# Experimental Tests of the Standard Model of Weak Interactions

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several experimental projects of

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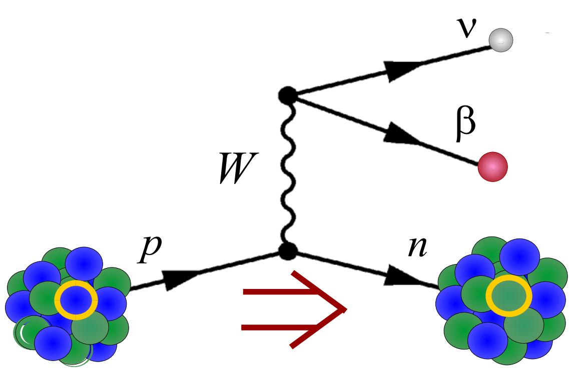
**Outline:**

- Motivation - Standard Model and beyond
- Low-energy processes sensitive to non-SM effects
- Experiments
  - LTNO – NICOLE/Leuven
  - WITCH
  - WISArD
- Summary

# Structure of the weak interaction in nuclear β-decay

Theory formulated originally almost 70 years ago
Lee & Yang, 1956; Jackson,Treiman,Wyld 1957
Wu et al., 1957 experiment - parity violation

→ **general Lorentz invariant 4-fermion interaction**




General form of Hamiltonian with 5 possible interaction types and coupling constants $C_i$ defining their properties

$$
\begin{aligned}
H_{\text{int}} = & (\bar{\psi}_p \psi_n)(C_S \bar{\psi}_e \psi_\nu + C'_S \bar{\psi}_e \gamma_5 \psi_\nu) \\
& + (\bar{\psi}_p \gamma_\mu \psi_n)(C_V \bar{\psi}_e \gamma_\mu \psi_\nu + C'_V \bar{\psi}_e \gamma_\mu \gamma_5 \psi_\nu) \\
& + \tfrac{1}{2} (\bar{\psi}_p \sigma_{\lambda_\mu} \psi_n)(C_T \bar{\psi}_e \sigma_{\lambda_\mu} \psi_\nu + C'_T \bar{\psi}_e \sigma_{\lambda_\mu} \gamma_5 \psi_\nu) \\
& - (\bar{\psi}_p \gamma_\mu \gamma_5 \psi_n)(C_A \bar{\psi}_e \gamma_\mu \gamma_5 \psi_\nu + C'_A \bar{\psi}_e \gamma_\mu \psi_\nu) \\
& + (\bar{\psi}_p \gamma_5 \psi_n)(C_P \bar{\psi}_e \gamma_5 \psi_\nu + C'_P \bar{\psi}_e \psi_\nu) \quad + h.c.
\end{aligned}
$$

Scalar (parity conserving and violating)
Vector
Tensor
Axial Vector
Pseudoscalar

# Standard Model of Electroweak Interactions

- **$C_V$=1** (CVC)
- **$C_A$=-1.27** ($g_A/g_V$=-1.26976 from n-decay)
- **$C_V$´=$C_V$ & $C_A$´=$C_A$** (maximal parity violation)
- **$C_S$=$C_S$´=$C_T$=$C_T$´=$C_P$=$C_P$´=0** (only V- and A-currents)
- no time reversal violation (except for the CP-violation described by the phase in the CKM matrix)

- **BUT:** experimental evidence (neutron and nuclear beta-decay)
- Experimental upper limits for $\left|C_S/C_V\right|$ & $\left|C_T/C_A\right|$ at the % level (*n* & nuclear β-decay)

# Standard Model and beyond

**Standard Model :** works well, but still problems

- too many ‘parameters’ (masses, fine structure constant, …)
- a number of not-well understood features (e.g. parity violation, baryon-antibaryon asymmetry, unification with gravitation, etc.)

- New physics beyond SM already experimentally found (neutrino oscillations !)

→ General belief that SM is a “low” energy (~ 200 GeV) approximation of more fundamental theory

Search for physics beyond the SM in the sector of the weak interaction :

- at high energy colliders (CERN, Fermilab, DESY, …)
- in neutrino physics (Antares, SuperKamiokande, AMANDA, β-beams, …)
- in atomic physics (e.g. parity violation)
- in nuclear beta decay (correlations, ft-values, …)

High-energy and low-energy experiments are complementary – it is useful to test the SM in different energy domains.

# Low energy search

**Correlations in β-decay** – search for new time reversal invariant S- and T-interactions

**β -asymmetry** – **A** parameter (**Tensor** interaction)
Study of low-energy β-decay (the lower energy, the higher sensitivity to possible tensor contribution)

Study of correlation between the spin of β-decaying nucleus and momentum of emitted β-particle
⇓
Measurement of the angular distribution of β-particles emitted during β-decay of oriented sample (nuclear orientation experiments - **NICOLE**)

**β-ν correlation** - **a** parameter (**Scalar**, **Tensor** interaction)
Difficulty to detect neutrinos ⇒ study recoil nuclei instead of neutrinos
⇓
1) Using ion or atom traps to get radioactive sources with required properties (isotopically pure, localized in small volume, negligible source scattering, decay at rest,…) , detect recoil nuclei
2) Doppler shift of energy of protons emitted in beta-delayed proton decay
⇓
1) **WITCH** – combination of double-Penning trap + retardation spectrometer at ISOLDE-CERN – measuring energy spectra of nuclei recoiling after β-decay (of $^{35}$Ar)
2) **WISArD** - measuring Doppler shift of beta-delayed protons in decay of $^{32}$Ar

# High energy search

search for "exotic" particles whose exchange could create possible scalar- or tensor-type interactions not included in Standard Model (charged Higgs, leptoquarks, right-handed bosons, …)

Correspondence of High x Low-energy searches (sensitivity of beta-neutrino correlation):

$\Delta a = 0.01 \rightarrow$ sensitive to masses of new bosons of $\sim (0.01)^{-1/4}$ M $\approx 215$ GeV/$c^2$

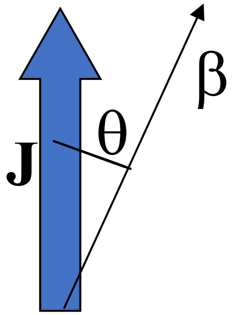
$\Delta a = 0.002 \rightarrow$ sensitive to masses of new bosons of $\sim (0.002)^{-1/4}$ M $\approx 320$GeV/$c^2$

("handwaving estimate")

- experimental upper limits for $\left|{}^{C_S}/_{C_V}\right|$ & $\left|{}^{C_T}/_{C_A}\right|$ are currently at the % level (*n* & nuclear β-decay) , extending the limit to ‰ level allows setting lower limits on new boson whose exchange could create possible Scalar or Tensor-type interactions (mass ~ 2.5 TeV)

# β-asymmetry – search for **TENSOR type weak interactions**

$$W(\theta) = 1 + \bar{J} \cdot \frac{\bar{p}}{E_e} A$$




$$\lambda_{J'J} = \begin{cases} -1 & \text{for } J \to J-1 \\ -\frac{J}{J+1} & \text{for } J \to J+1 \end{cases}$$

$$\gamma = \sqrt{1-(\alpha Z)^2}$$

**Asymmetry parameter A for a pure Gamow-Teller transition :**

$$A_{GT}^{\beta^{\mp}} \cong \lambda_{J'J} \left[ \mp 1 + \frac{\alpha Z m}{p} \mathrm{Im}\left( \frac{C_T + C_T'}{C_A} \right) + \frac{\gamma m}{E_e} \mathrm{Re}\left( \frac{C_T + C_T'}{C_A} \right) \right]$$

(assuming maximal P-violation and T-invariance for V- and A-interactions, tensor interaction admixture rather small)

**$-0.008 < \mathrm{Im}\,(C_T+C'_T)/C_A < 0.014$ (90% CL)** from $^8$Li @ PSI, R. Huber et al., PRL 90 (2003) 202301

***$\Delta A/A$* = 0.01 → (for $\gamma m/E_e \cong 0.5$) Re $[(C_T+C_T') / C_A] < 0.040$ (95% CL)**

recoil corr. (induced form factors) ≈ $10^{-3}$; radiative corrections ≈ $10^{-4}$

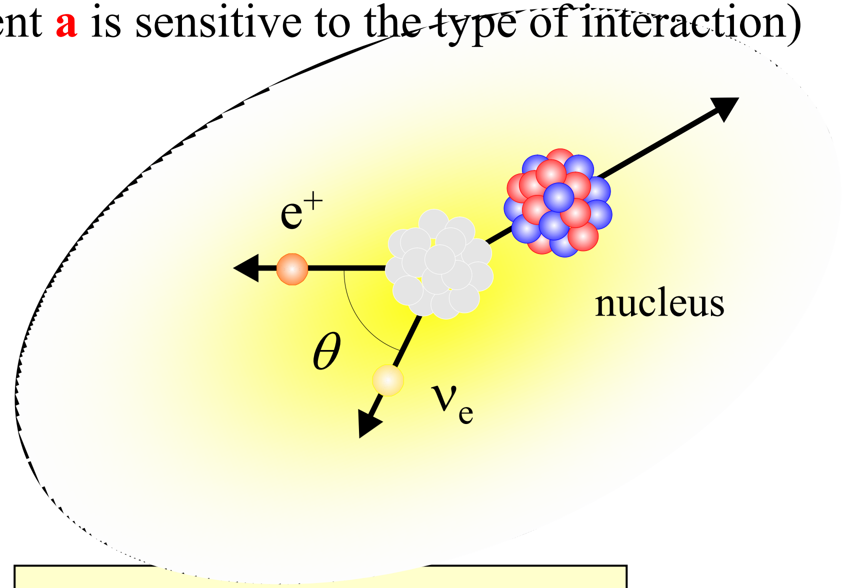
# Study of β-ν correlations in β-decay ⇒ study of structure of weak interactions

(search for SCALAR and TENSOR type weak interactions)

**β-ν correlation** (angular correlation coefficient **a** is sensitive to the type of interaction)

$$\Rightarrow \quad W(\theta) = 1 + \frac{\bar{p}\cdot\bar{q}}{E_e E_\nu}\tilde{a}$$

with $\tilde{a} \equiv \dfrac{a}{1+\dfrac{\Gamma m}{E_e}b}$ and $\Gamma = \sqrt{1-(\alpha Z)^2}$




$$a_F \cong 1 - \frac{|C_S|^2 + |C'_S|^2}{|C_V|^2}$$

$$a_{GT} \cong -\frac{1}{3}\left[1 - \frac{|C_T|^2 + |C'_T|^2}{|C_A|^2}\right]$$

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

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

(assuming maximal P-violation and T-invariance for V- and A-interactions)

# NICOLE

# β-asymmetry measurements - Nuclear Orientation (NO)

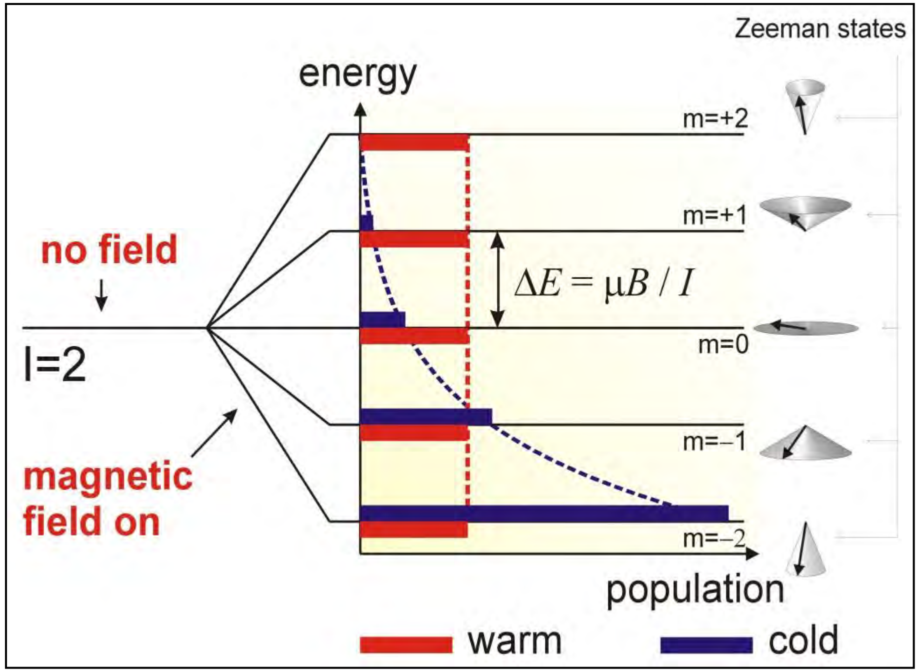
study of correlation between the spin of decaying nucleus and the momentum of emitted beta-particle

