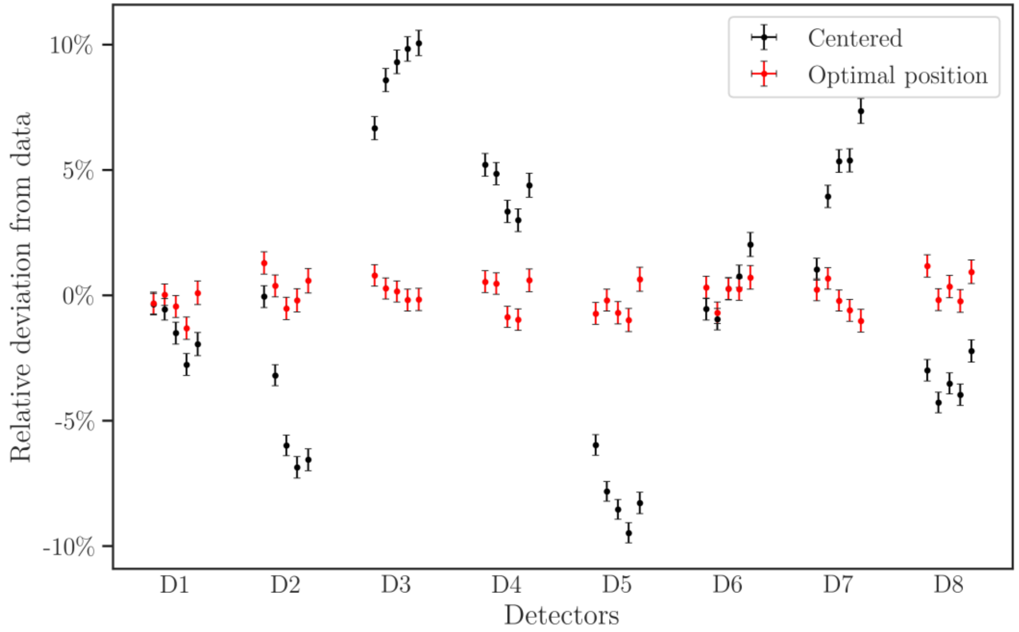
Setup



Software reconstruction



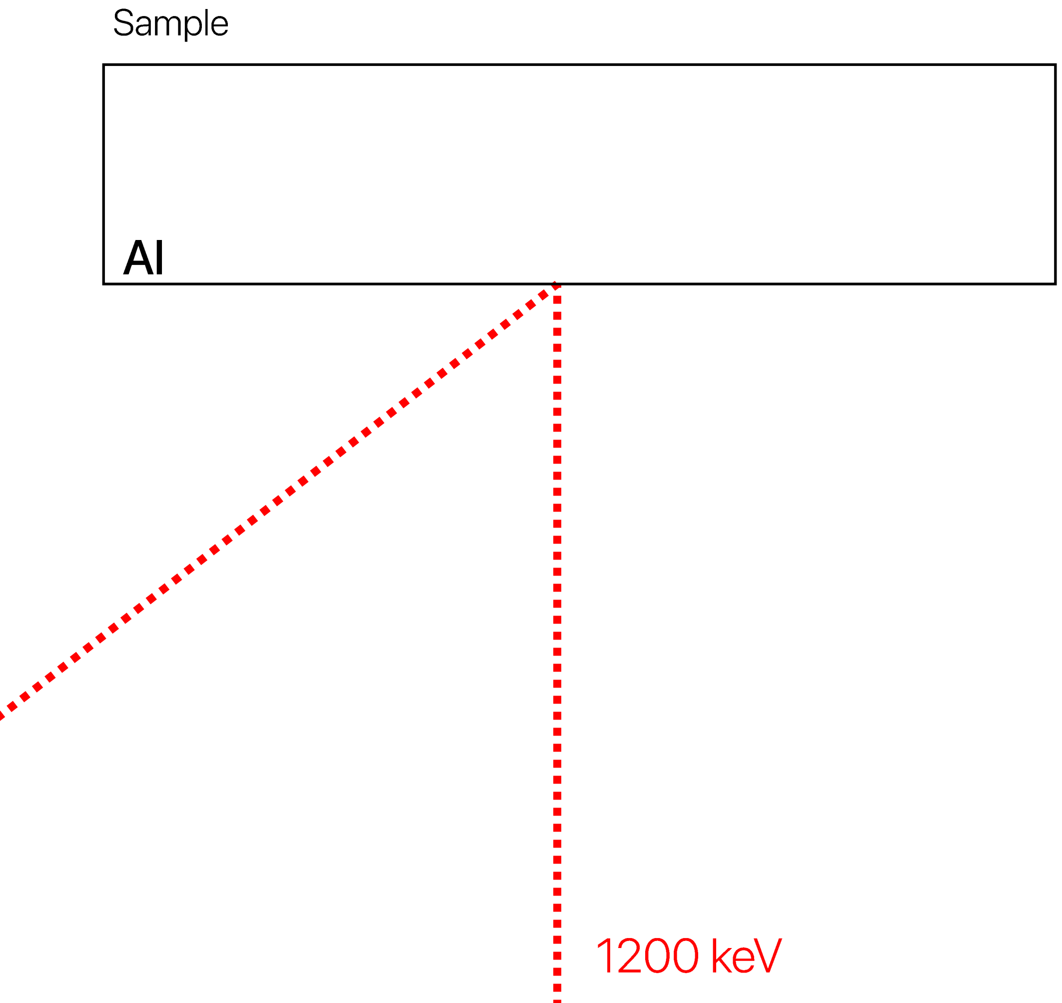
Position of Silicon detectors reference frame in Geant4



Catcher thickness

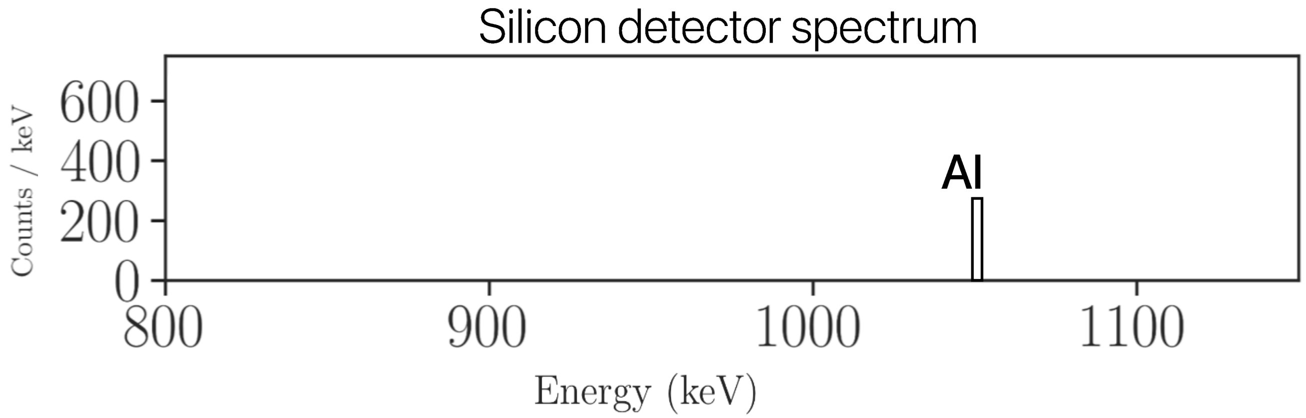
Rutherford Backscattering Spectroscopy:

- Used to analyze composition and/or thickness of samples with ion beam



Elastic collision condition:

