Probing the structure of the weak interactions

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Experimental project **WISArD** (**W**eak-**I**nteraction **S**tudies with ^{32}**Ar D**ecay) online at ISOLDE/CERN

Study the structure of weak interactions : search for ‘forbidden’ scalar & tensor components by precise measurements of sensitive correlations in low-energy beta-decays

Motivation, sensitive variables

Standard model of electro-weak interactions: **V-A character of interaction**

C_V=1 (CVC) **C_A=-1.27, $C_V'=C_V$ & $C_A'=C_A$, $C_S=C_S'=C_T=C_T'=C_P=C_P'=0$** **No Scalar or Tensor**

But experimental evidence for $|C_T^{(\prime)}/C_A|$ and $|C_S^{(\prime)}/C_V|$ only at the % level (After 60 years of efforts !!!)

β-ν correlation in β-decay - **a** parameter (sensitive to both **Scalar**, **Tensor** interaction)

- can simultaneously study both "forbidden interactions" – Scalar in Fermi decays, Tensor in Gamow-Teller decays
- difficulty to directly detect neutrinos ⇒ study **recoil nuclei instead of neutrinos** ⇒ **-** measurement of the **shape of p-spectrum** from **β-delayed proton decay** (WISArD) → coefficient *a*

a > 0 → emission favored at θ=0°, large recoil *a < 0 → emission favored at θ=180°, small recoil*

Decay rate for non polarized nuclei

$$dW = dW_0\left(1 + a\frac{\mathbf{p}_e \cdot \mathbf{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e}\right)$$

$$a_F \cong 1 - \frac{|C_S|^2 + |C_S'|^2}{|C_V|^2} \quad =1 \text{ SM}$$

$$a_{GT} \cong -\frac{1}{3}\left[1 - \frac{|C_T|^2 + |C_T'|^2}{|C_A|^2}\right] \quad =-1/3 \text{ SM}$$

β-ν correlation coefficient

$$b_F \cong Re\,\frac{C_S + C_S'}{C_V}$$

$$b_{GT} \cong Re\,\frac{C_T + C_T'}{C_A}$$

Fierz interference term

Best measurements:
a_F ~ 0.45%,
a_{GT} < ~1%

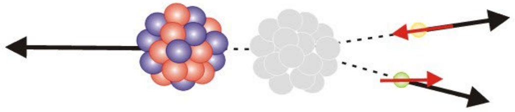
WISArD: measuring $\tilde{a}$, sensitive to both a & b

$$\tilde{a} \approx \frac{a}{1 + b\langle m_e / E_e\rangle}$$

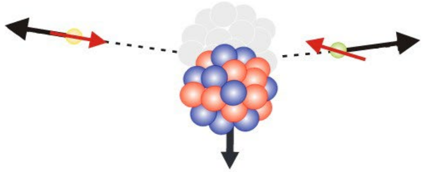
measuring **recoil nucleus energy**⇒ ratio **Scalar/Vector**

F decay $\tilde{a}_F$ limits Scalar, GT $\tilde{a}_{GT}$ limits Tensor

Vector interaction (SM)
High energy of recoil nucleus,
moving opposite to emitted particles



Scalar interaction (beyondSM)
Very small energy of recoil nucleus

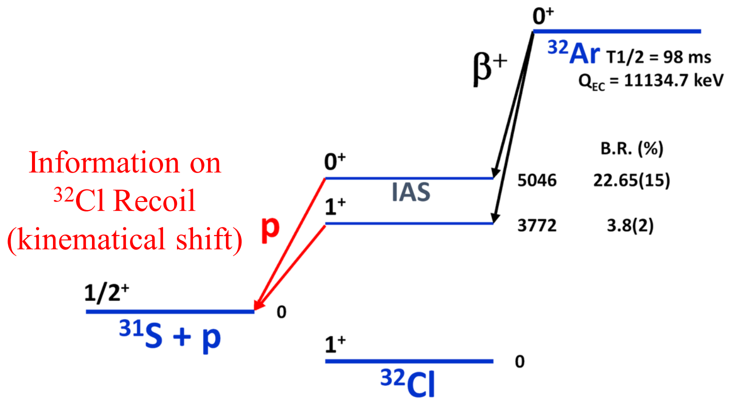


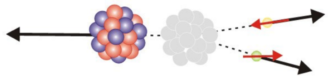
β-delayed proton decay (case of ^{32}Ar)

- ^{32}Ar decays by β-decay to the ^{32}Cl which subsequently decays by proton decay to ^{31}S
- Interested in super-allowed Fermi β-decay ^{32}Ar→ ^{32}Cl to Isobaric Analog State followed by the proton decay ^{32}Cl → ^{31}S
- Protons are emitted from the moving nucleus ^{32}Cl recoiling after previous β-decay ⇒ energy of protons is kinematically shifted
- Significant difference between the effect of kinematic shift on proton energy between **scalar** β-decay (small recoil energy) and **vector** β-decay (high recoil energy)

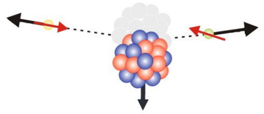
⇓

- Shape of proton spectrum reflects energy spectrum of recoil nuclei after the β-decay - that is sensitive to the **scalar / vector** character of the weak interaction
- Precise measurements of **proton spectra in coincidence with positrons** can search for deviations from the shape of allowed vector decay and look for admixture of a "forbidden" scalar one