**Nuclear Orientation :**

Interaction of the nuclear magnetic moment with the external mgt. field ⇒ **equidistant** splitting of sublevels

**“warm” sample** ⇒ same population of sublevels ⇒ unoriented sample ⇒ **isotropic** emission of particles

**“cold” sample** (cooled to ~10mK) (thermal energy lower than the energy of magnetic interaction) ⇒ different population of sublevels ⇒ **anisotropy**




- Necessity to get **high** enough magnetic **field** **AND** **low** enough **temperature**
- Practically reachable values : ~ 10-20mK, ~$10^0$-$10^2$ T ($^3$He–$^4$He dilution refrigerator)
- 1) **Standard NO** : implantation in a ferromagnetic matrix oriented by the weak external mgt. field ($10^{-1}$ T) ⇒ nuclei oriented by interaction with hyperfine field (could be easily $10^2$ T), small influence of low external field on emitted beta-particles, BUT “fraction in good sites”
- 2) **Brute force NO** : strong external mgt. field ⇒ no fraction, but drastic influence of mgt. field on low-energy beta-particles

# Nuclear orientation (for β-particles)

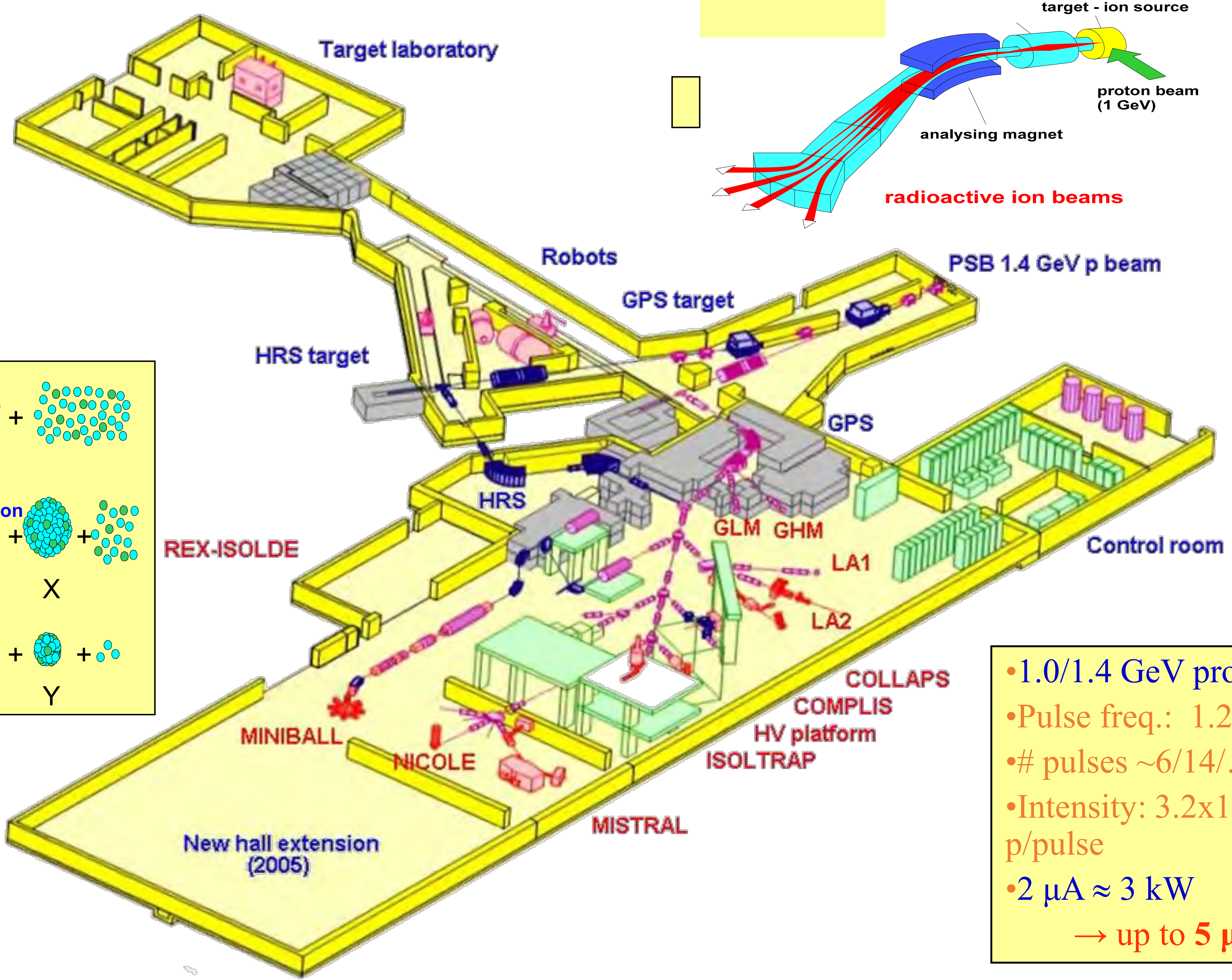
- Measure $$W(\theta) \equiv \frac{N_{cold}(\theta)}{N_{warm}(\theta)} = 1 + f\,\tfrac{v}{c}\,A_1 B_1 Q_1 \cos(\theta)$$

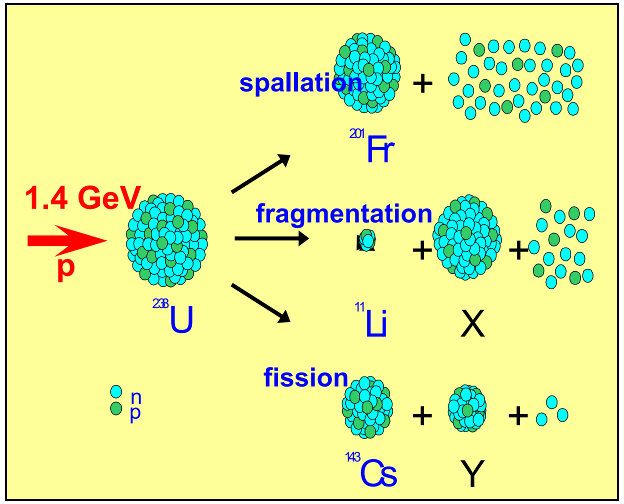
- f : fraction of nuclei feeling $B_{hf}$
  from γ transition asymmetry or measurement of other isotope
- v/c : relative velocity of β-particles
  energy spectrum of β
- ***A*** : angular distribution coefficient
  to determine $C_T$
- *B* (*T*, μ *B* / *I* ): orientation parameter
  measure T + known μ and $B_{hf}$ (or NMR/ON)
- *Q* : solid angle (+ effects of magnetic field & scattering & geometry)
  calculate (MonteCarlo simulations)

**Standard NO**: difficult to determine **f**, **Q** simulated with good precision

**Brute force NO**: **f** drops out, very difficult **Q** (strong mgt. field)

# ISOLDE



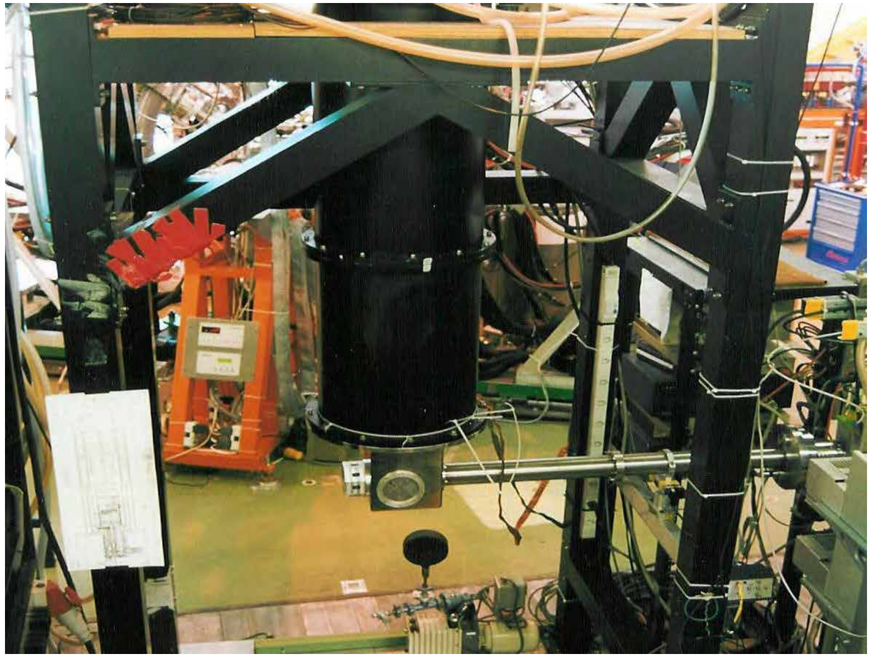



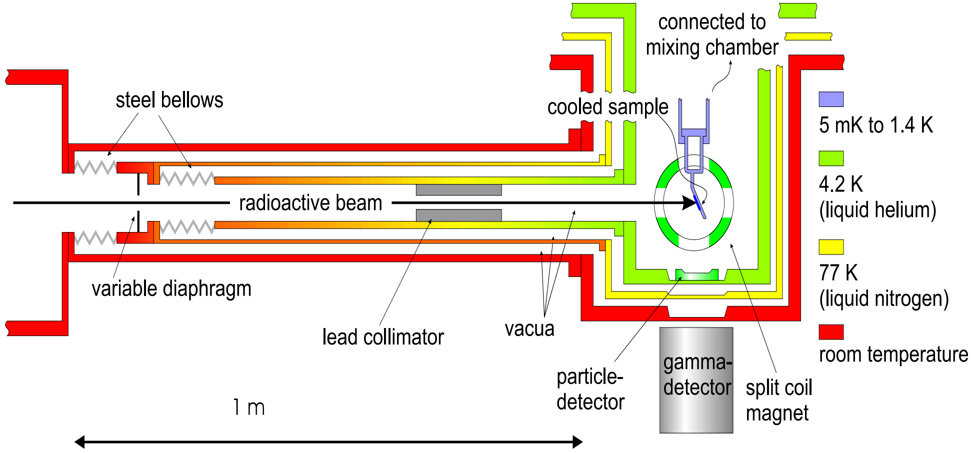

- 1.0/1.4 GeV protons
- Pulse freq.: 1.2 s
- # pulses ~6/14/…/40
- Intensity: $3.2 \times 10^{13}$ p/pulse
- 2 μA ≈ 3 kW
  → up to **5 μA**

# Nuclear Orientation - NICOLE

## $^3$He–$^4$He online dilution refrigerator

- RA isotopes implanted into the ferromagnetic foil (high purity Fe)
- sample holder cooled to ~10mK
- nuclei oriented in mgt. field
  - external field from the superconducting magnet ~0,3T
  - hyperfine field ~ $10^1 \div 10^2$ T
- $\beta^+$-decay of oriented nuclei → emission of positrons → angular distribution