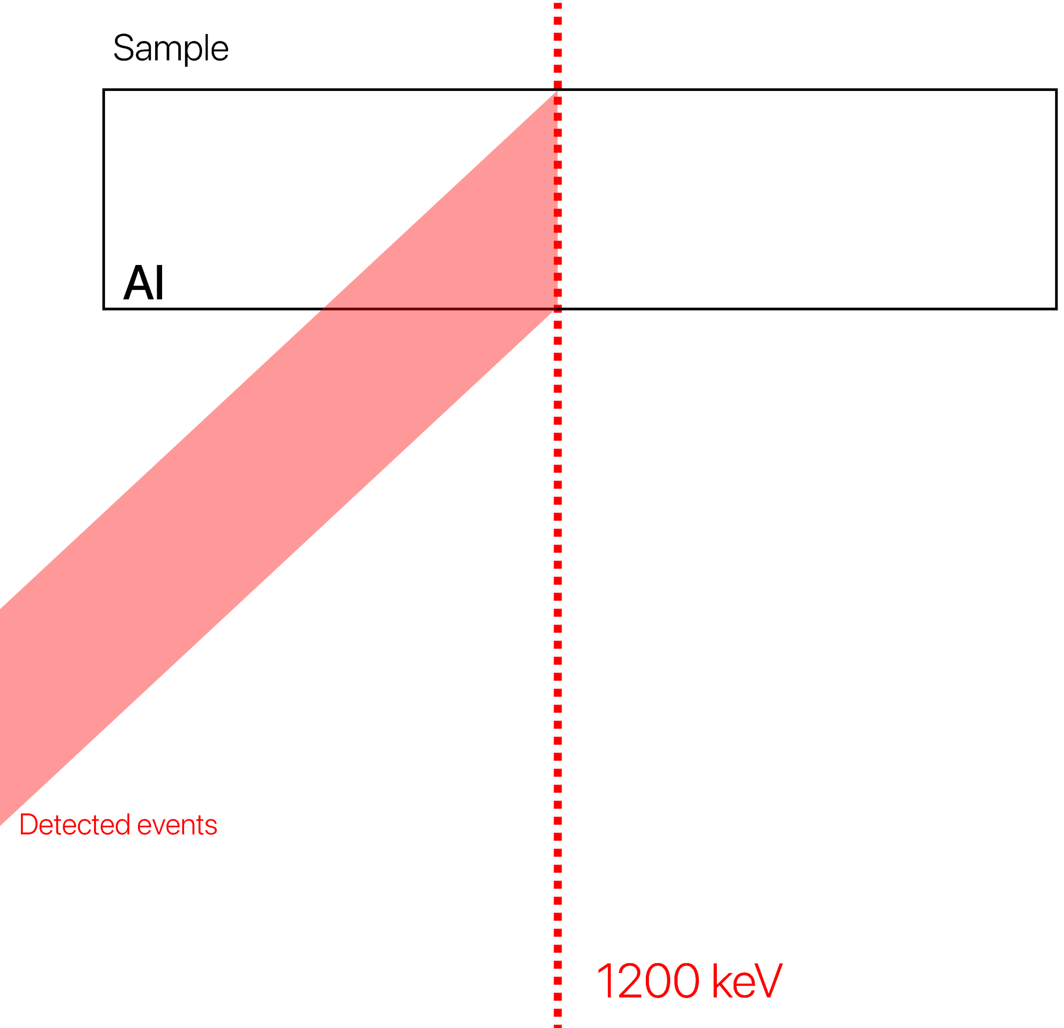
- Sample: Al
- Beam: H^+
- Angle 135°
- Energy: 1200 keV



Catcher thickness

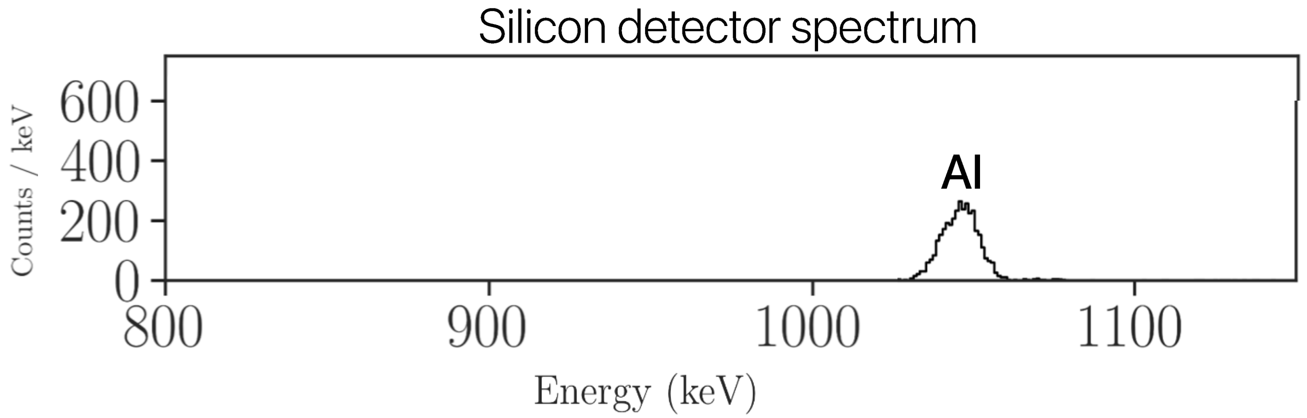
Rutherford Backscattering Spectroscopy:

- Used to analyze composition and/or thickness of samples with ion beam



Elastic collision condition:

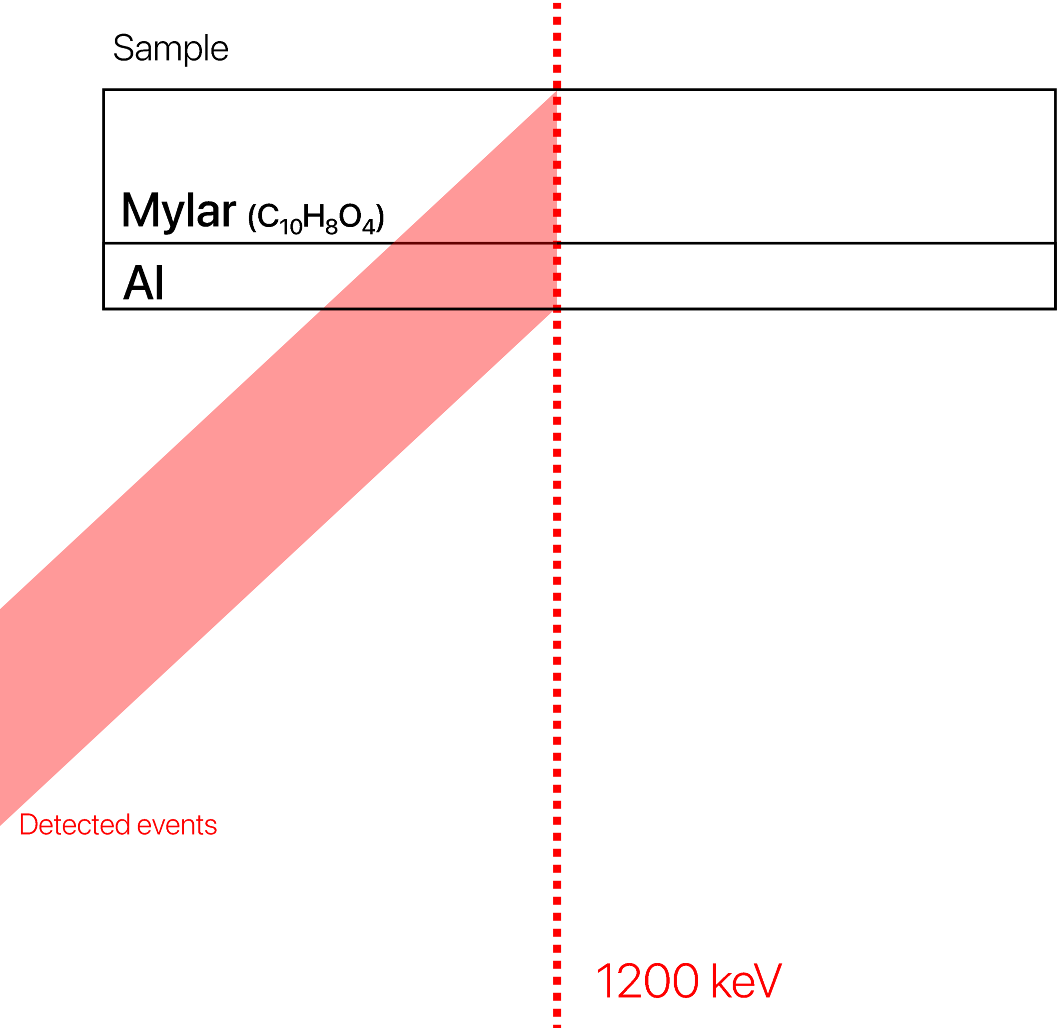
- Sample: Al
- Beam: H^+
- Angle 135°
- Energy: 1200 keV



Catcher thickness

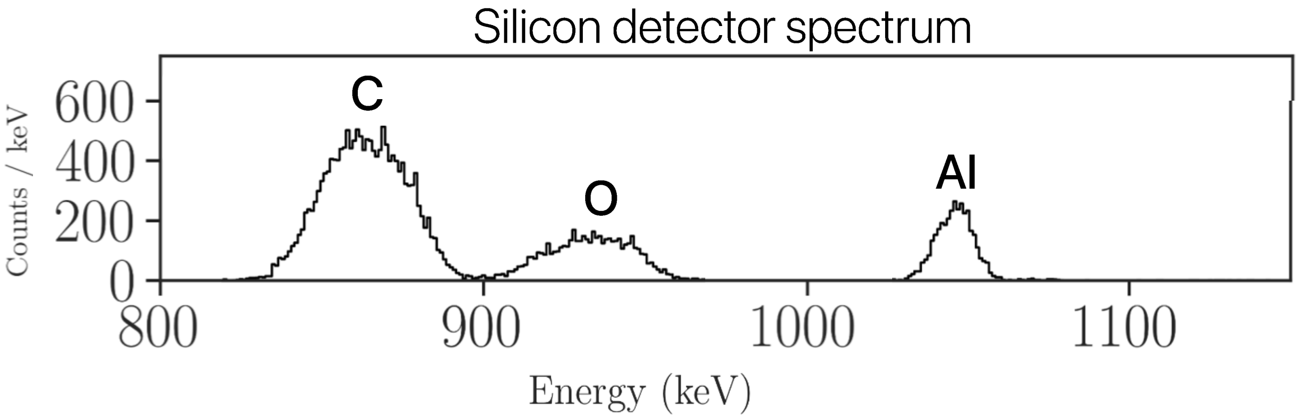
Rutherford Backscattering Spectroscopy:

- Used to analyze composition and/or thickness of samples with ion beam



Elastic collision condition:

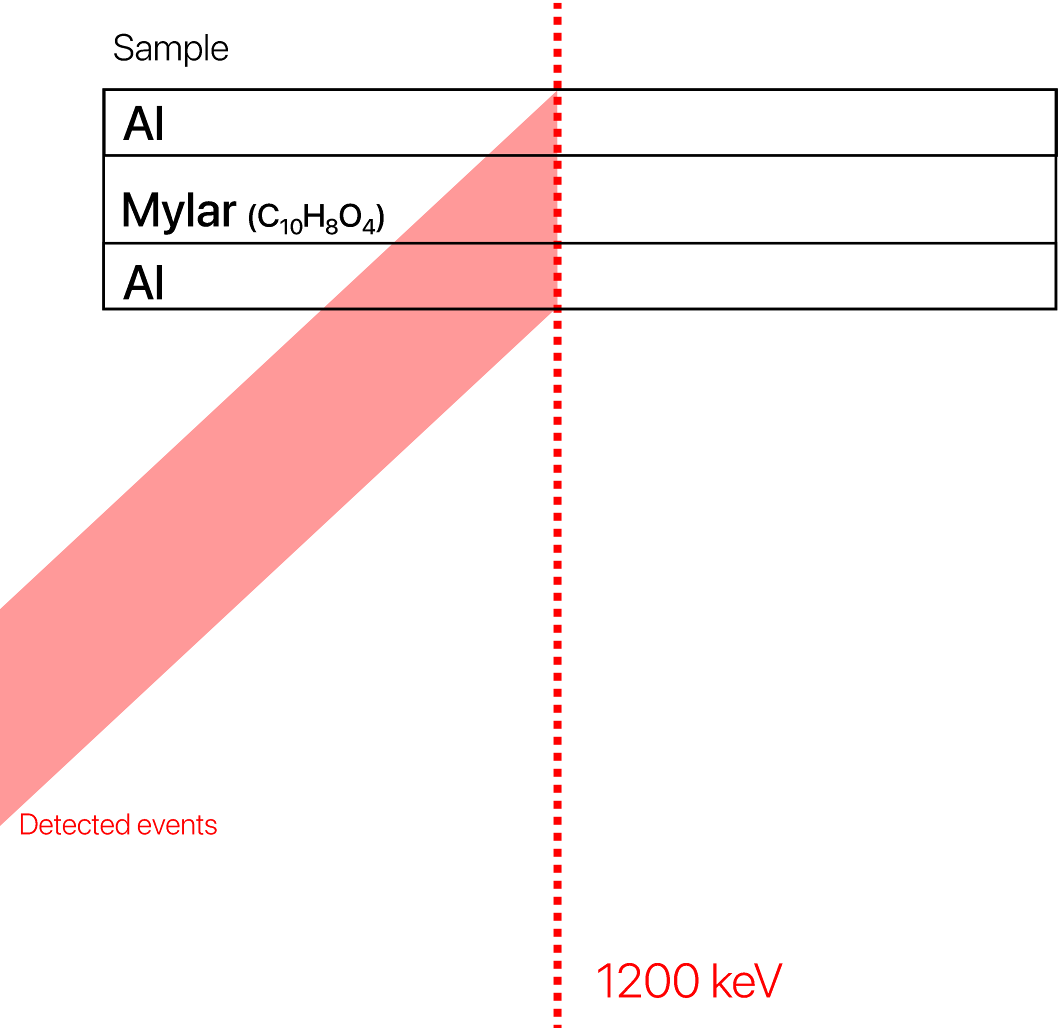
- Sample: Al-Mylar
- Beam: H^+
- Angle 135°
- Energy: 1200 keV



Catcher thickness

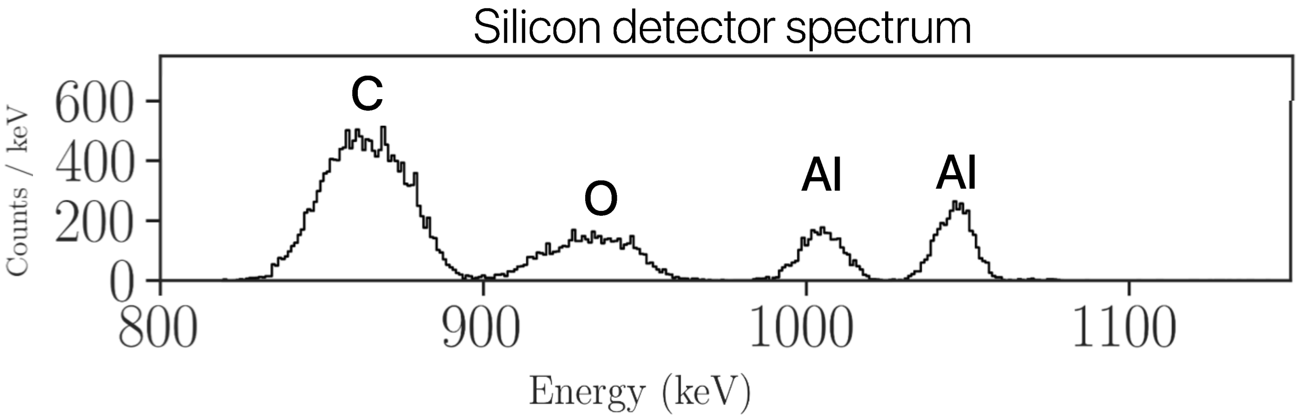
Rutherford Backscattering Spectroscopy:

- Used to analyze composition and/or thickness of samples with ion beam



Elastic collision condition:

- Sample: Al
- Beam: H^+
- Angle 135°
- Energy: 1200 keV



Catcher thickness

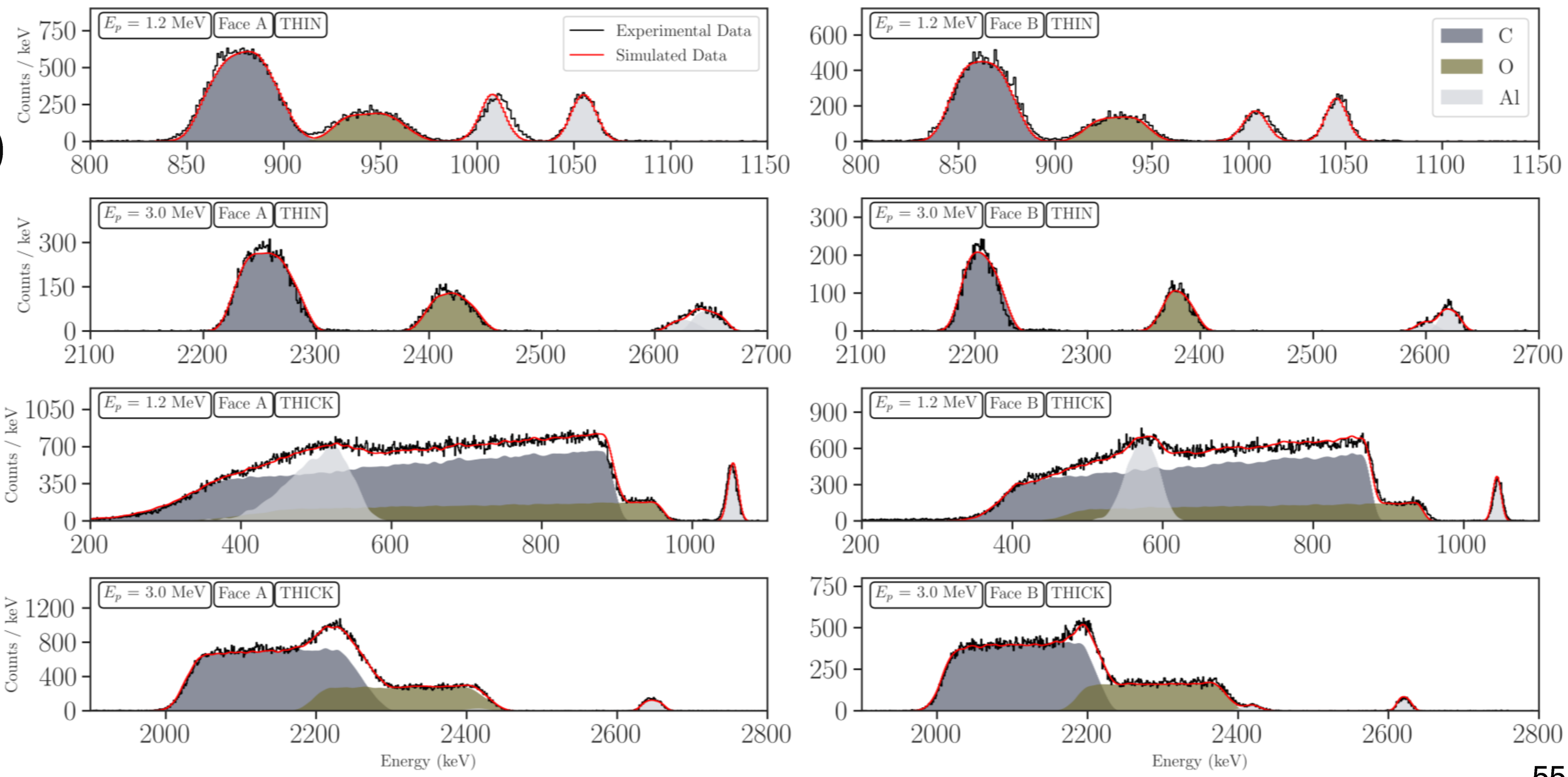
Will change:
- Energy loss → calibration
- β backscattering