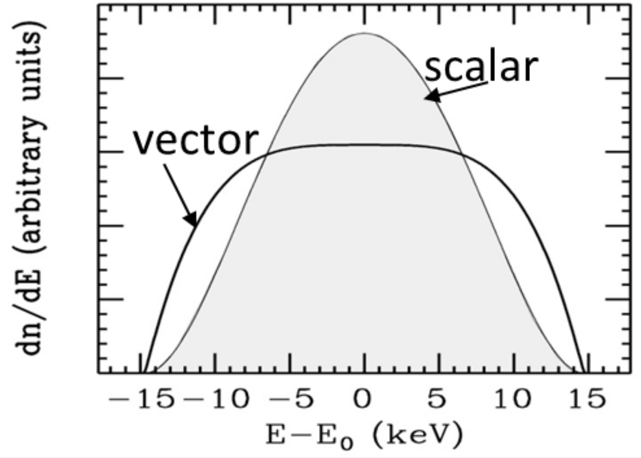




Vector, *a*=1
high recoil energy
large broadening



Scalar, *a*=-1
low recoil energy
small broadening

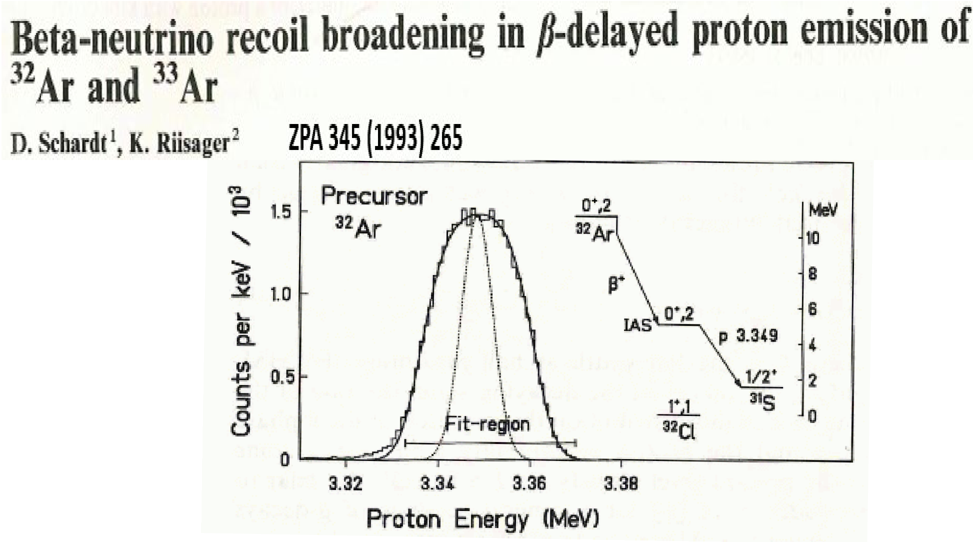


Proton peak shape

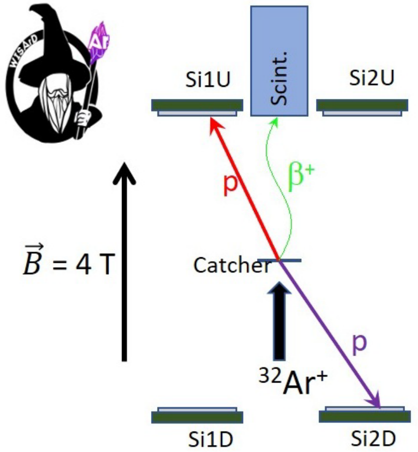
Experiments with β-delayed proton decay of ^{32}Ar at ISOLDE

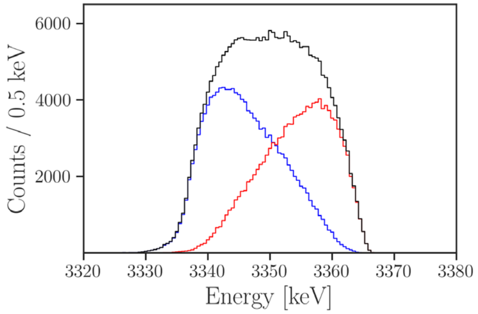
Idea to deduce the shape of energy spectrum of recoil nuclei after the β-decay from the kinematical shift of proton-spectrum from β-delayed proton decay of 32Ar is not new

Experiment performed already 30years ago at ISOLDE – but only the proton peak **broadening** has been measured – very sensitive to peak shape, proton detector response function


Beta-neutrino recoil broadening in β-delayed proton emission of ^{32}Ar and ^{33}Ar

D. Schardt[1], K. Riisager[2]   ZPA 345 (1993) 265

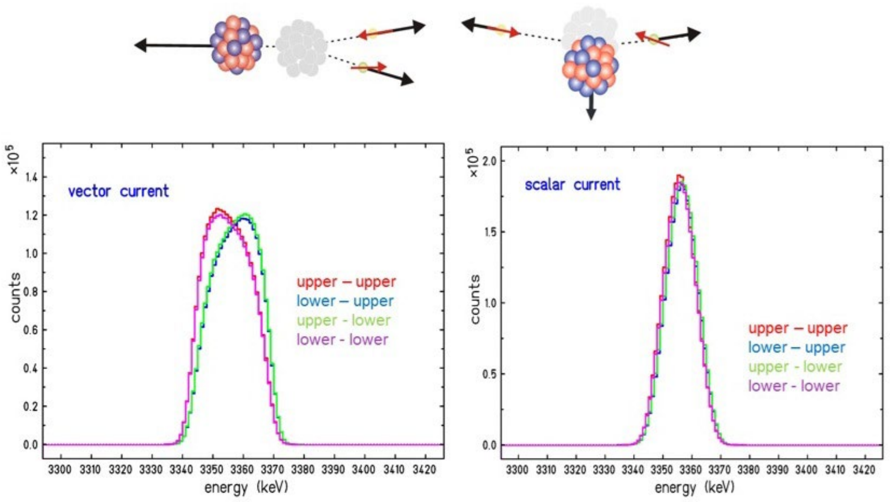




WISArD : detection of **proton spectra in coincidence with positrons** at extreme angles 0 and 180° ⇒ **energy shifts** for same & opposite emission directions rather than **broadened width ⇒ shift is a linear function of $\tilde{a}$**

- Higher sensitivity on $\tilde{a}$ **(~ x 2.5)** and on ***b*** **(~ x 4.5)**
- no dependence on ***p*** peak intrinsic shape and ***p*** detector response function
- the **strong magnetic field** allows to spatially separate positrons and protons allowing to observe them with different detectors

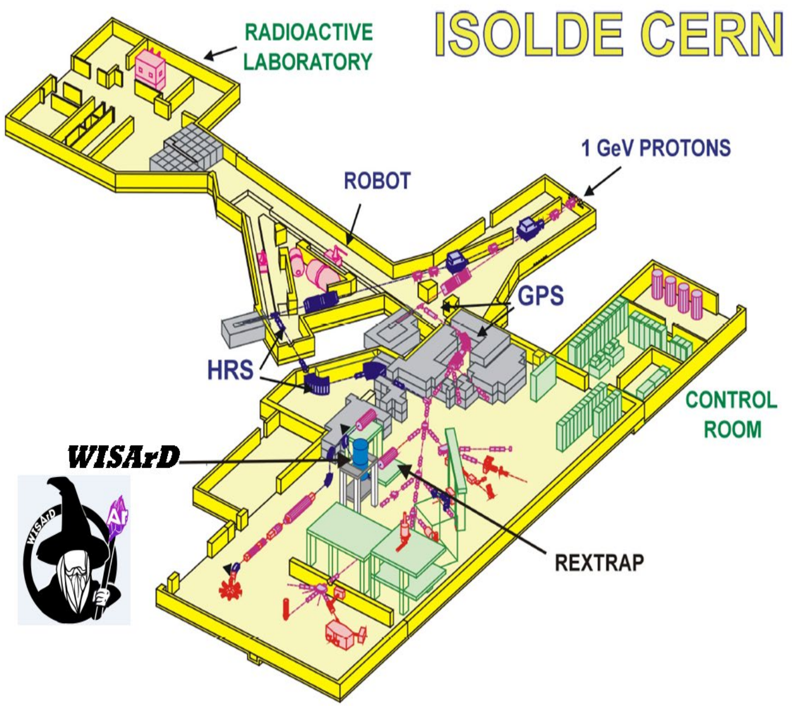
Simulated proton spectra in coincidence with positrons for the "Fermi peak"