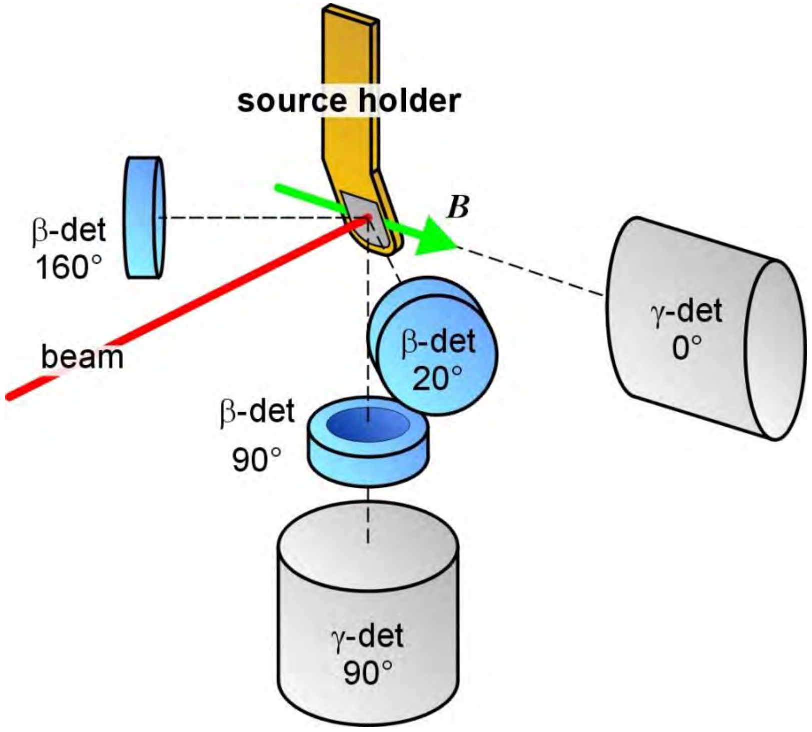


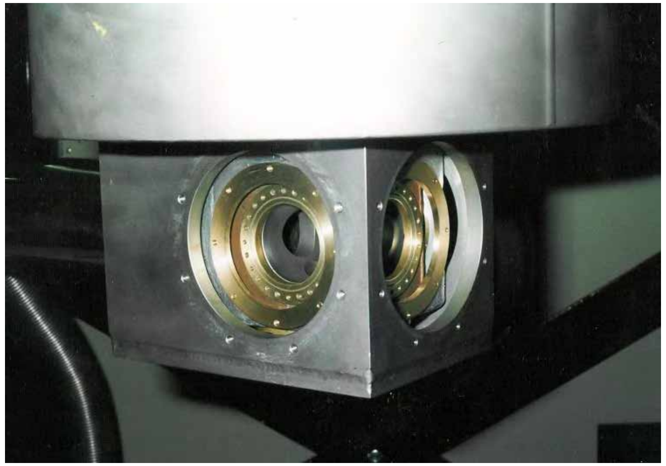


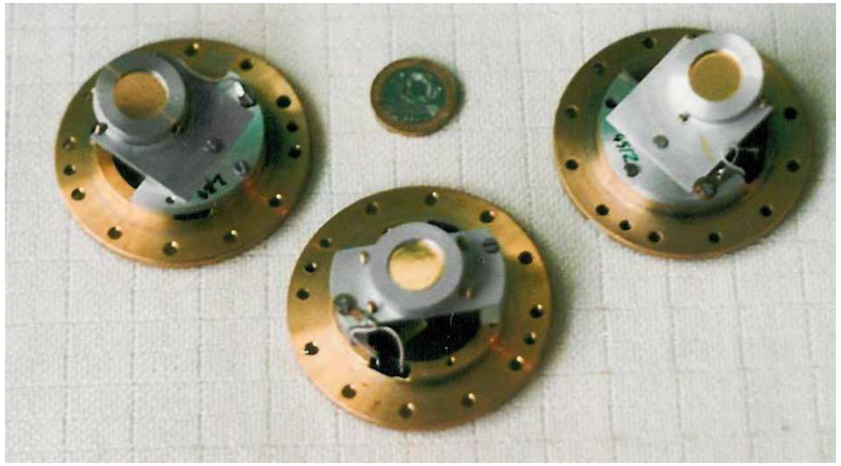
# NICOLE – detector's geometry

**Detectors:**

- 3 **HPGe β particle detectors** inside of the refrigerator (operating at 5 K)
- 2 **γ detectors** outside of refrigerator



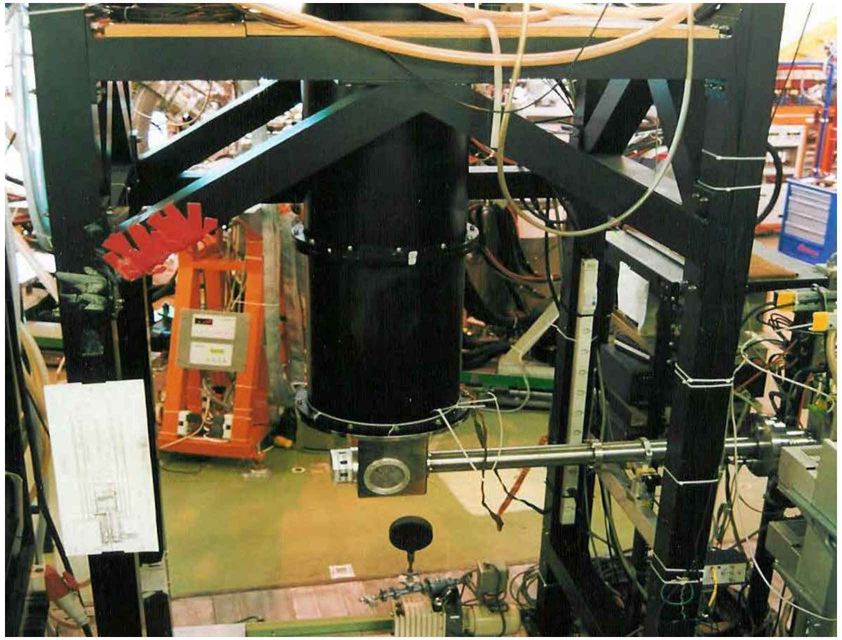





# β-asymmetry measurements at ISOLDE-CERN

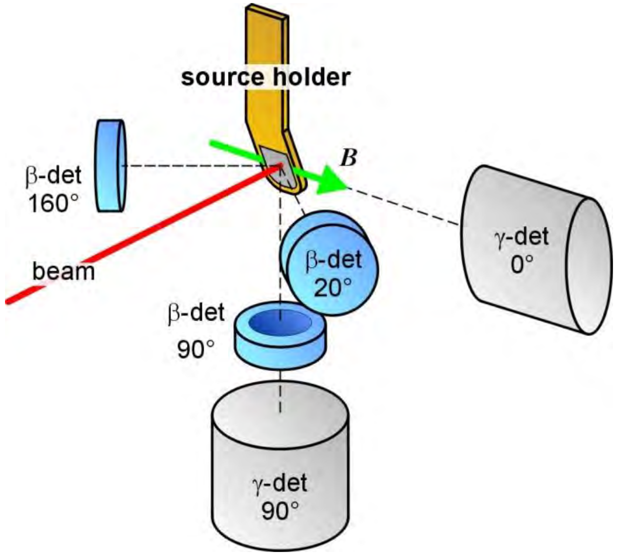
## (search for Tensor type weak interaction)

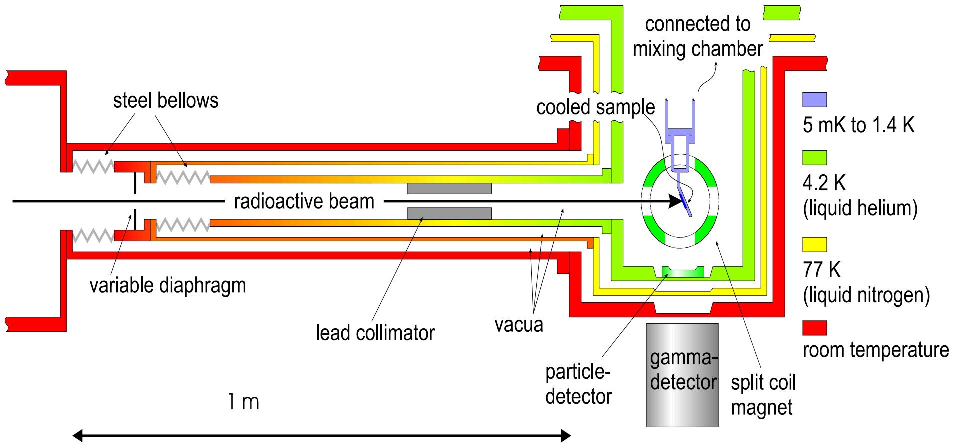
## LTNO online dilution refrigerator NICOLE at ISOLDE

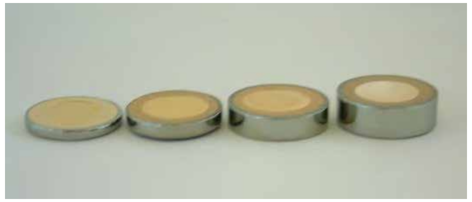


- sample holder at ~10mK
- external mgt. field ~0,3T : superconducting magnet
- 3 **HPGe β particle detectors** inside of the refrigerator
- 2 γ detectors outside of the refrigerator