Impact on:
- E_{shift}
- Proton energies (spectroscopy purpose)

RBS measurement @ AIFIRA:
- Beam: H^+ @ 1.2 and 3.0 MeV
- 2 catchers (6 µm and 0.5 µm)
- Both sides

Analysis:
- Auto-calibration method
- Geant4 simulations (fully custom and optimized implementation of RBS process)

Result:
- Al 85(10)nm + Mylar 525(15)nm
- Al 110(25)nm + Mylar 6100(35)nm

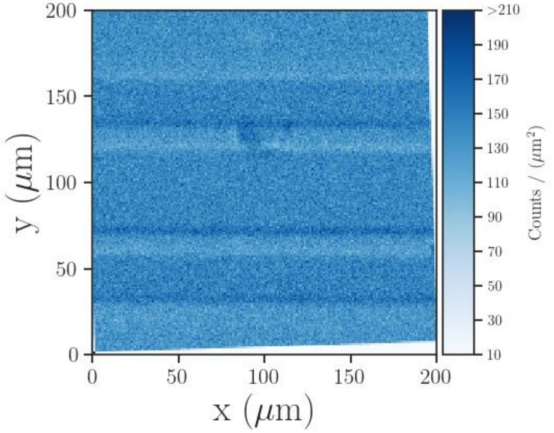


Thanks to J.Jouve and S.Sorieul

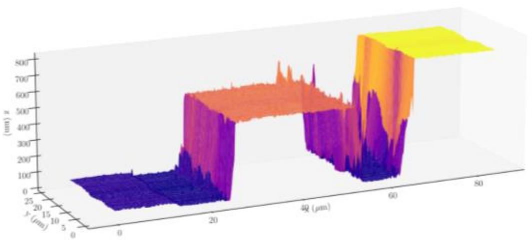
Silicon detectors interstrip geometry

Width

AIFIRA 2D beam scan

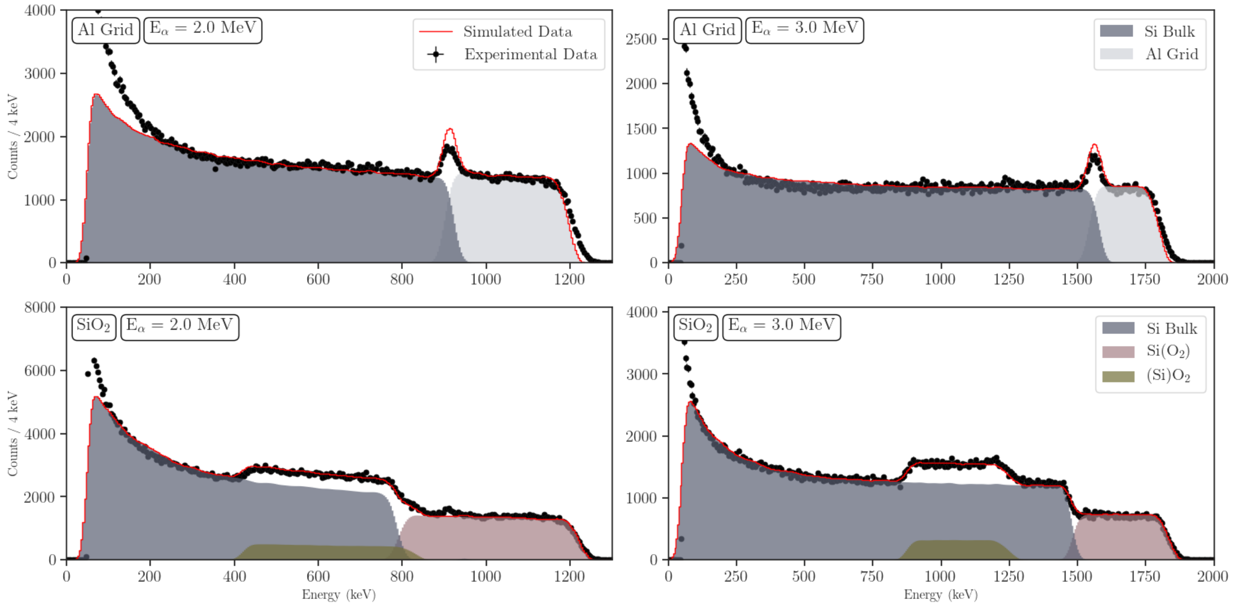


AFM 2D scan



Technique / Region	Si - Interstrip	Al - Grid	SiO2 Interstrip
AFM	12(2) um	28(1) um	-
MICROSCOPE	12(2) um	27(2) um	48(2) um
RBS	12(4) um	27(4) um	48(4) um

Composition and thickness

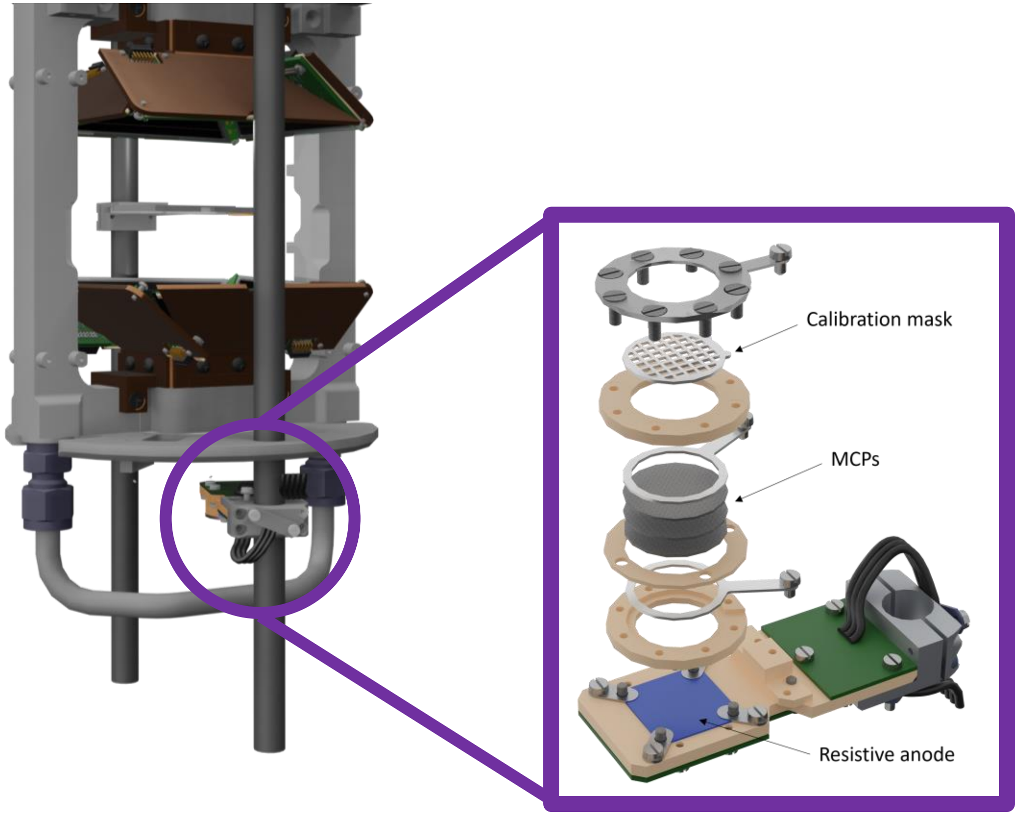


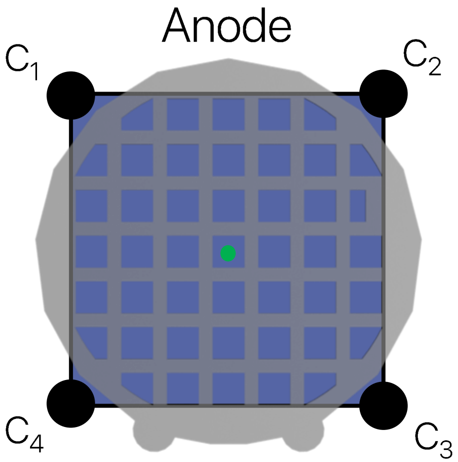
Beam characteristics

Will change:
- Solid angle
- β backscattering

Impact on:
- E_{shift}
- Branching ratio (spectroscopy purpose)

Position sensitive MCP





$$X = \frac{-C_1 + C_2 + C_3 - C_4}{C_\Sigma}$$
$$Y = \frac{+C_1 + C_2 - C_3 - C_4}{C_\Sigma}$$