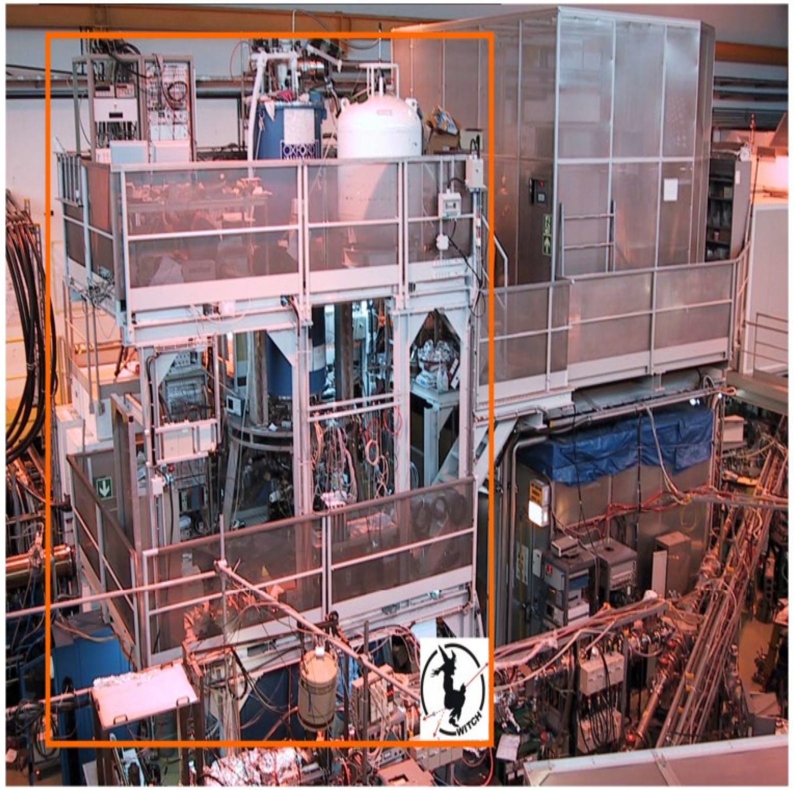


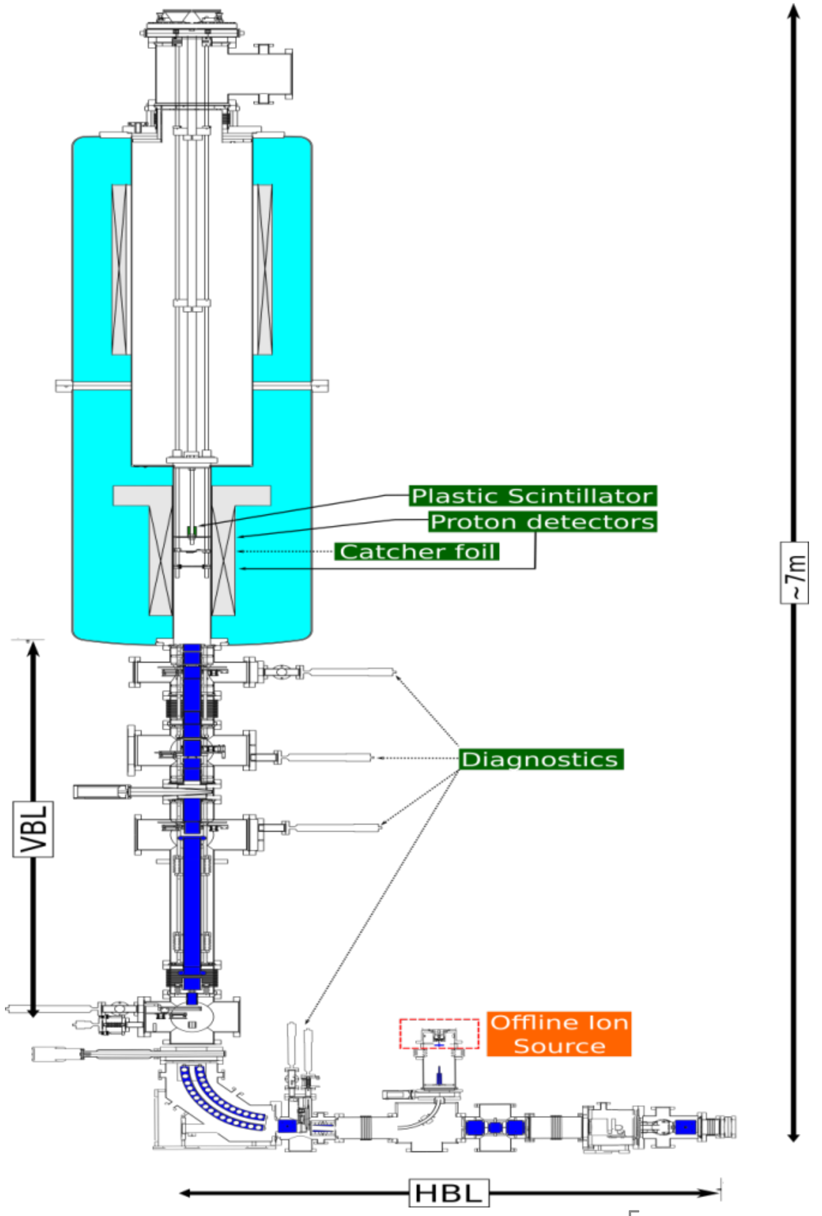
WISArD (Weak-Interaction Studies with ^{32}Ar Decay) experiment

WISArD – measuring β-delayed proton decay of ^{32}Ar
in β-p coincidence measurement we measure the proton energy shift for same & opposite β emission directions which is a linear function of $\tilde{a}$

- Whole setup in the magnetic field 4T (up to 9T))
- ^{32}Ar ions at 30keV implanted into the thin mylar foil
- Positrons from the β-decay detected by the narrow forward scintillation detector placed on axis
- Protons from the subsequent p-decay of ^{32}Cl detected by arrays of Si detectors in forward and backward direction
- Spiraling positrons cannot reach the proton detectors placed off axis







Proof-of-principle experiment 2018

WISArD online proof-of-principle experiment

Nov 2018, latest run before the CERN shutdown

Readily available beta and proton detectors

~ 1700 pps of ISOLDE ^{32}Ar beam instead of 3000 nominal

~ 35h of beamtime

- implantation rate into the catcher foil ~100 ^{32}Ar ions/s

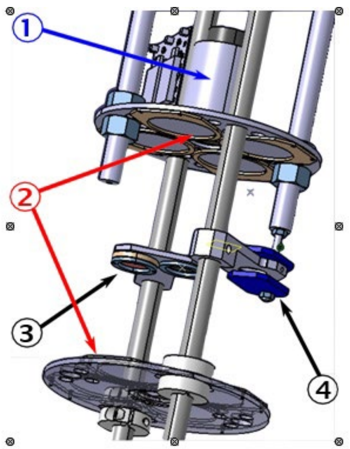
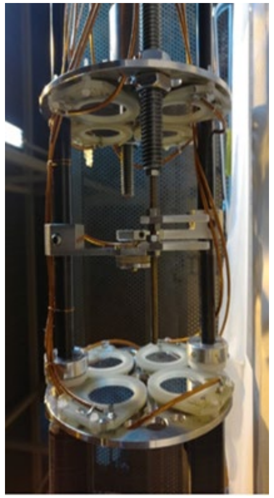


Figure 3: CAD drawing of the Nov2018 detectors system.

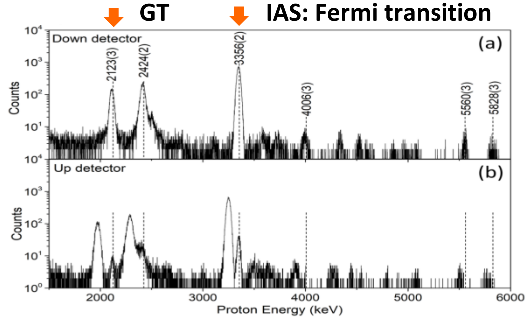


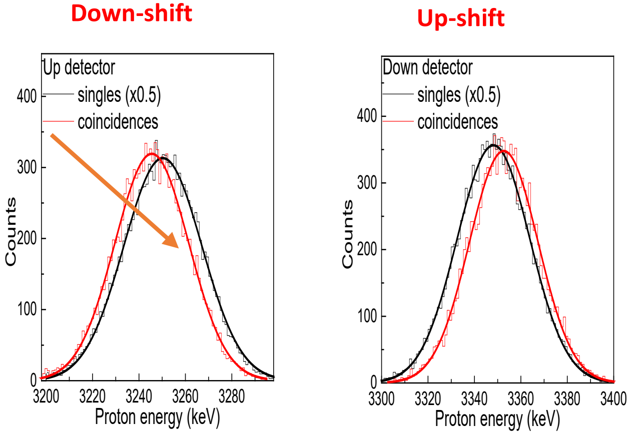
Systematic error budget (in ‰) :