**Geometry of detectors**

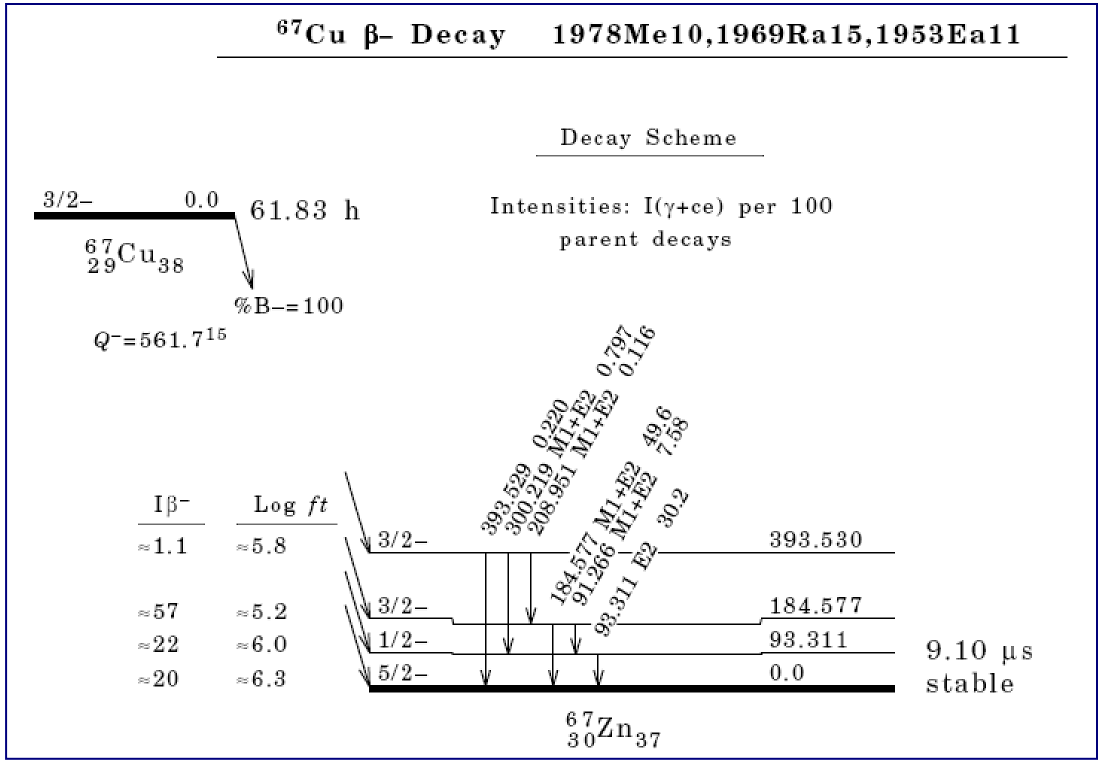


**β-detectors:**
**planar HPGe (NPI-Řež),**
**∅ = 18 mm, at T ~ 10 K**

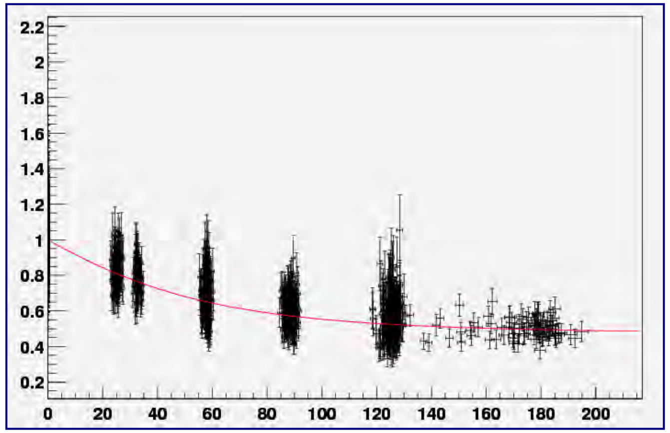
# Experiment $^{67}$Cu




**Experimental conditions**

$^{67}$Cu 60 keV implantation in Fe

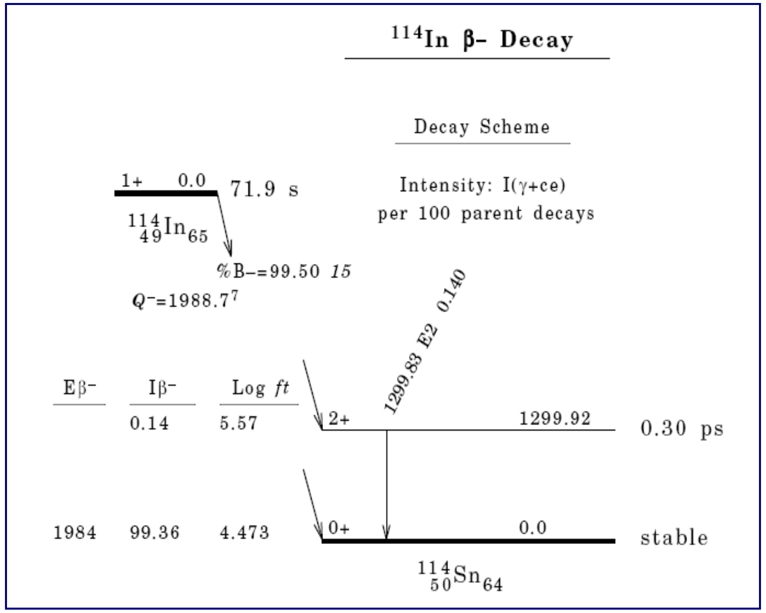
- $B_{hf}$ Cu(Fe) = -21.82(1) T
- γ\`s from $^{57}$Co for temperature determination and γ\`s from $^{68}$Cu for calibration
- Measured with HPGe particle detectors at NICOLE (ISOLDE)
- External field of 0.1 T




- Pure GT decay ( $3/2^- \rightarrow 5/2^-$)
- Log ft just low enough
- Low endpoint energy (576 keV), large sensitivity for tensor currents ($\gamma m/E_e$ = 0.43)

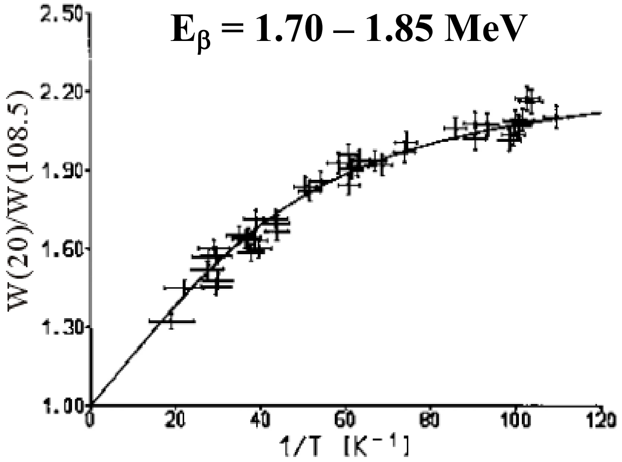
- Good quality data, but low statistics (production Cu in ISOLDE)
- preliminary value of A (with only estimated systematic effects) : **A= 0.427(6) ($A_{SM}$ = 0.447)**

# Experiment $^{114}$In




## Experimental conditions

- Orientation with hyperfine interactions, small external field (0.046 T, 0.093T and 0.186 T)
- $B_{hf}$ = -28.7 T
- Use of HPGe detectors




## Analysis

- Only endpoint region used to extract A parameter
- γ`s from $^{114m}$In and $^{60}$Co used for calibration
- The GEANT4 correction (v/c*Q*cos(θ)) very small (only 2 % difference from the geometrical solid angles of the detectors)

- Pure GT decay ($1^+ \rightarrow 0^+$)
- Low Log ft (4.473) → small recoil corrections (‰ level)
- 1,98 MeV endpoint energy ($\gamma m/E_e$ = 0.21)

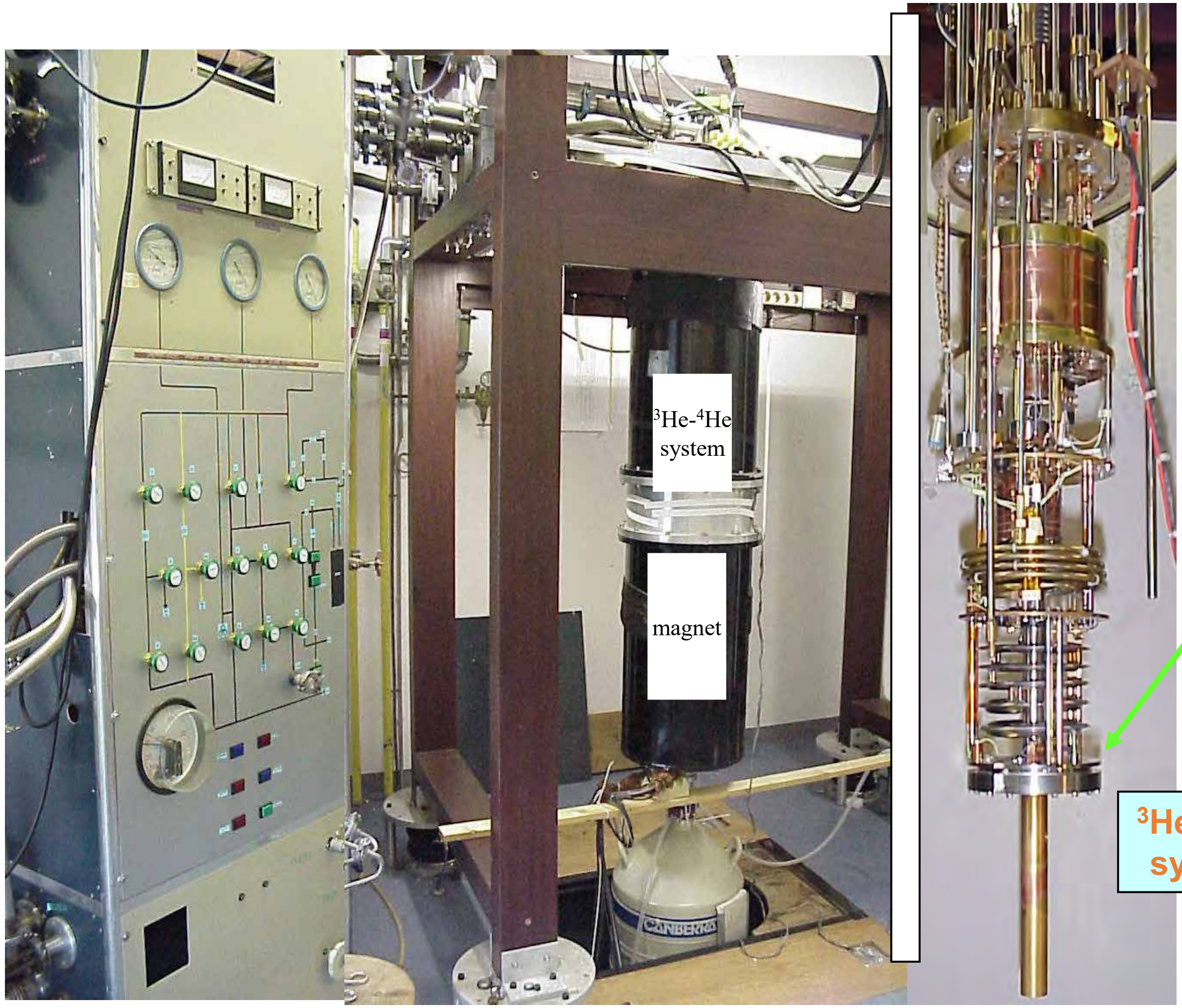
**Results:**

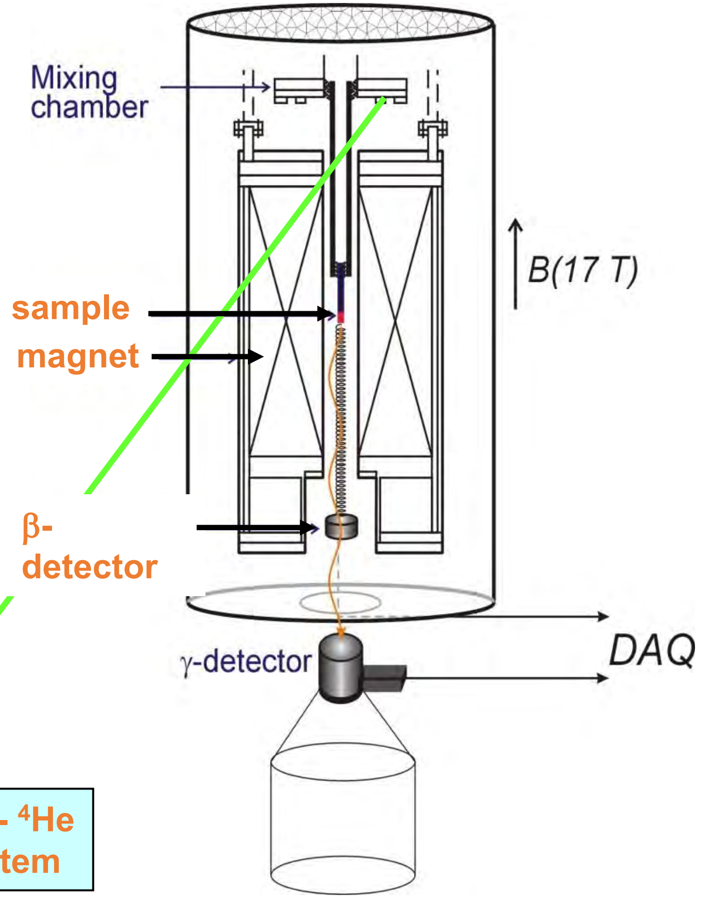
**Most precise result of the β-asymmetry parameter A for a fast pure GT-transition to date.**
Competitive/Comparable limits on time reversal invariant tensor currents with those from other experiments.
Very precise result for the correlation parameter but due to small value of sensitivity factor **$\gamma m/E_e$ = 0.21** the limits on tensor currents are less strict ⇒ need still a better precision and/or an isotope with a better γm/E

| $B_{ext}$ [T] | fraction $f$ | $\tilde{A}$ |
|---|---|---|
| 0.046 | 0.734(5) | -1.003(9) |
| 0.093 | 0.803(8) | -0.987(13) |
| 0.186 | 0.874(7) | -0.972(11) |
| weighted average | | -0.990(11) |

$$A = -0.990 \pm 0.011(stat) \pm 0.009(syst)$$
$$= -0.990(14) \quad \text{SM-Value} = -1$$
$$\rightarrow -0.05 \le \mathrm{Re}\left(\frac{C_T + C_T'}{C_A}\right) \le 0.17 \text{ (90\% C.L.)}$$

# Brute force LTNO setup in Leuven ($^3He$ - $^4He$ dilution refrigerator with 17T magnet)

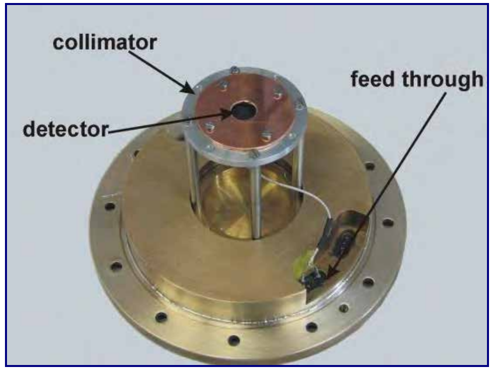


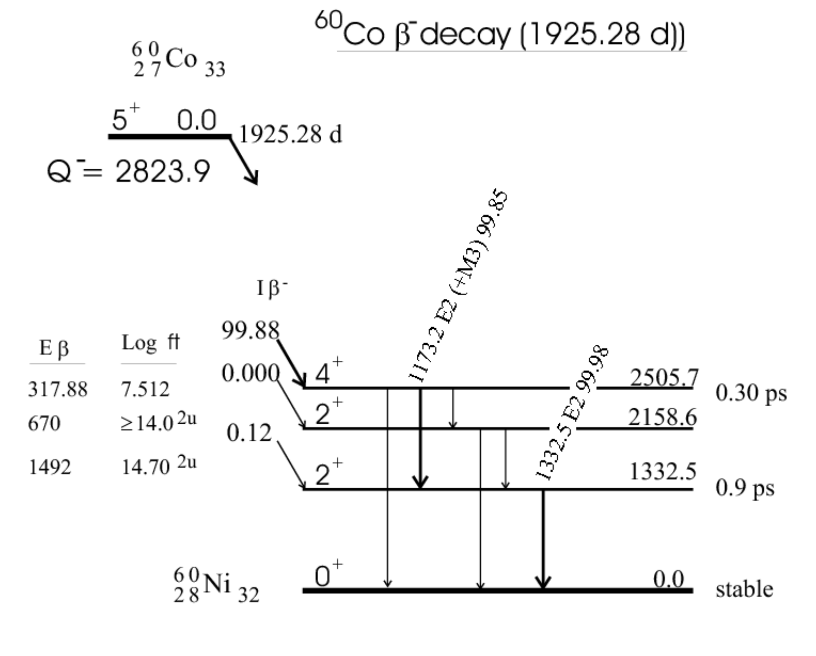

- Off-line setup
- 17T magnet for "brute force" NO
- position for 1 γ-detector and 1 particle detector at $0^o$