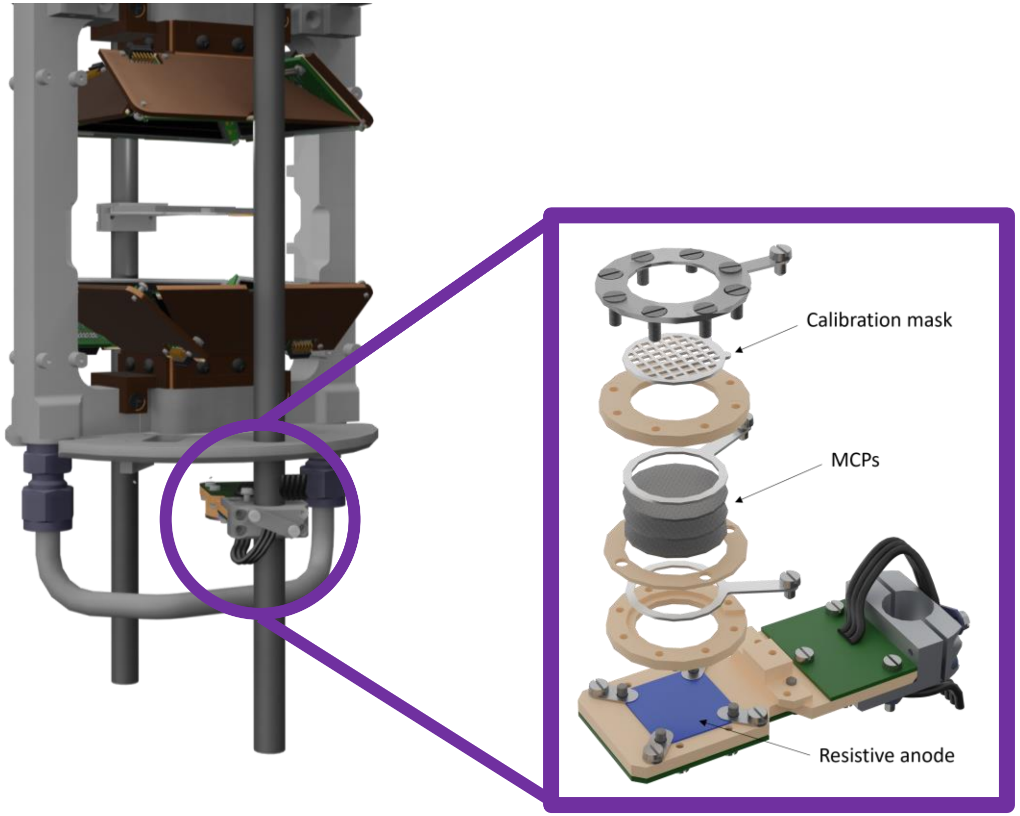
In preparation: S.Lecanuet et al.

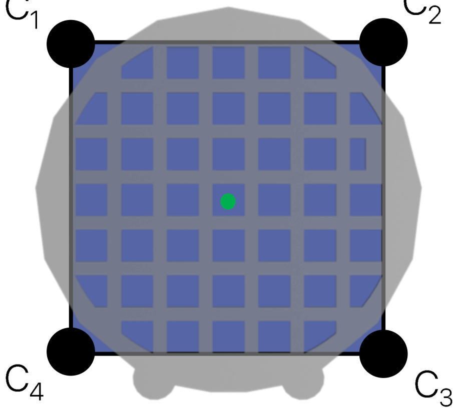
Beam characteristics

Will change:
- Solid angle
- β backscattering

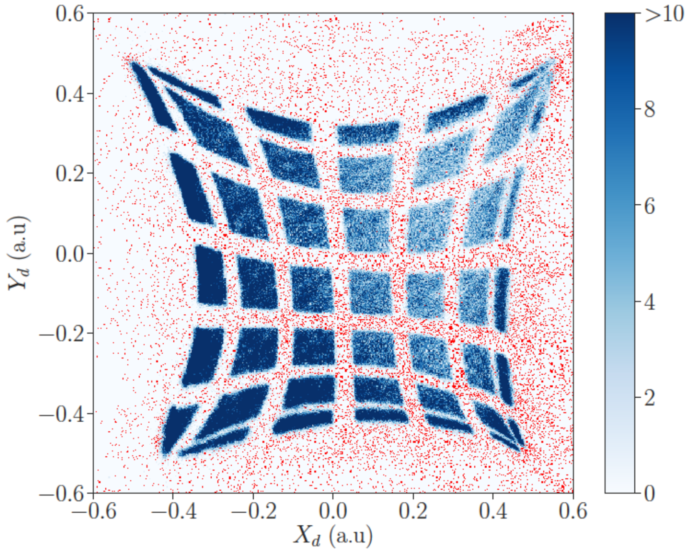
Impact on:
- E_{shift}
- Branching ratio (spectroscopy purpose)

Position sensitive MCP





RAW reconstruction
(highly deformed)



$$X = \frac{-C_1 + C_2 + C_3 - C_4}{C_\Sigma}$$

$$Y = \frac{+C_1 + C_2 - C_3 - C_4}{C_\Sigma}$$

In preparation: S.Lecanuet et al.

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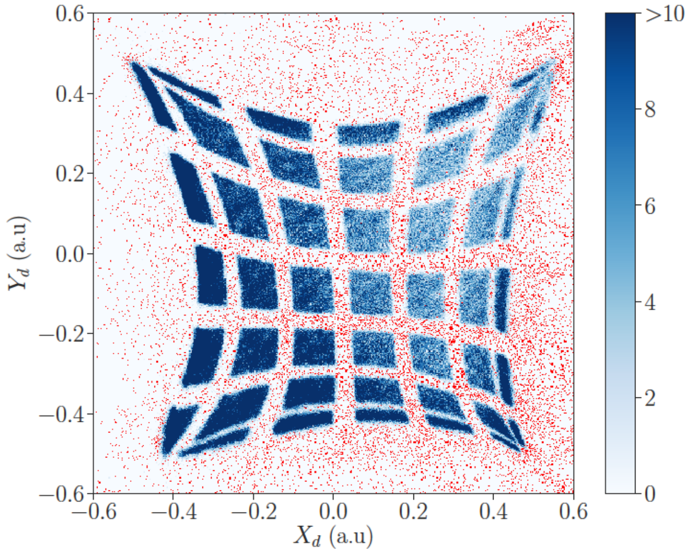
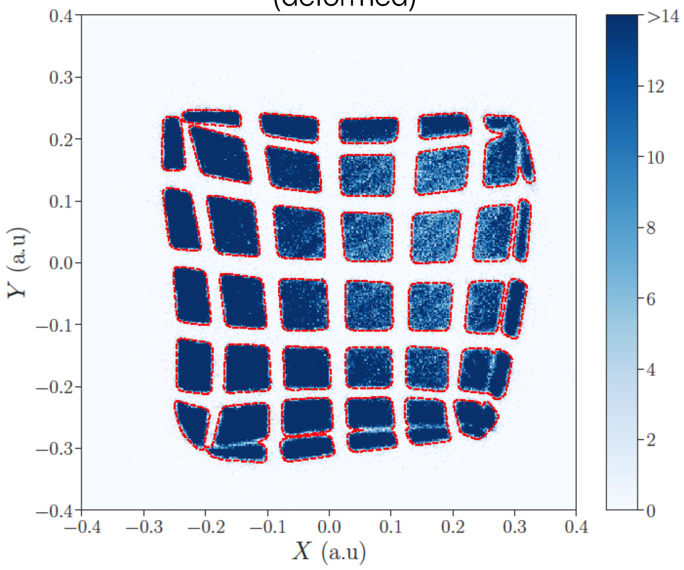
(highly deformed)



$$X = \frac{-C_1 + C_2 + C_3 - C_4}{C_\Sigma}$$

$$Y = \frac{+C_1 + C_2 - C_3 - C_4}{C_\Sigma}$$

First empirical correction
(deformed)



Calibration on the mask

2D fit with corner holes as fit parameters
- Mask geometry
- Detector resolution

$$F_{scan}(X,Y) = \frac{A}{16}\sum_{j=1}^{N}\left\{\left[1+\mathrm{erf}\left(\frac{Y-f_j^{AB}(X)}{\sqrt{2}\delta_Y}\right)\right] \times \left[1-\mathrm{erf}\left(\frac{X-f_j^{BC}(Y)}{\sqrt{2}\delta_X}\right)\right] \times \left[1-\mathrm{erf}\left(\frac{Y-f_j^{CD}(X)}{\sqrt{2}\delta_Y}\right)\right] \times \left[1+\mathrm{erf}\left(\frac{X-f_j^{DA}(Y)}{\sqrt{2}\delta_X}\right)\right]\right\}$$

In preparation: S.Lecanuet et al.