	Source	Uncertainty	$\Delta\tilde{a}_{\beta\nu}(10^{-3})$
background	false coinc.	8%	< 1
proton	detector calibration	0.2%	2
	detector position	1 mm	< 1
	source position	3 mm	3
	source radius	3 mm	1
	B field homogeneity	1%	< 1
	silicon dead layer	0.3 μm	5
	mylar thickness	0.15 μm	3
positron	detector backscattering	15%	2
	catcher backscattering	15%	21
	threshold	12 keV	8
total			24

-unknown detectors DL
-source profile poorly known
→Can be easily reduced by factor ~10

→Must be reduced by factor >20





Typical resolution ~35 keV FWHM

$$\Delta E_F = 4.49(3)\ \text{keV}$$

$$\tilde{a}_F = 1.01(3)_{\text{stat}}(2)_{\text{syst}}$$

$$\tilde{a}_{GT} = -0.22(9)_{\text{stat}}(2)_{\text{syst}}$$

3rd most precise measurement of $\tilde{a}_F$

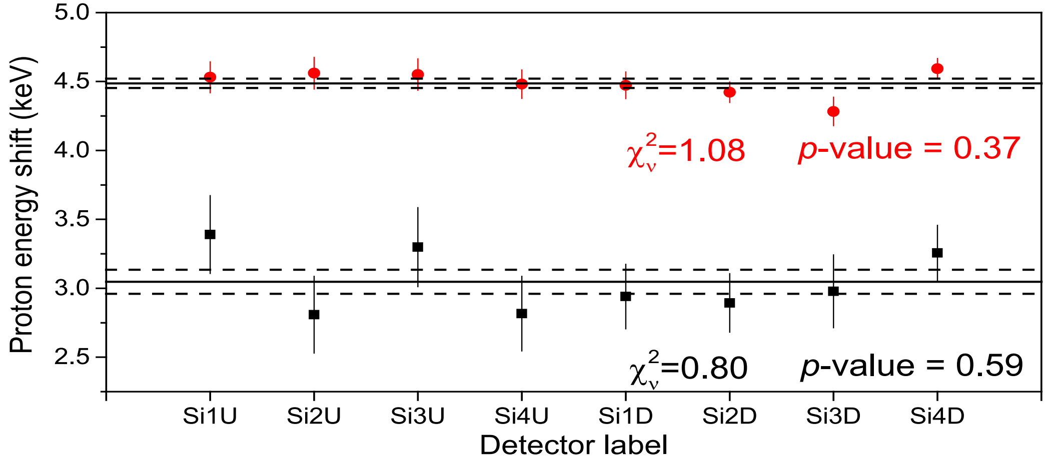
V. Araujo-Escalona et al, PRC 101 055501 (2020)

Results 2018

Fermi (IAS): 4.49(3) keV

$$\Delta E = \left|\bar{E}_{coinc} - \bar{E}_{single}\right|$$

GT: 3.05(9) keV



- Extraction of ã: MC simulation (GEANT4 for β^+ & *pstar* for protons)

- with decay involving different values of *a* (-1, -1/3 ,0 ,1 /3, 1) → $\tilde{a} = \alpha \times E_{shift} + Cst$
- varying instrumental parameters in MC → Systematic errors estimation

$\tilde{a}^{F}_{\beta\nu} = 1.01(3)_{(stat)}(2)_{(syst)}$ $\tilde{a}^{GT}_{\beta\nu} = -0.22(9)_{(stat)}(2)_{(syst)}$ V.Araujo-Escalona et al., PRC 101 (2020) 5, 055501

Further experiments planned with upgraded setup

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

Measurement 2021, perspectives

First data taking in 2021 after CERN long shutdown:
after major upgrade of the WISArD setup
implantation rate of ^{32}Ar ions into catcher foil ~150/s

Statistical error reduced to order of 1 ‰
production + transmission + time (beamlines upgrade, 2weeks beamtime) → x ~50 in decay statistics
dedicated detection setup (higher p-resolution, higher solid angle, lower beta threshold) → x ~5 in sensitivity

⇒ able to reach **~0.9 ‰ (F), ~1.4 ‰ (GT)**

Systematic errors - see the systematic error budget
- improving all relevant sources of systematic errors
- no real show stopper to reduce to the ~1 ‰ level

Several further campaigns planned at ISOLDE with successive major upgrades

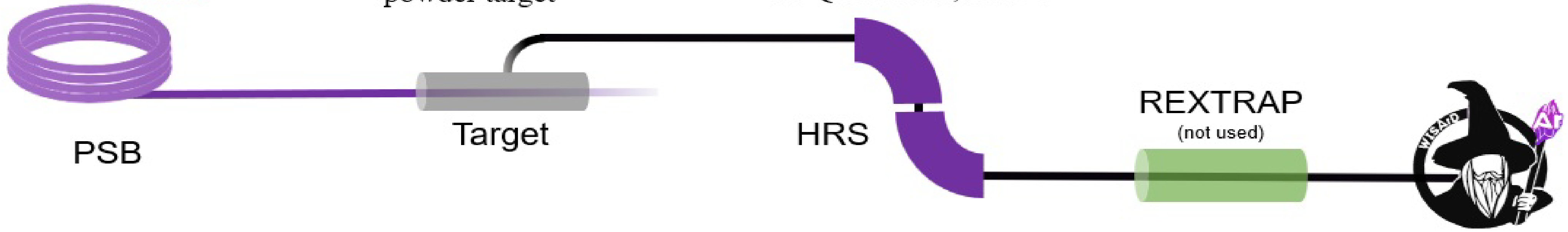
^{32}Ar production at ISOLDE: $p + CaO \rightarrow Ar$

2.5uA protons from PSBooster

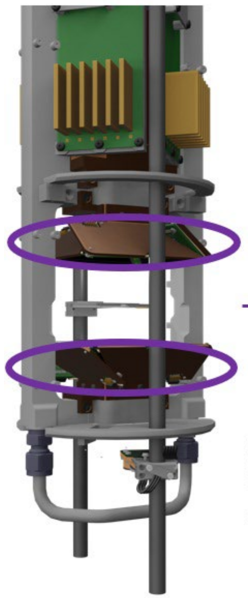
CaO nanostructured powder target

ISOLDE HRS separator, A/Q selection, 30keV

implantation rate into the catcher foil ~500 ^{32}Ar ions/s

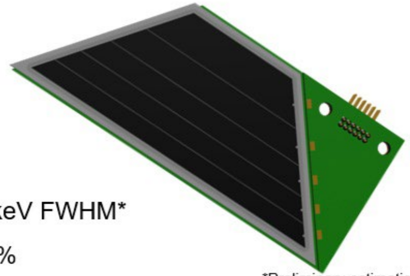


proton detectors



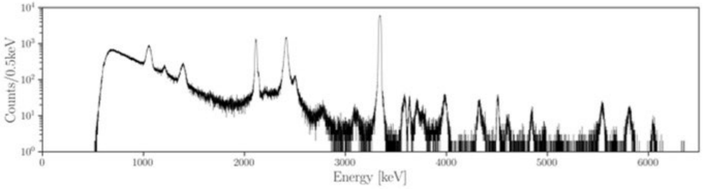
8 Silicon detectors:

- Thickness: 300 µm
- Dead-Layer: 100 nm
- Strips: 5
- Proton resolution: 10keV FWHM*
- Total solid angle: ~50%