**β-detector:**

500 μm Si PIN photodiode ($\varnothing$ = 9 mm), at T ~ 10 K



# Experiment $^{60}$Co



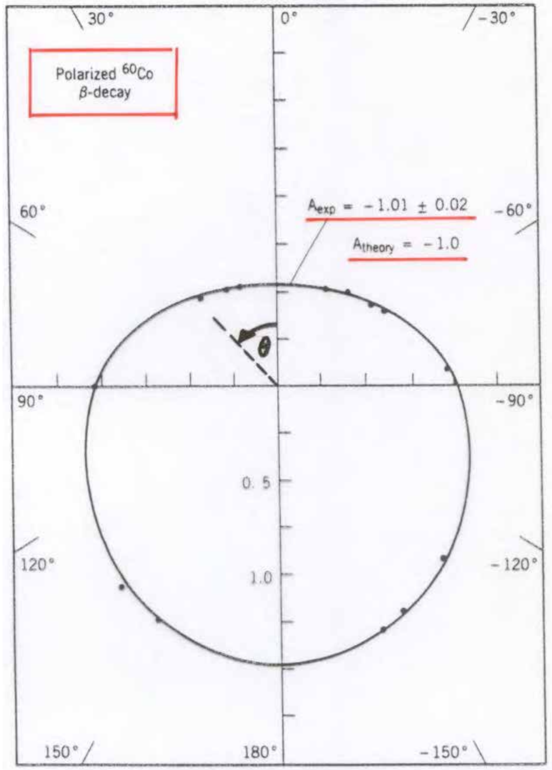

- Pure GT decay ($5^+ \rightarrow 4^+$)
- Log ft of 7,512 → recoil corrections become important
- 317,88 keV endpoint energy ($\gamma m/E_e = 0.604$)
- 1925 days halflife

## Experimental conditions

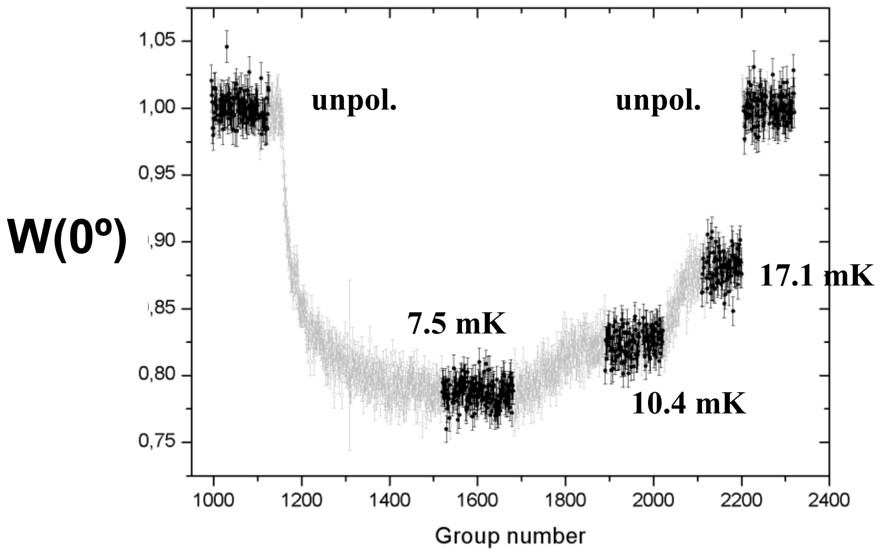
- Orientation with high external field (up to 13 T)
- $^{60}$Co activity diffused in thin Cu foil
- Use of Si PIN diodes detectors
- γ`s from $^{60}$Co, $^{57}$Co and $^{54}$Mn for temperature determination and calibration
- Brute Force Orientation

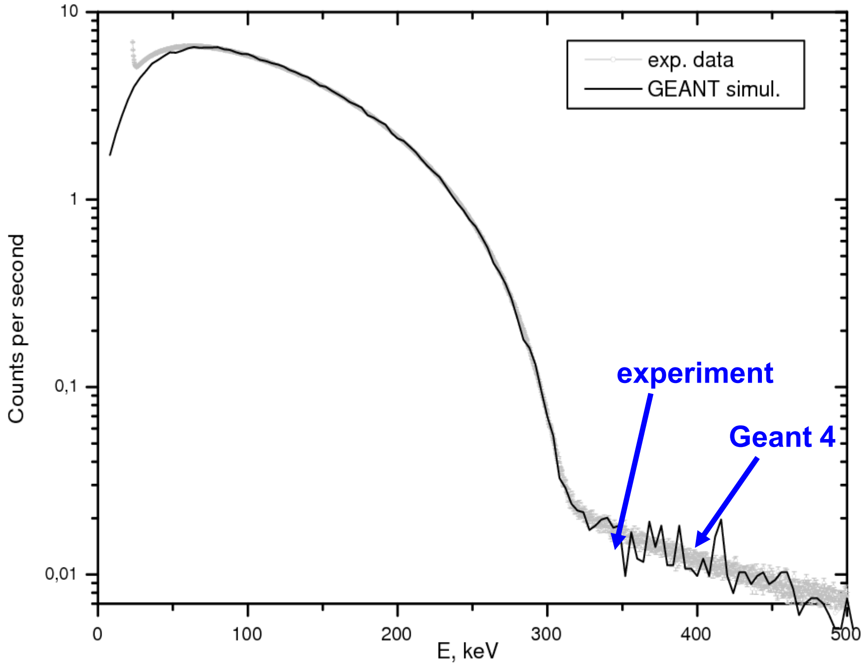
Proof of principle experiment for this method

Try to improve the best experimental value for the β-asymmetry parameter measured with $^{60}$Co (**A = -1.01(2)** , Chirovsky et al., 1984)

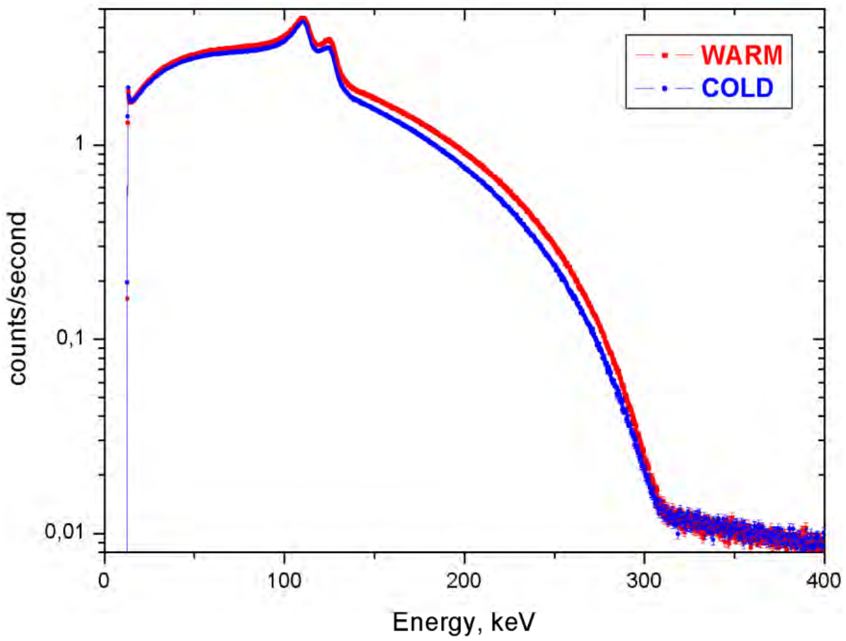


## $^{60}$CoCu β-asymmetry (B = 13 T)




## $^{60}$Co exp. β-spectrum vs. Geant4 (B = 13 T)

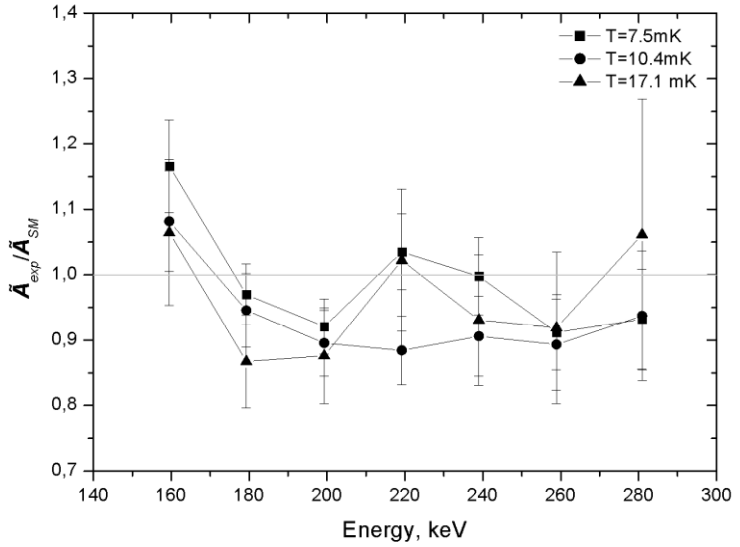



$$W(\theta) \equiv \frac{N_{cold}}{N_{warm}}$$

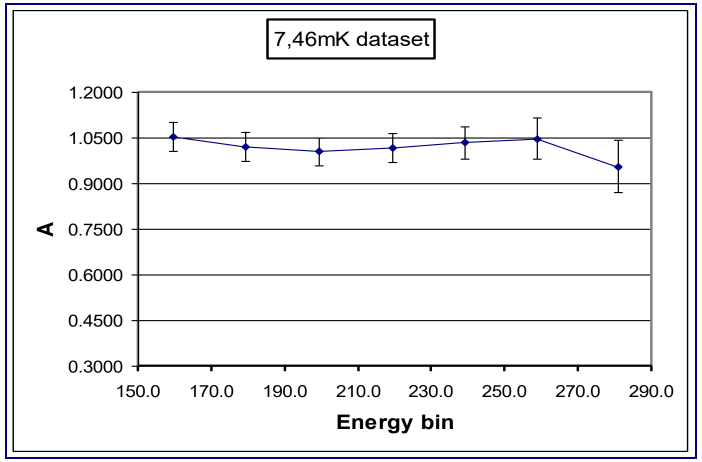
**"cold" – polarized (T ≈ 10 mK)**

**"warm" – unpolarized (T ≈ 4K)**

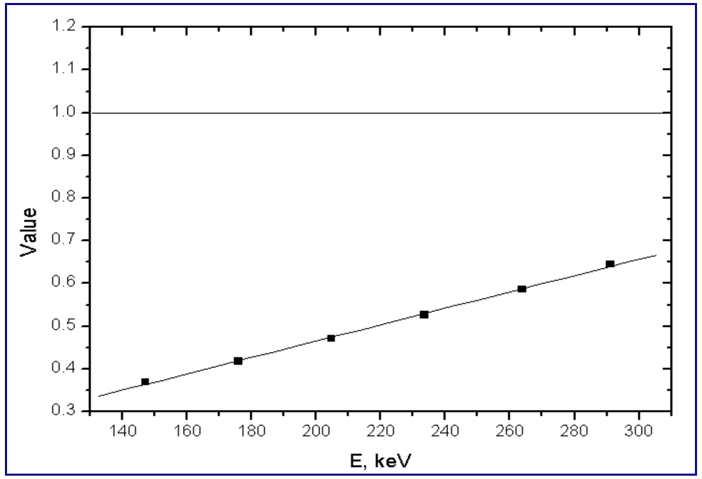
# Exp. result : the β-asymmetry parameter of $^{60}Co$