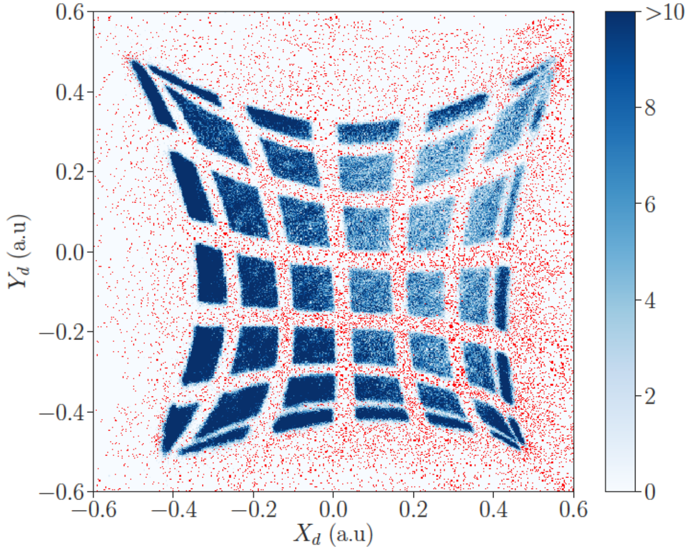
Beam characteristics

Will change:
- Solid angle
- β backscattering

Impact on:
- E_{shift}
- Branching ratio (spectroscopy purpose)

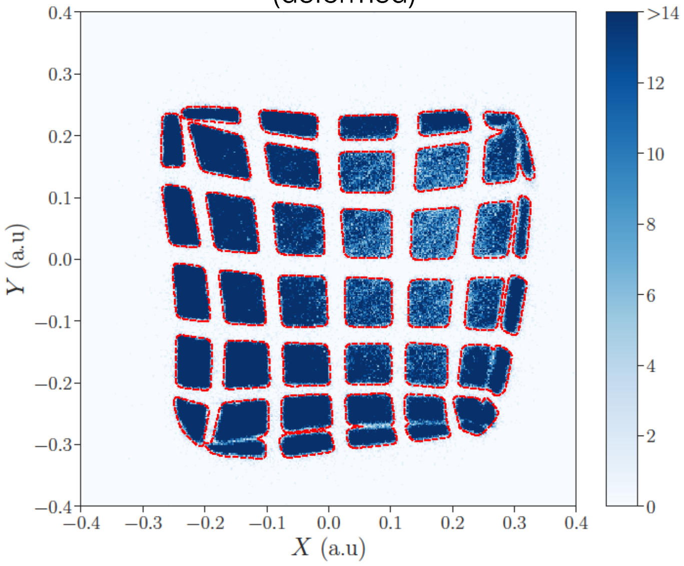
Position sensitive MCP

RAW reconstruction
(highly deformed)

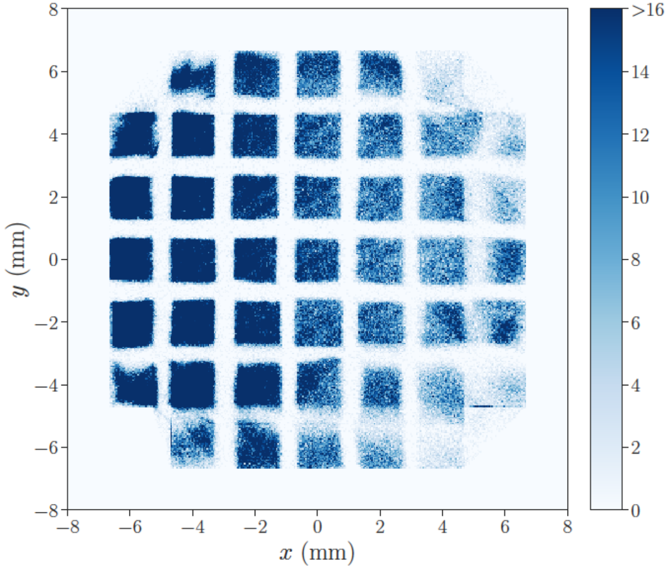


$$X = \frac{-C_1 + C_2 + C_3 - C_4}{C_\Sigma}$$
$$Y = \frac{+C_1 + C_2 - C_3 - C_4}{C_\Sigma}$$

First empirical correction
(deformed)



Calibrated



In preparation: S.Lecanuet et al.

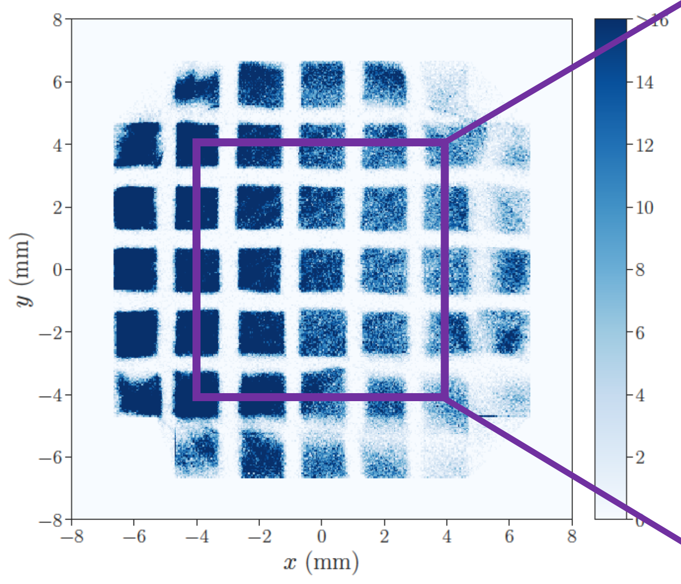
Beam characteristics

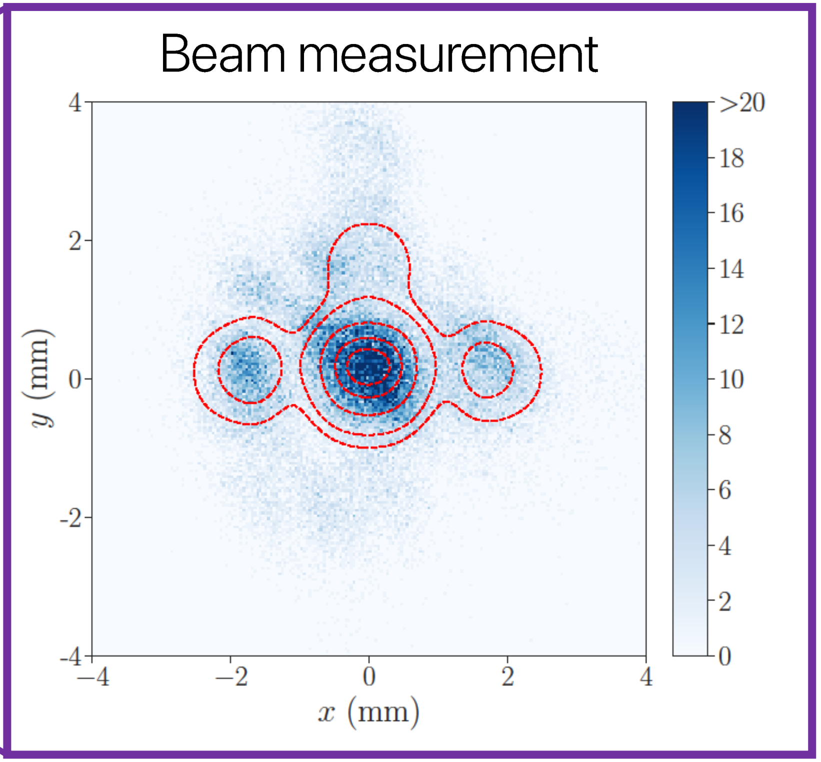
Will change:
- Solid angle
- β backscattering

Impact on:
- E_{shift}
- Branching ratio (spectroscopy purpose)

Position sensitive MCP

Beam scan





$((Beam \times Grid) * Resolution)(x, y)$

Fitted beam characteristics:
x = -0.05(8) mm
y = 0.41(6) mm
σ_x = 1.05(7) mm
σ_y = 0.61(8) mm

$$(\Delta a_{\beta\nu})_{beam} = 0.07(1)\,\%$$

In preparation: S.Lecanuet et al.