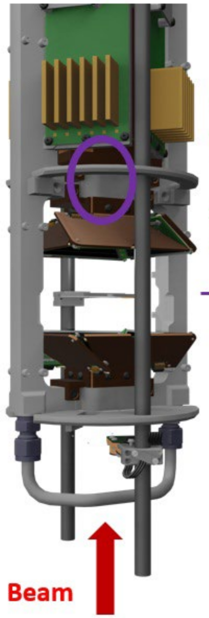


*Preliminary estimation

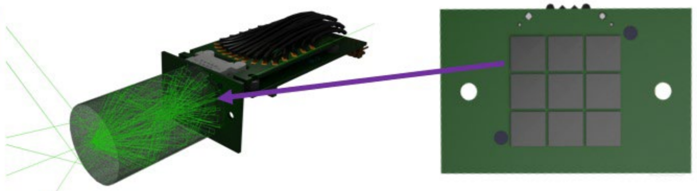
Spectra of a strip with ^{32}Ar beam

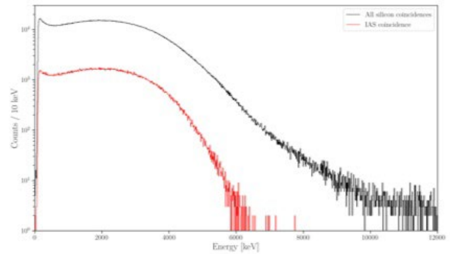


positron detector

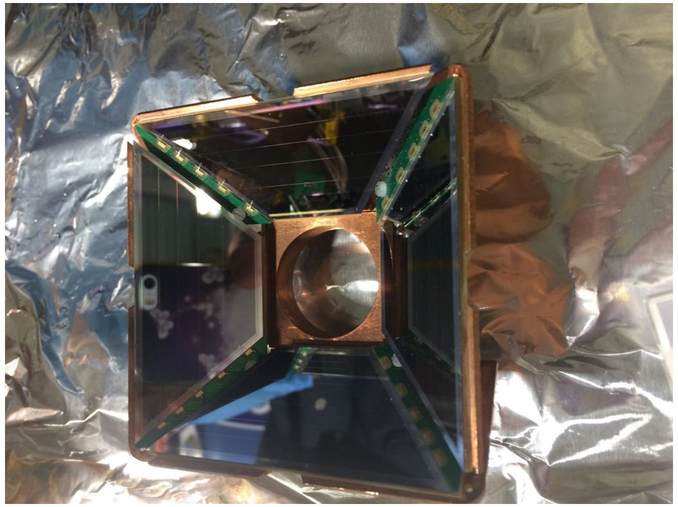


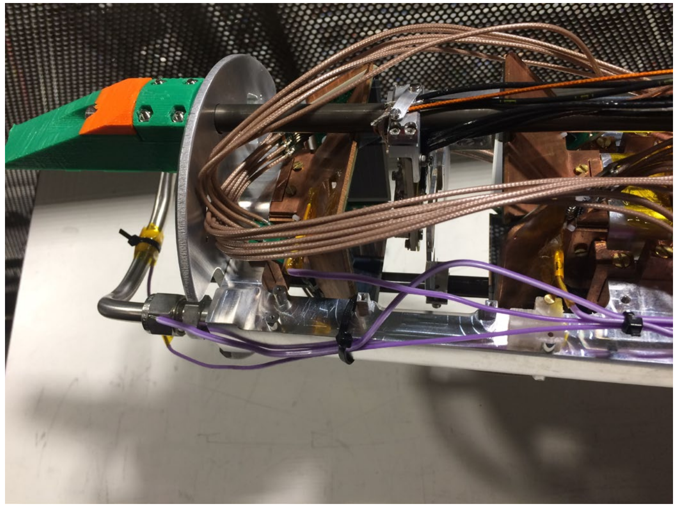
3x3 SiPMs: Onsemi MicroFJ−60035−TSV
Plastic Scintillator: EJ212