With GEANT




Without GEANT




| | 13 T , 7.5mK | 13 T , 10.4mK | 13 T , 17.1mK | 9T , 7,4mK |
|---|---|---|---|---|
| A | -1.015(15) | -0.999(45) | -1.05(32) | -0,984(32) |

⇩

$$A_{exp} = -1.014(12)_{stat}(16)_{syst}$$

($A_{SM}$ = -1; recoil corrected value $A_{SM}$ = -0.987(9) )

$\Rightarrow$ $-0.094 < \mathrm{Re}\,[(C_T + C_T')/C_A] < 0.018$

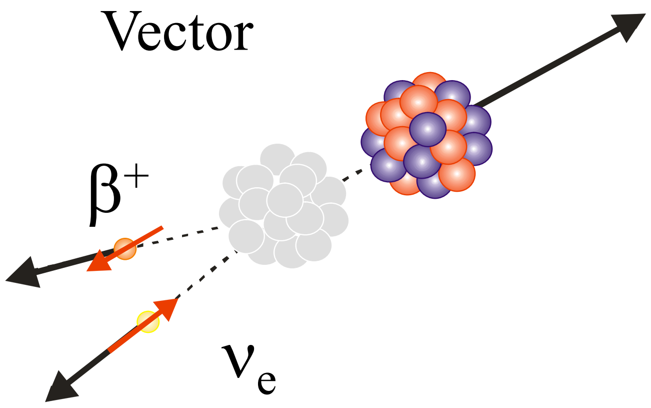
# WITCH

# Physics principle

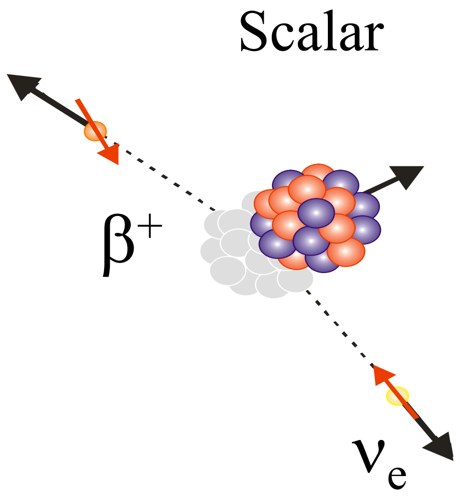
β-ν correlation

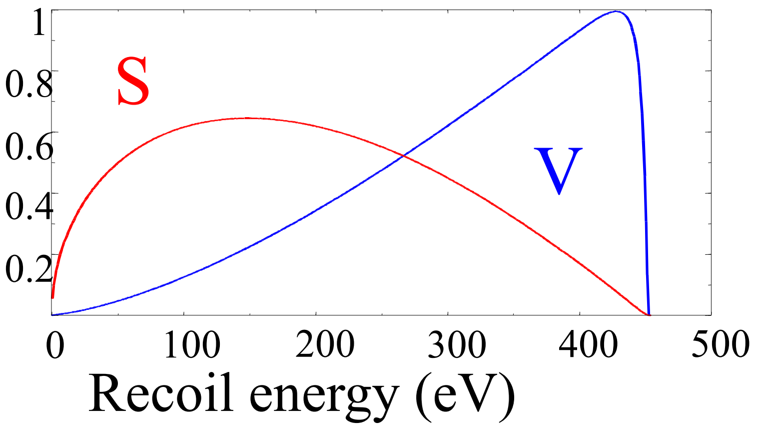
$$W(\theta) \cong 1 + a\frac{v}{c}\cos(\theta)$$

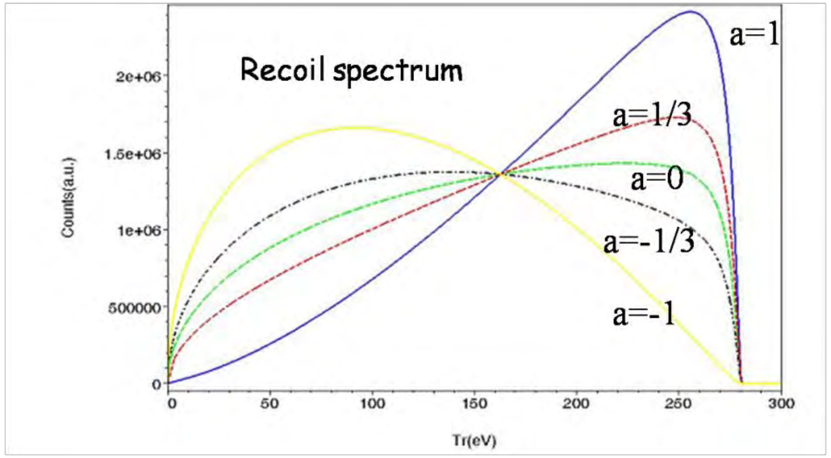
$$a \approx 1 - \frac{|C_S|^2 + |C'_S|^2}{|C_V|^2}$$




**Fermi β+-decay**



# β-ν correlation

Difficulty to detect neutrinos ⇒ study recoil nuclei instead of neutrinos

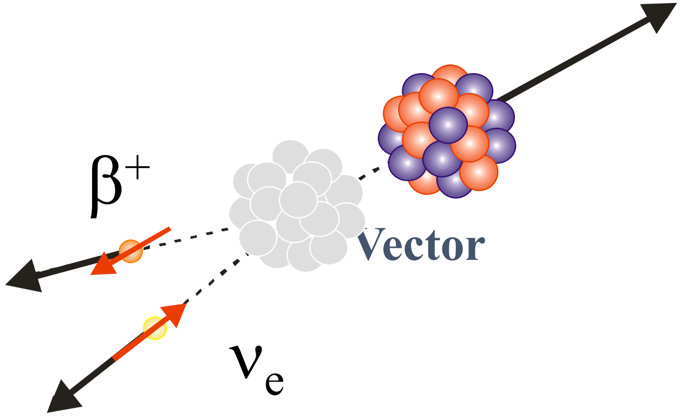
⇓

Using ion or atom traps to get radioactive sources with required properties (isotopically pure, localized in small volume, negligible source scattering, decay at rest,…)

⇓

**WITCH (Weak Interaction Trap for Charged Particles)** – combination of double-Penning trap + retardation spectrometer at ISOLDE-CERN – measuring energy spectra of nuclei recoiling after β-decay

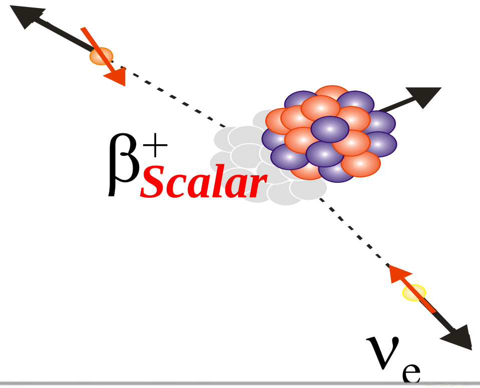
**Main goal :** search for **scalar weak interaction** by measuring shape of **recoil ion energy spectrum** after β-decay

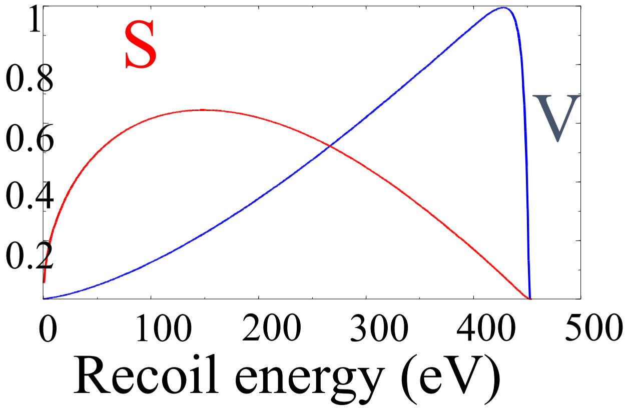



Fermi $\beta^+$-decay

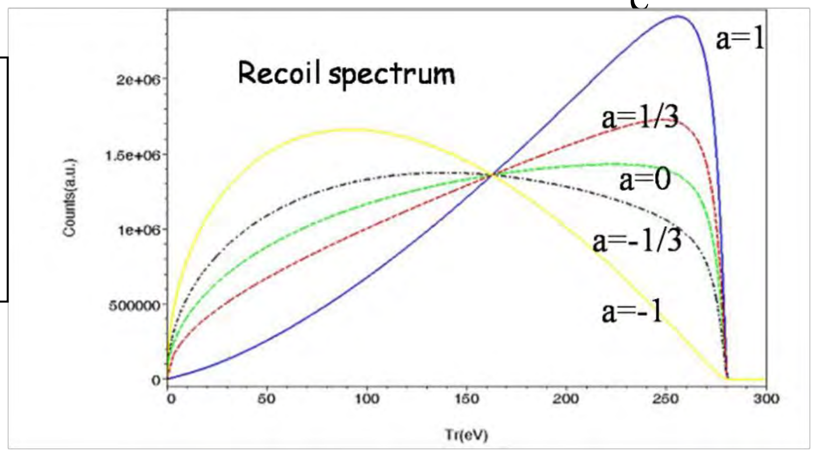
$$W(\theta) \cong 1 + a\frac{v}{c}\cos(\theta)$$

$$a \approx 1 - \frac{|C_S|^2 + |C_S'|^2}{|C_V|^2}$$



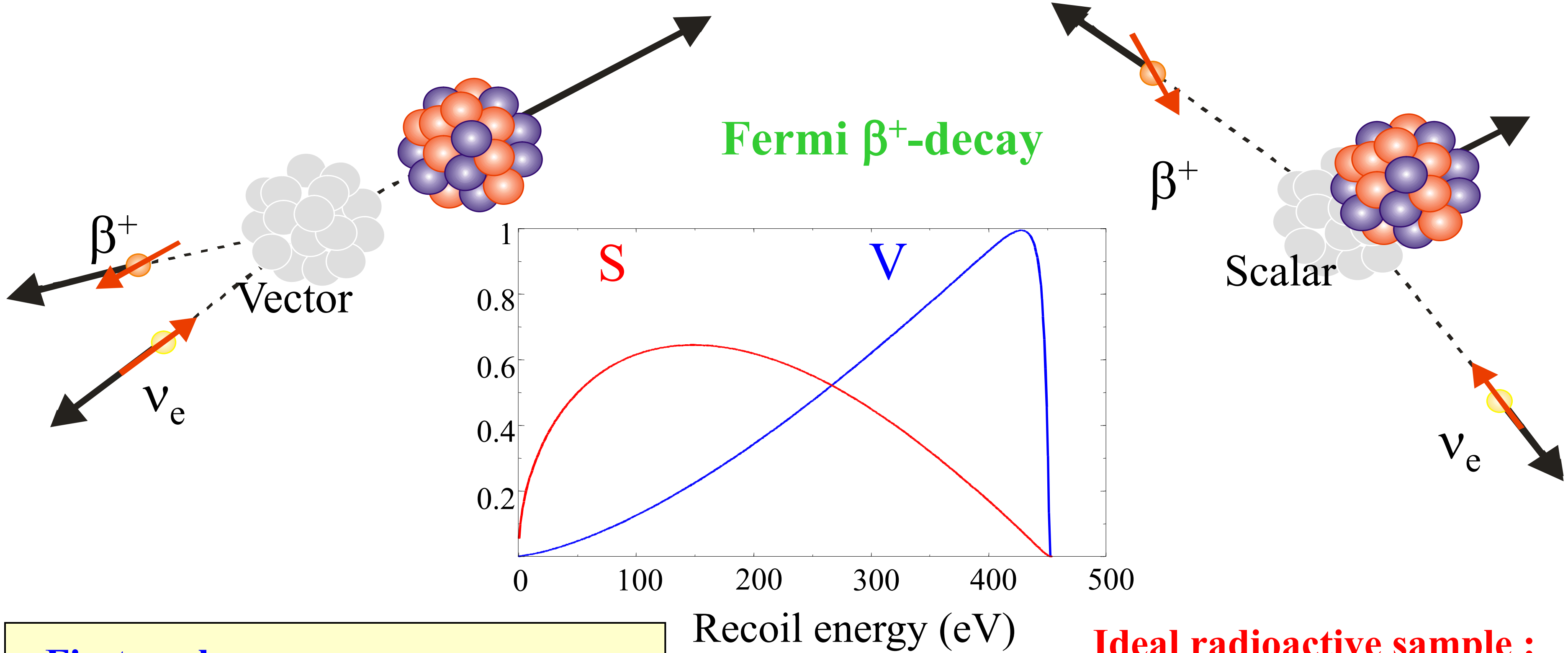

Shape of recoil nuclei energy spectra is very different for the scalar and vector components