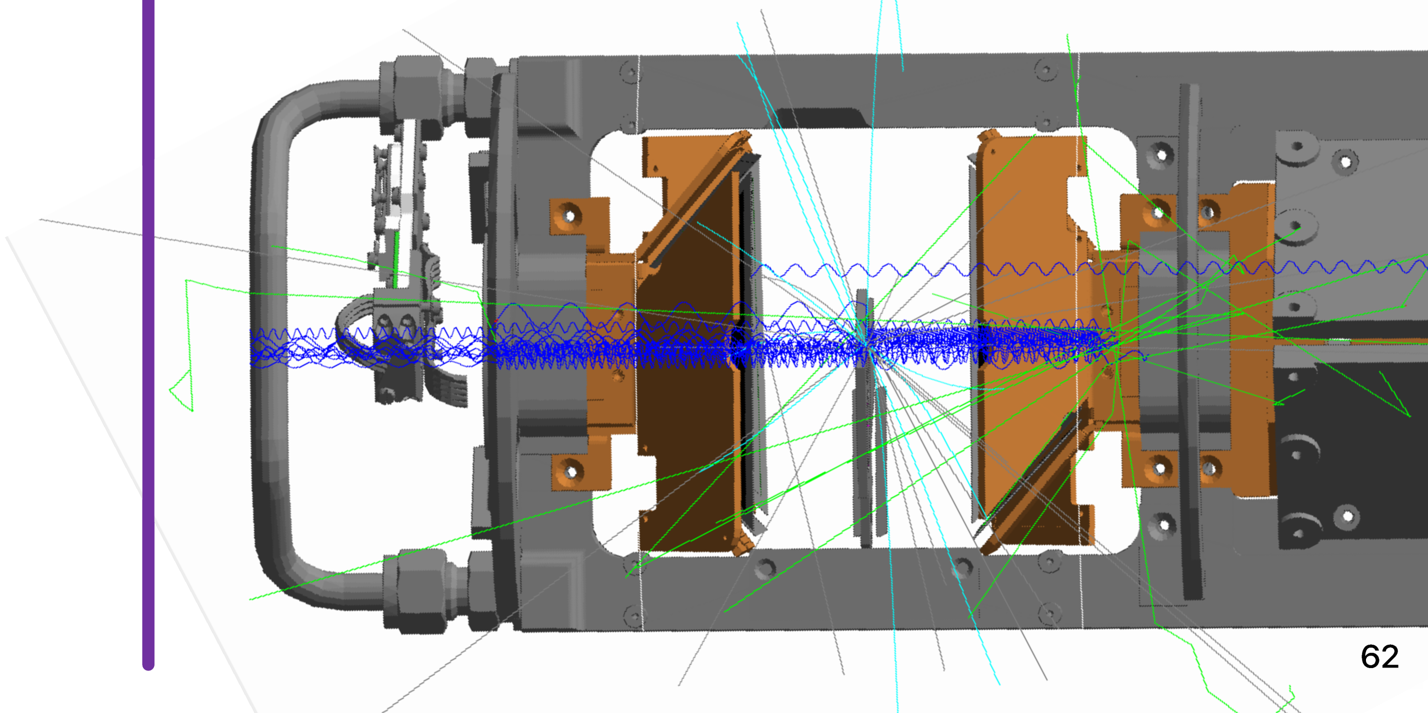
Simulation

Event generator: CRADLE++

- β, α, γ, EC, IC, and proton decay implemented
- Precise β spectrum*
- Generate a decay chain with kinematics
- Able to generate Beyond Standard Model cases

Transport: Geant4

- Efficient CRADLE file reader
- Event by event tracking
- Homogeneous magnetic field
- 40 silicon detectors detailed geometry



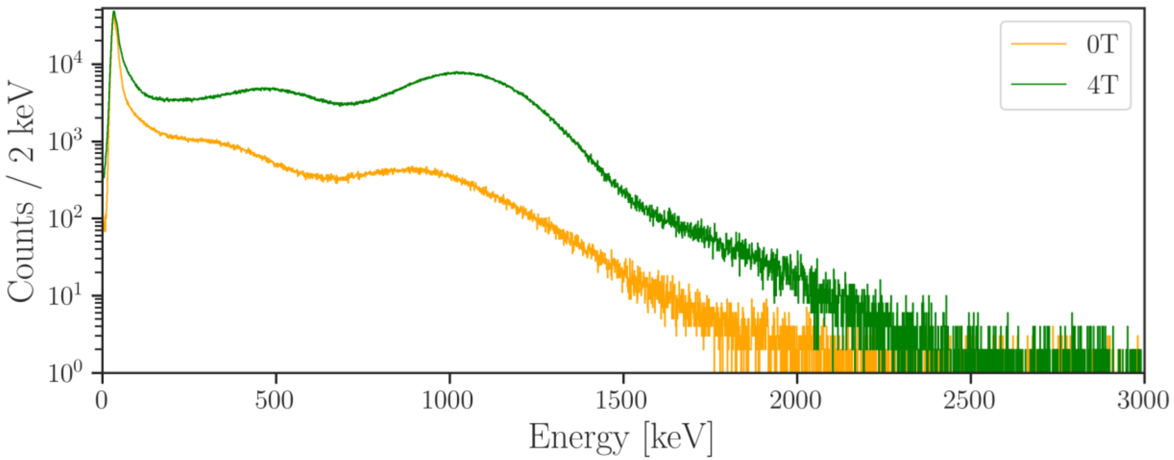
*L.Hayen and al. : Rev. Mod. Phys. 90, 015008 (2018)

2024 Data taking: Source measurement

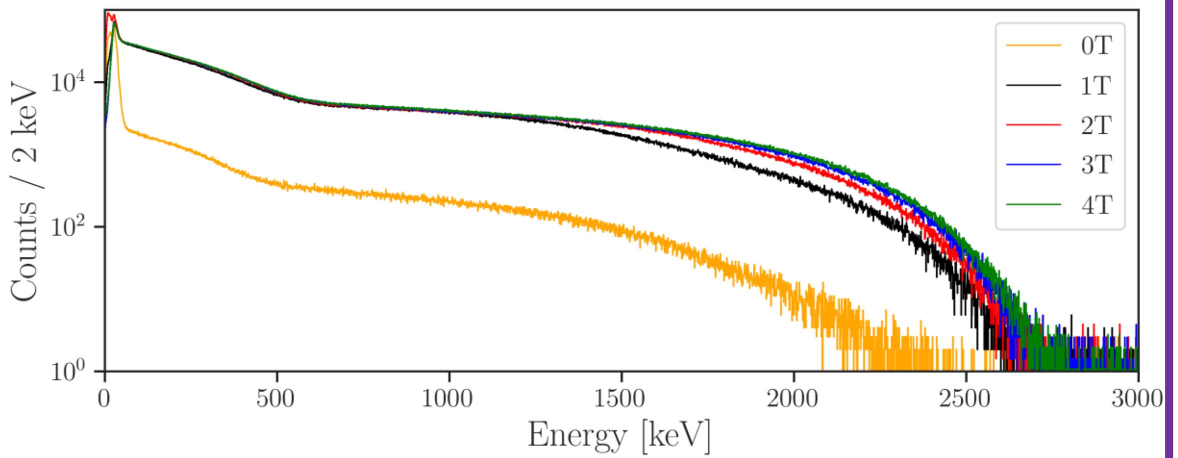
May 2024

β sources: detection efficiency as a function of B

^{207}Bi

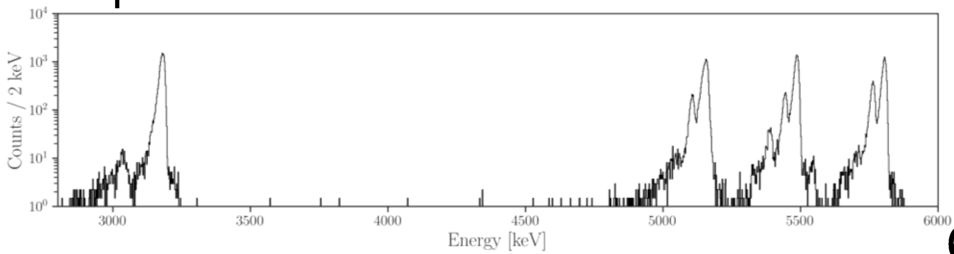


^{90}Sr



α sources: detection efficiency as a function of B, silicon detectors response function

^{148}Gd ^{239}Pu ^{241}Am ^{244}Cm



Data taking

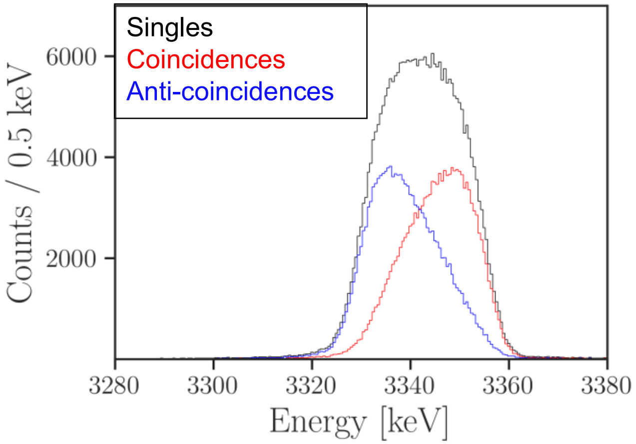
2024:

- All 72 channels worked

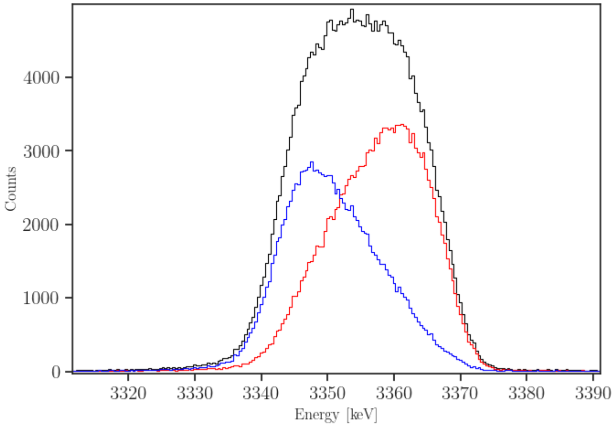
Data taking

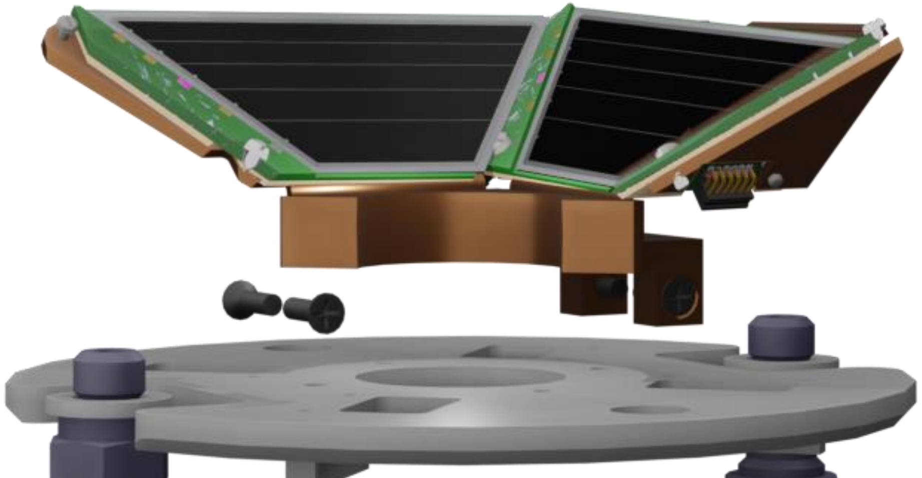
2024:
- All 72 channels worked
- Collimator β-backscattering

Without collimator



With collimator



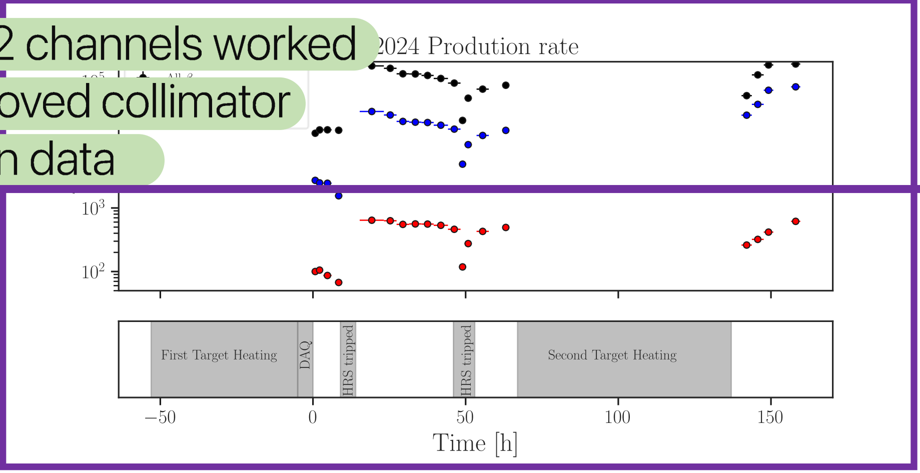


Data taking

2024:
- All 72 channels worked
- Collimator β-backscattering
- Contamination (pileups and random coincidences)

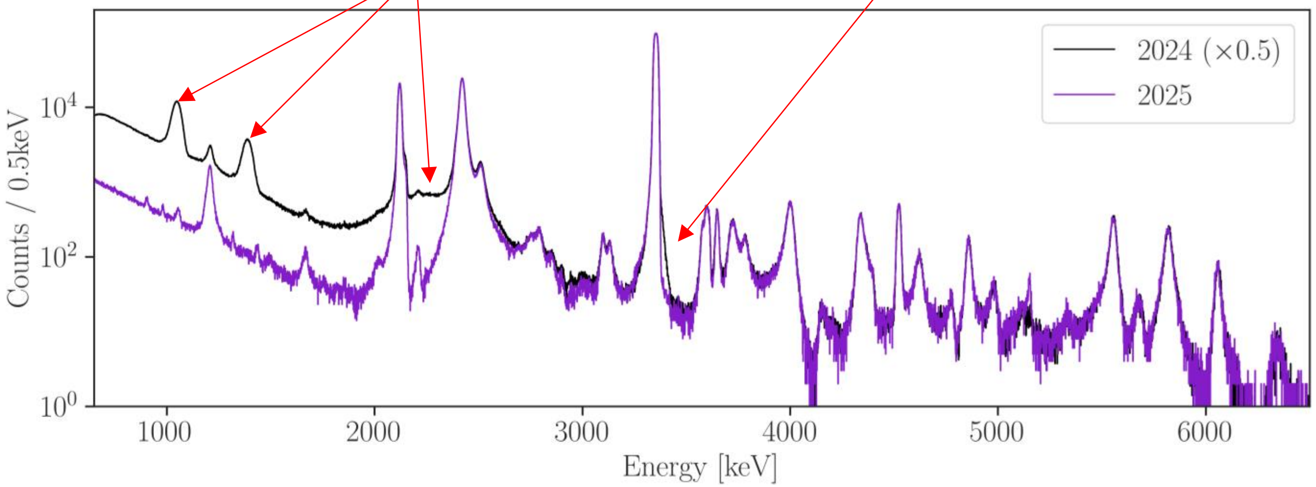
2025:
- All 72 channels worked
- Removed collimator
- Clean data

Only 0.5% of ^{32}Ar in the radioactive beam in 2024

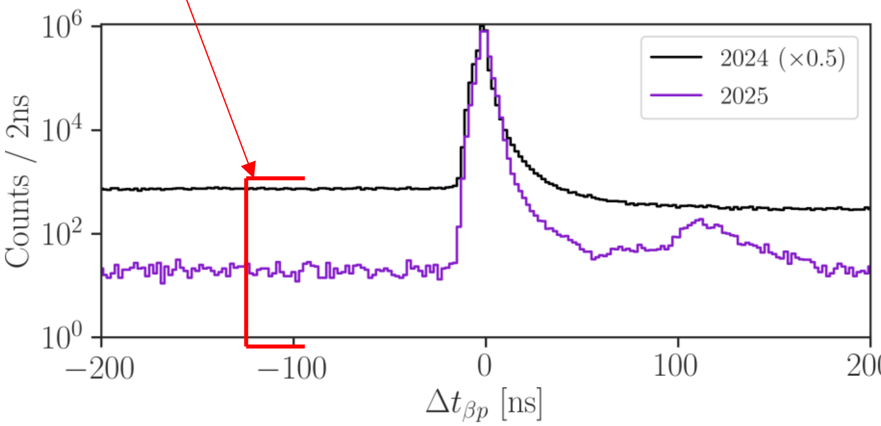


$^{18}N^{14}N$ radioactive molecule decaying by βα

Pile-Up / Summing

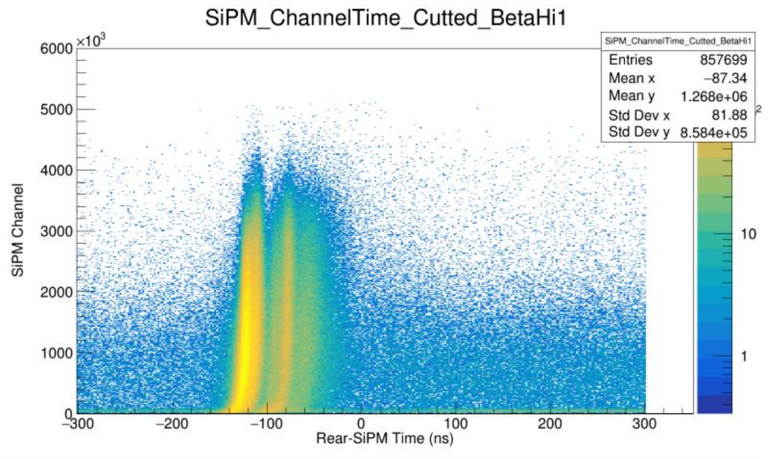


Random coincidences

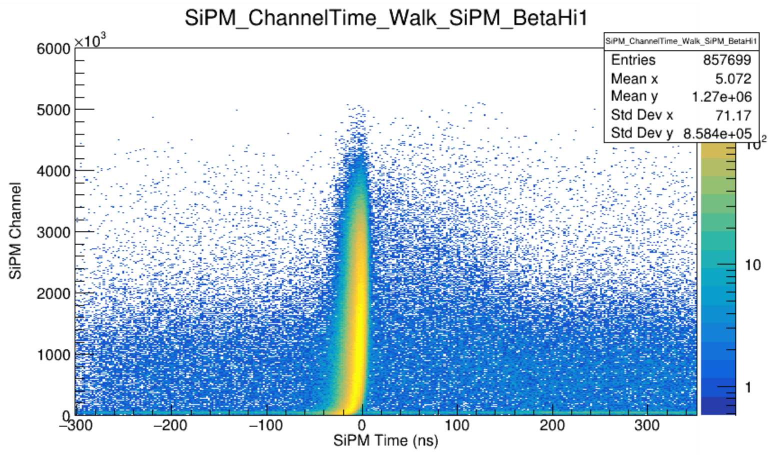


Walk corrections

RAW



Silicon detector corrected



SiPM corrected