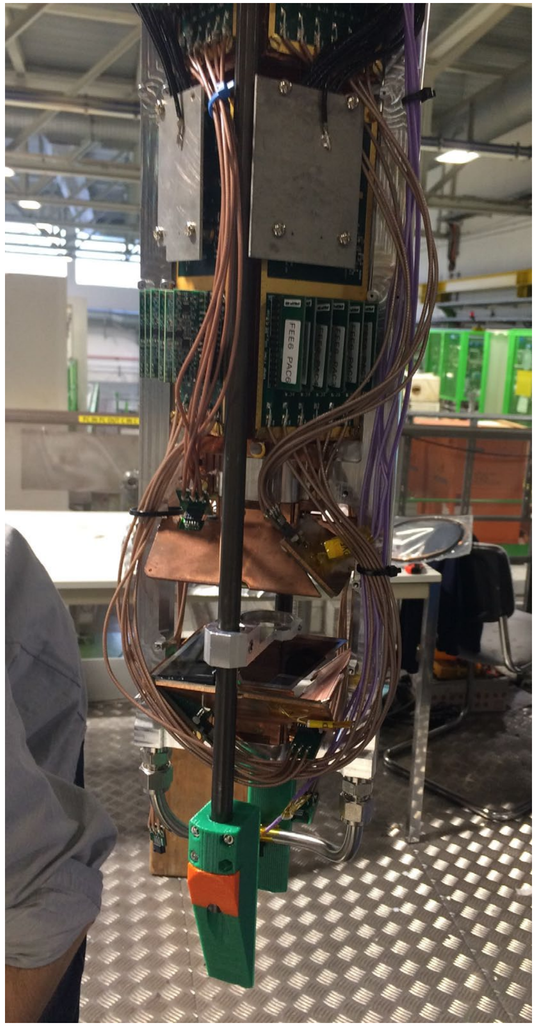


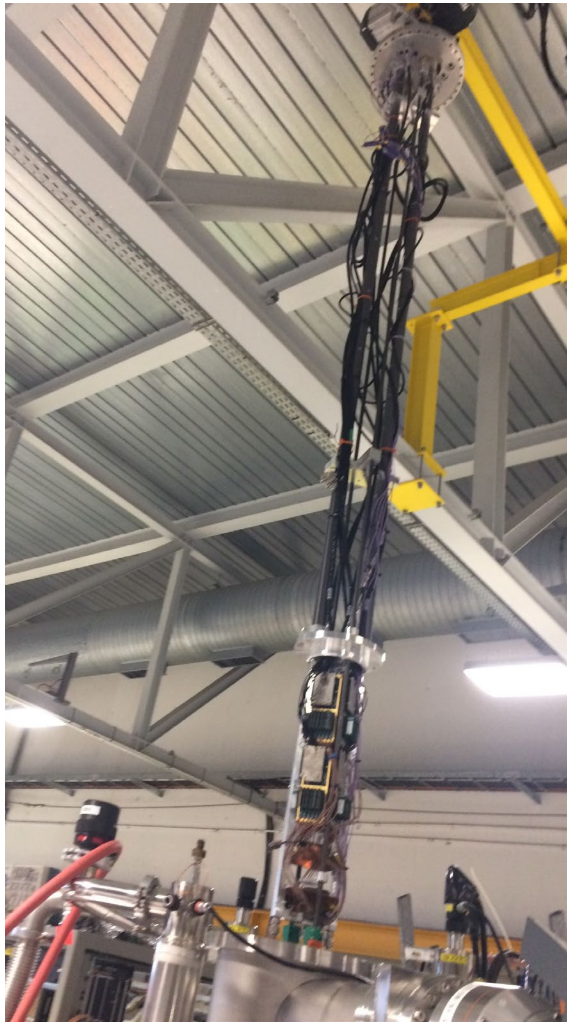


WISArD detection tower

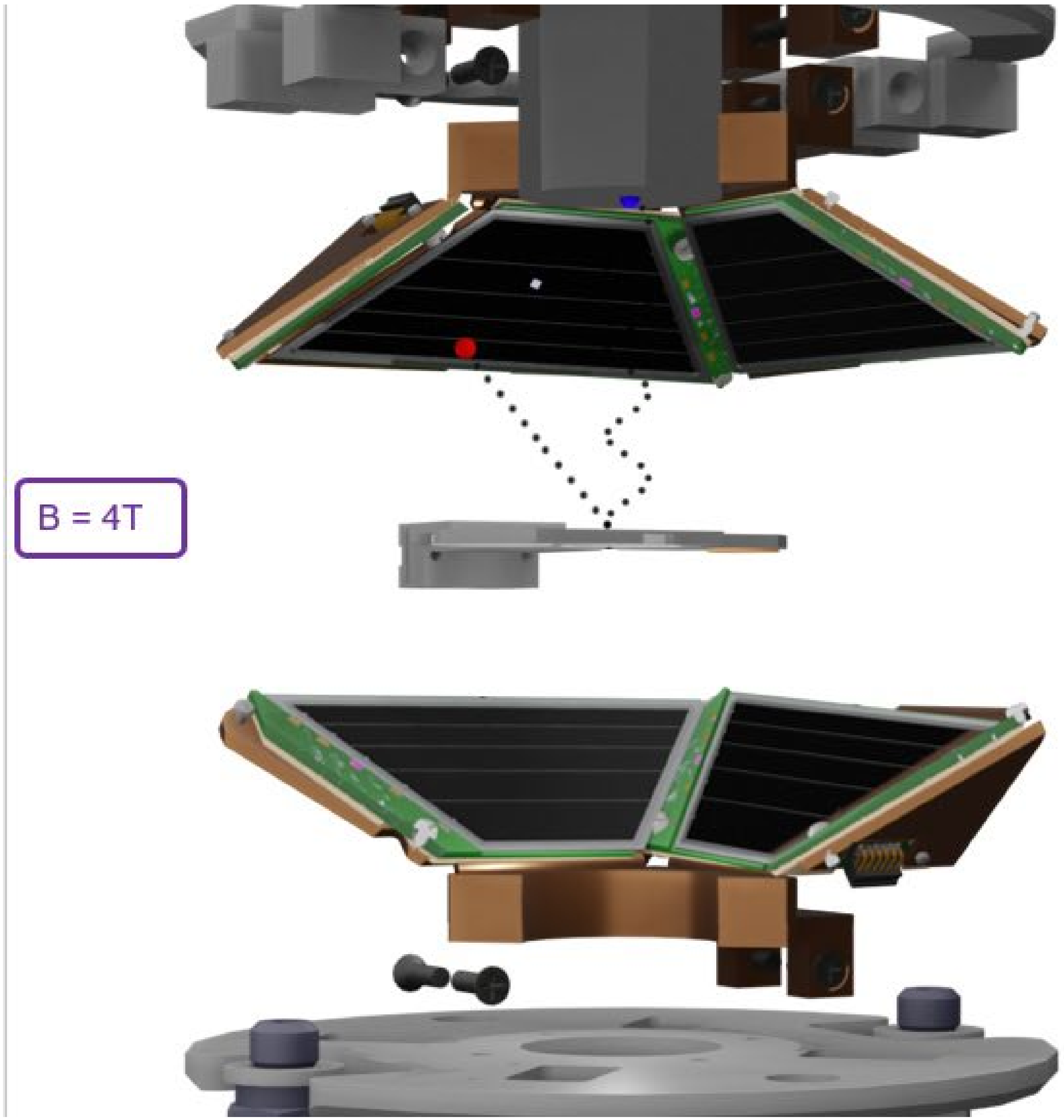








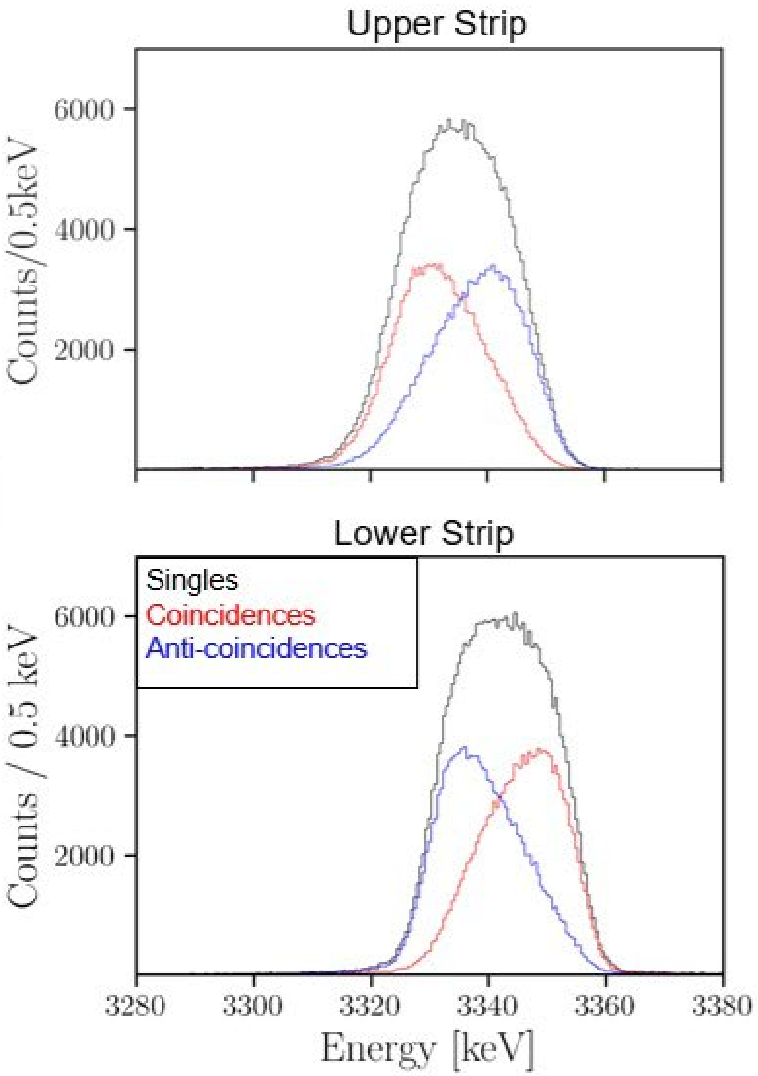
Extraction of a



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

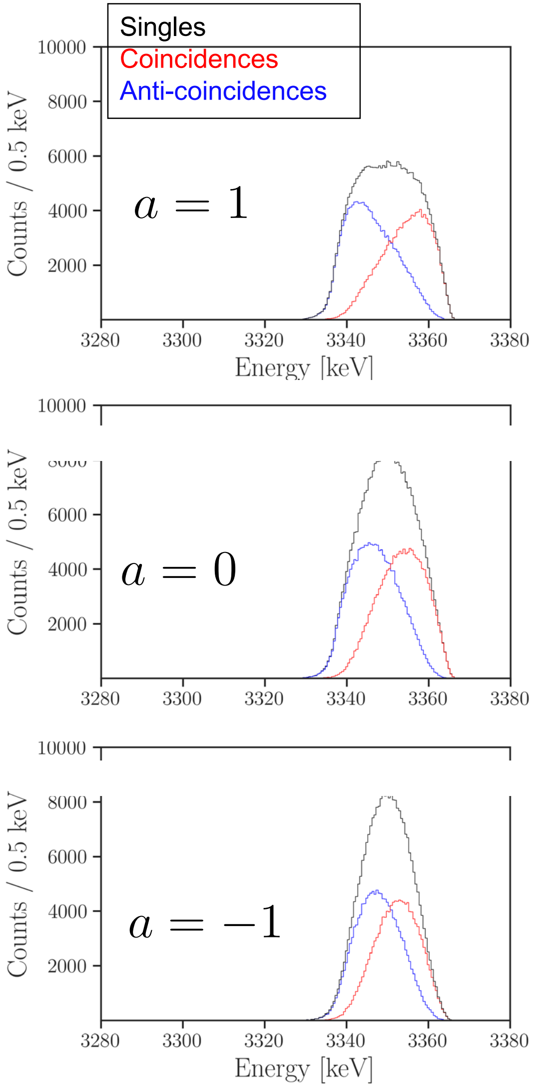
Simulations

$\tilde{a}$

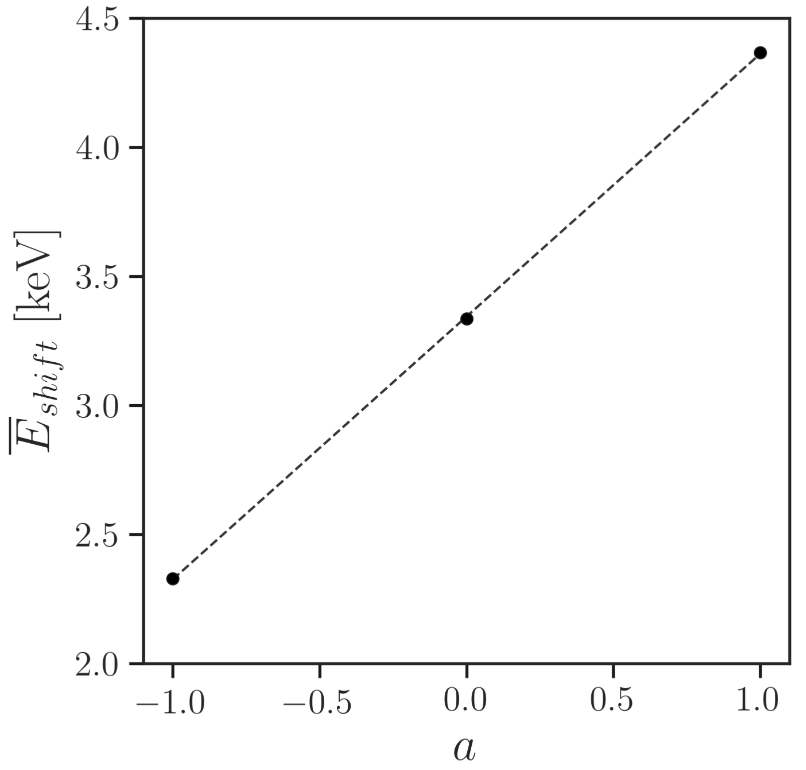


Extraction of a

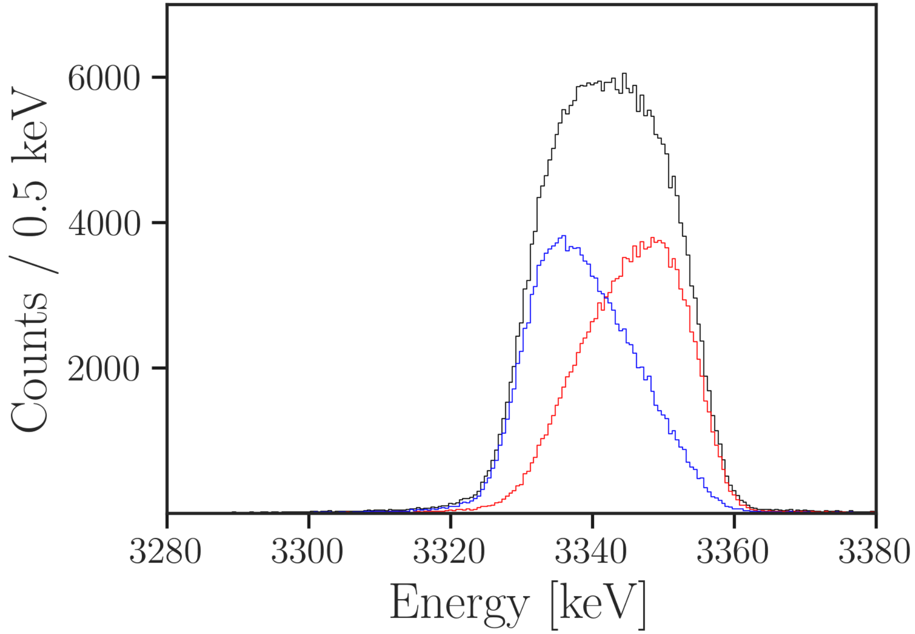
Simulations



Linear dependency between $\overline{E}_{shift}$ and a



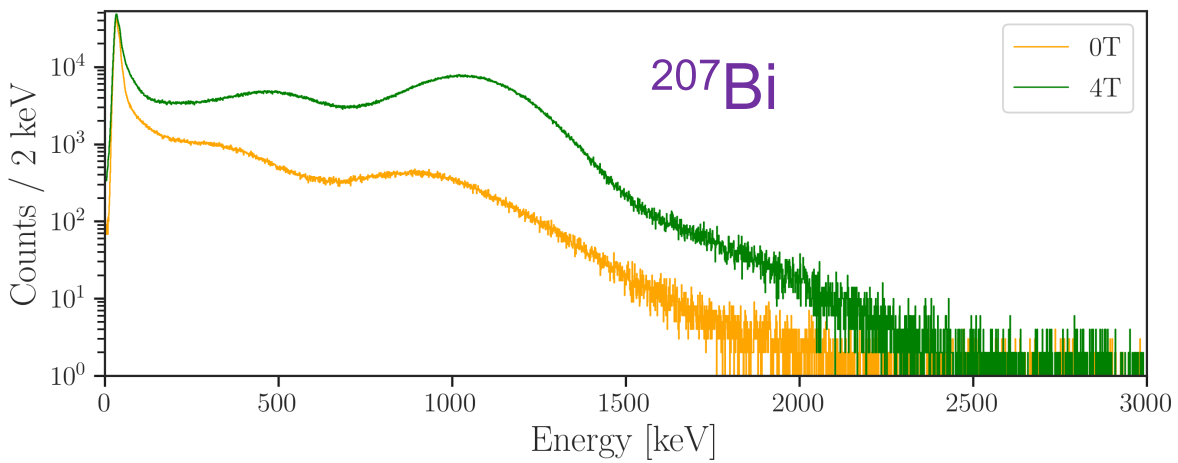
Experimental data from May 2024

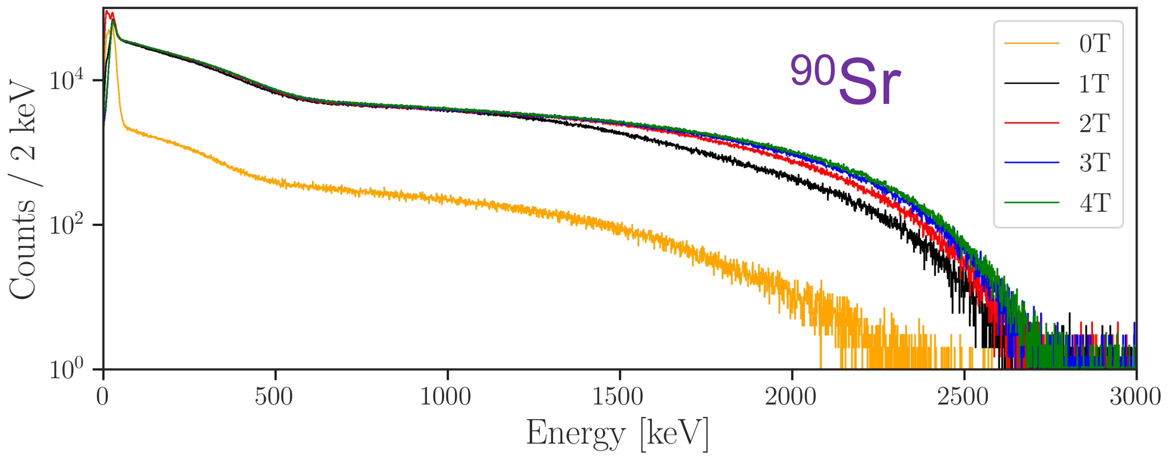


0.1% precision on $\tilde{a}$ → ~5 eV precision on $\overline{E}_{shift}$