# WITCH – Weak Interaction Trap for CHarged particles

ISOLDE-CERN (K.U.Leuven, Univ. Munster, CERN, Rez)

**cooler & decay Penning trap + retardation spectrometer**




**First goal :**

**search for scalar weak interaction by measuring shape of recoil ion energy spectrum after β-decay**

**Ideal radioactive sample :**

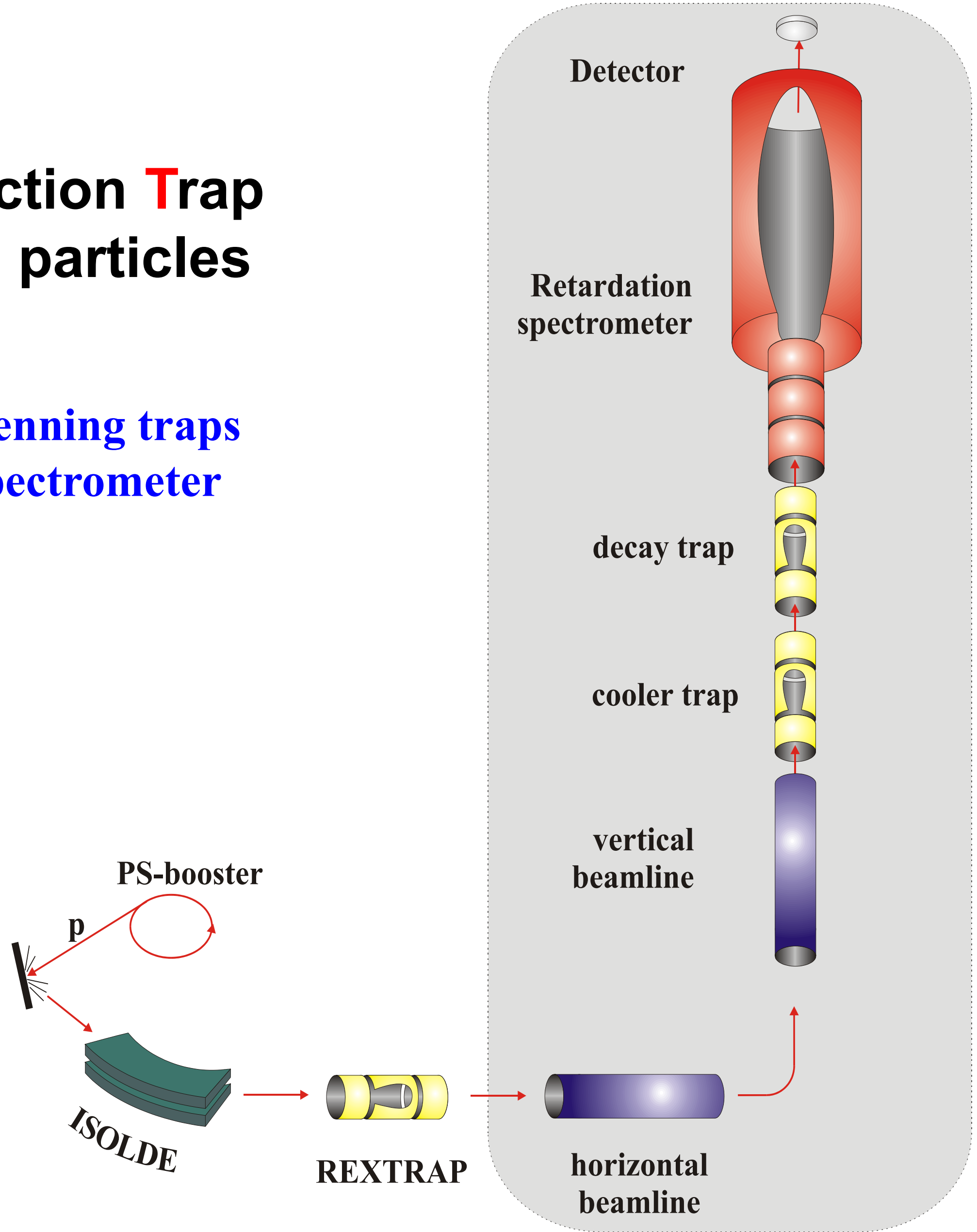
- sample is isotopically pure
- localized in small volume
- source scattering negligible
- atoms/ions decay at rest
- potential for polarized sample

# WITCH double-Penning trap system at ISOLDE-CERN

K.U.Leuven, ISOLDE-CERN, Uni Münster, GSI, NPI-Řež (Prague)

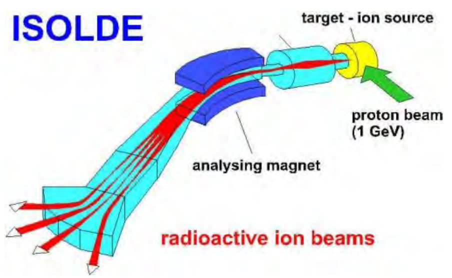
**Weak Interaction Trap**
**for CHarged particles**

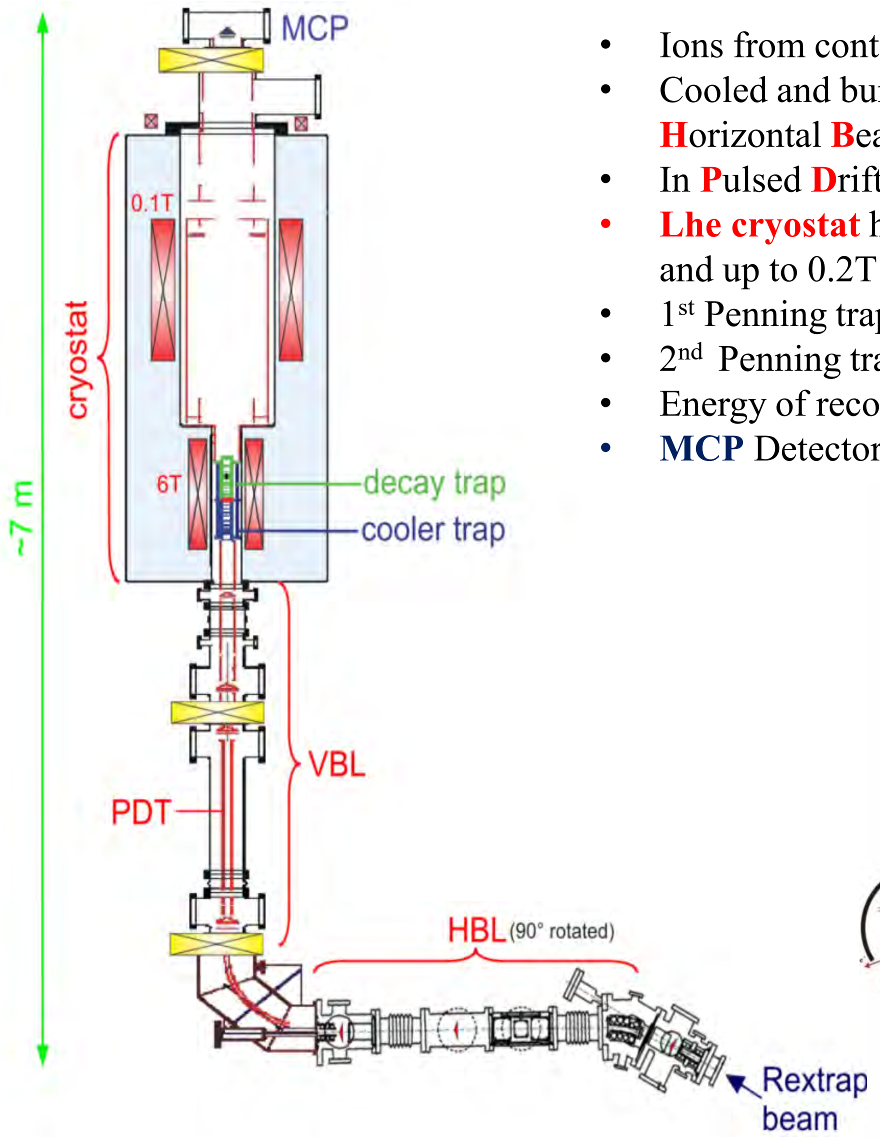
**cooler & decay Penning traps**
**+ retardation spectrometer**



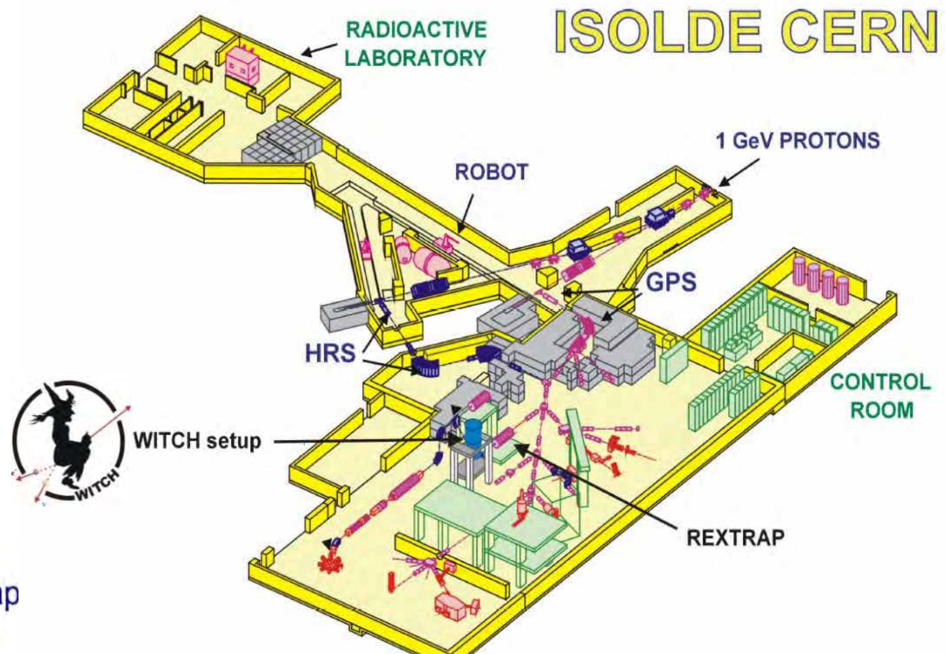
# WITCH - Weak Interaction Trap for CHarged Particles

- CERN PS booster beam of $10^{13}$ 1.4GeV protons hits solid ISOLDE target
- Isotopes are ionised, extracted and mass separated by ISOLDE separators (**G**eneral **P**urpose **S**eparator GPS or **H**igh **R**esolution **S**eparator HRS)




- Ions from continuous 30/60keV ISOLDE beam are bunched in REXtrap
- Cooled and bunched 30keV beam from REXtrap is transported through **H**orizontal **B**eam **L**ine to WITCH
- In **P**ulsed **D**rift **T**ube ions are slowed down to ~$10^2$eV
- **Lhe cryostat** houses 2 superconducting magnets with up to 9T field (traps) and up to 0.2T (spectrometer)
- $1^{st}$ Penning trap (**Cooler**) with pure He buffer gas cools the ions to ~$10^{-1}$eV
- $2^{nd}$ Penning trap (**Decay**) stores a scattering free source of decaying nuclei
- Energy of recoiling ions is probed by the retardation spectrometer
- **MCP** Detector counts the ions (plus position sensitive "redundant info")