Offline calibration by RA sources after the ^{32}Ar online run

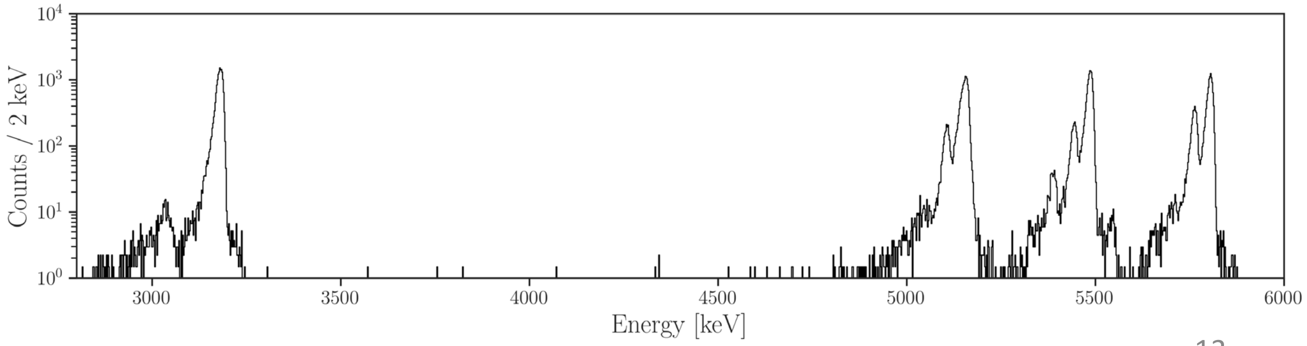
β sources: Threshold determination, calibration, detection efficiency as a function of mgt. field B





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

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



Extraction of a

Current results of WISArD:

$2018: \ \tilde{a} = 1.007(32)_{stat}(25)_{sys}$
$2021: \ \tilde{a} = 1.002(17)_{stat}$
$2024: \ \tilde{a} = ?$ On going analysis

Statistical error

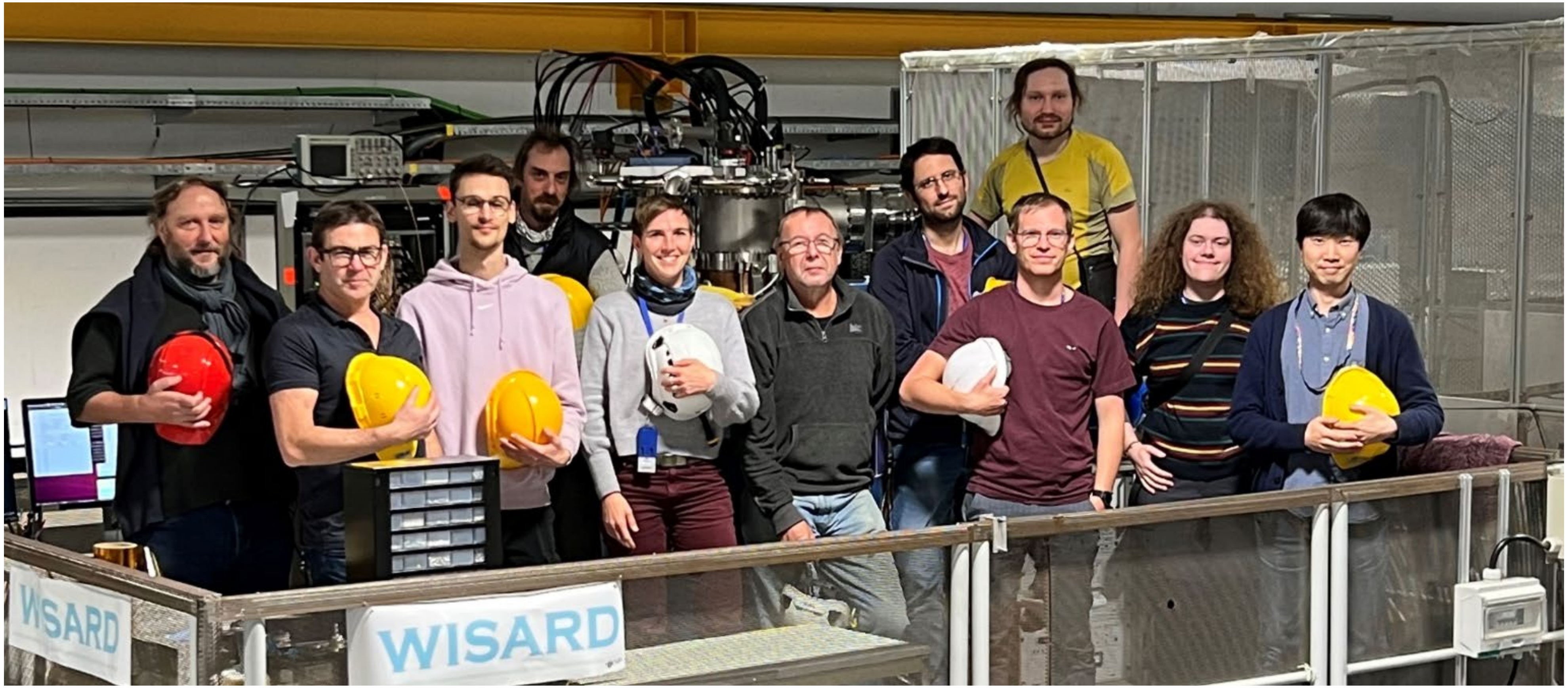
2018* ~200 000 events $\Delta\tilde{a} = 0.032$
2021 ~700 000 events $\Delta\tilde{a} = 0.017$
2024 ~12 000 000 events $\Delta\tilde{a} = 0.002$ (estimated)

Systematic error

Main sources	Uncertainty				Improvement
	2018*	$\Delta\tilde{a}$	(estimated) 2024	$\Delta\tilde{a}$	
β-backscattering	±15%	17	?	?	Thinner catcher, lower threshold
Dead layer thickness	430 ± 300 nm	12	100 ± 5 nm	0.3	New detectors
Catcher thickness	6.70 ± 0.15 µm	5	0.60 ± 0.02 µm	0.3	RBS measurement
Source radius/position	± 3 mm	1	± 0.5 mm	0.2	MCP beam profile
Detector position	± 1 mm	0.3	± 0.5 mm	0.2	Laser alignment
Silicon calibration	~ 5 keV	10	~ 1 keV	2	^{33}Ar runs, new detectors
		x10^{-3}		x10^{-3}	

*V. Araujo-Escalona PhysRevC.101.055501

Thanks to the whole WISArD team



Thanks for your attention