# WITCH = experimental set-up

**5)** Ion decays in Decay trap (no scatter)

**6)** **If** the energy of the ion > retardation barrier,

**then** the ion is counted by the MCP

**else** the ion is bumped back, not detected

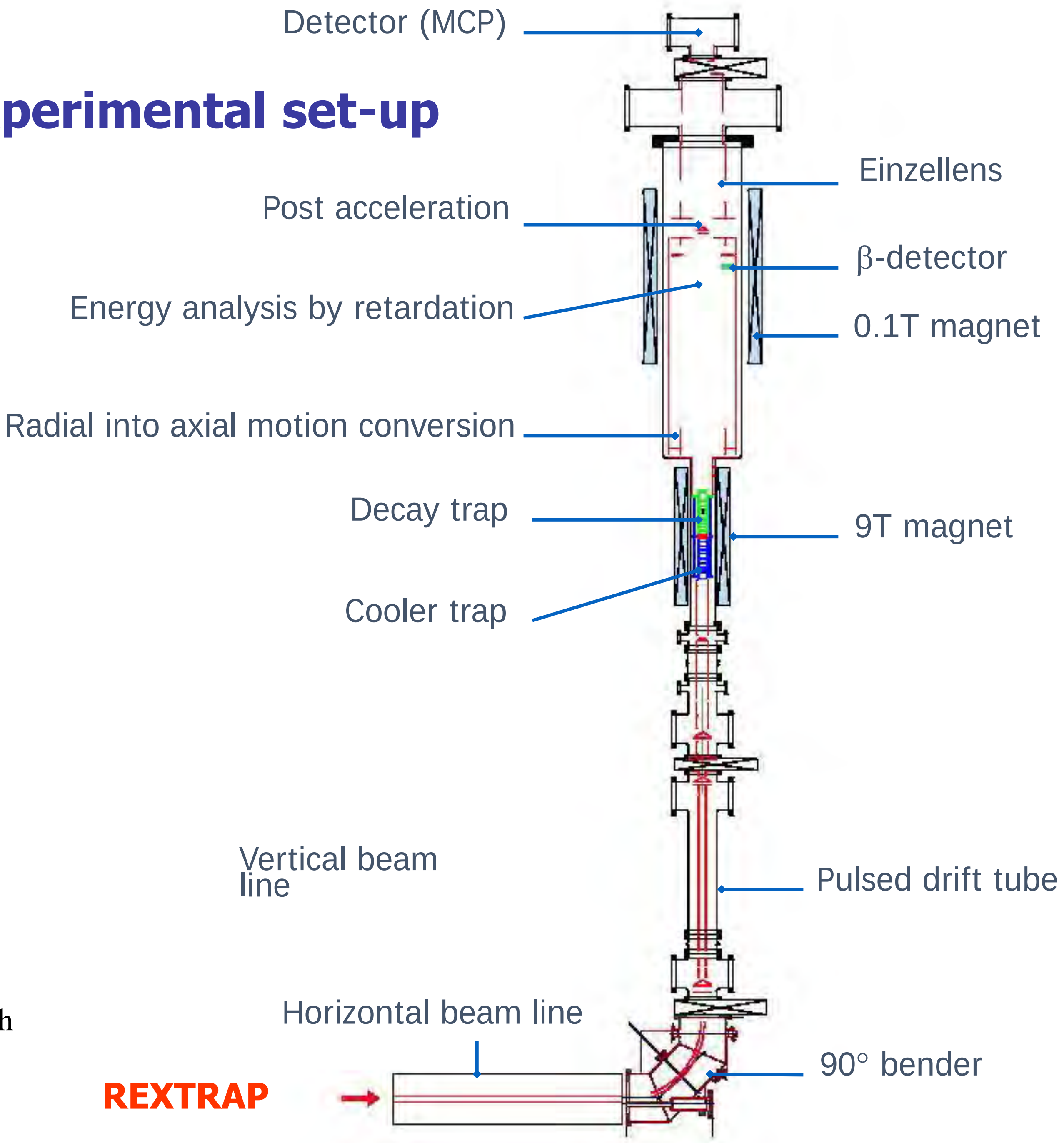
**7)** By changing the retardation barrier, one gets the (integral) recoil energy spectrum

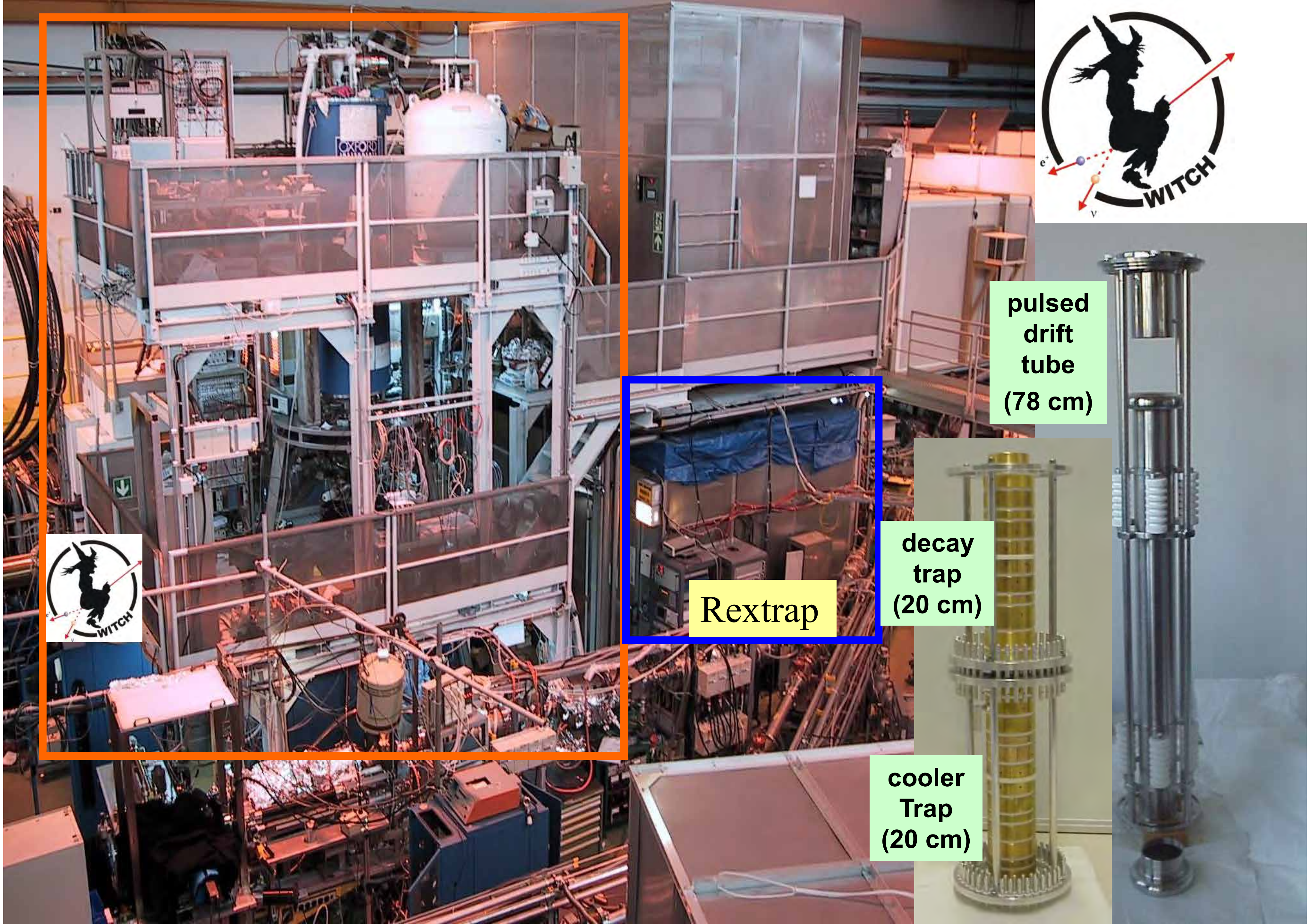
**1)** Pulsed ions from REXTRAP (30keV energy) are delivered to WITCH

**2)** Their energy is reduced in the **Pulsed drift tube** to ~$10^0$eV

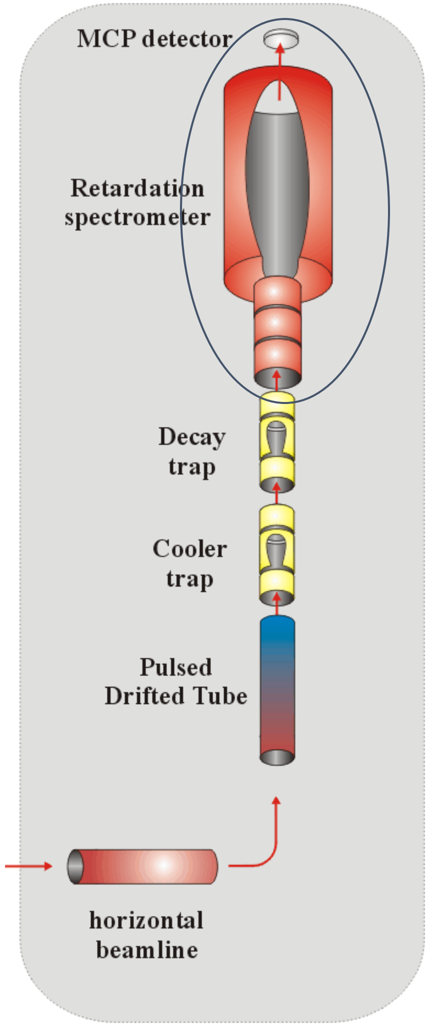
**3)** Ion bunch is trapped and cooled in the **Cooler trap**.

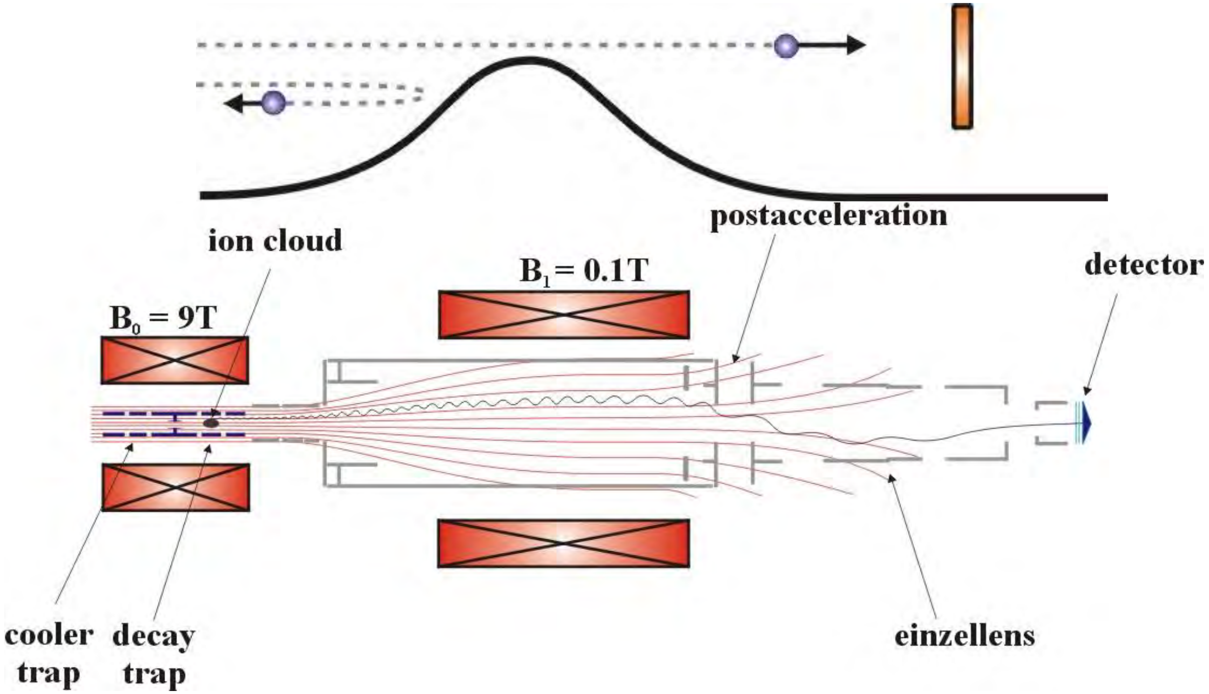
**4)** After transfer to the **Decay trap**, which acts as a scattering free RA source, the actual experimental cycle starts.

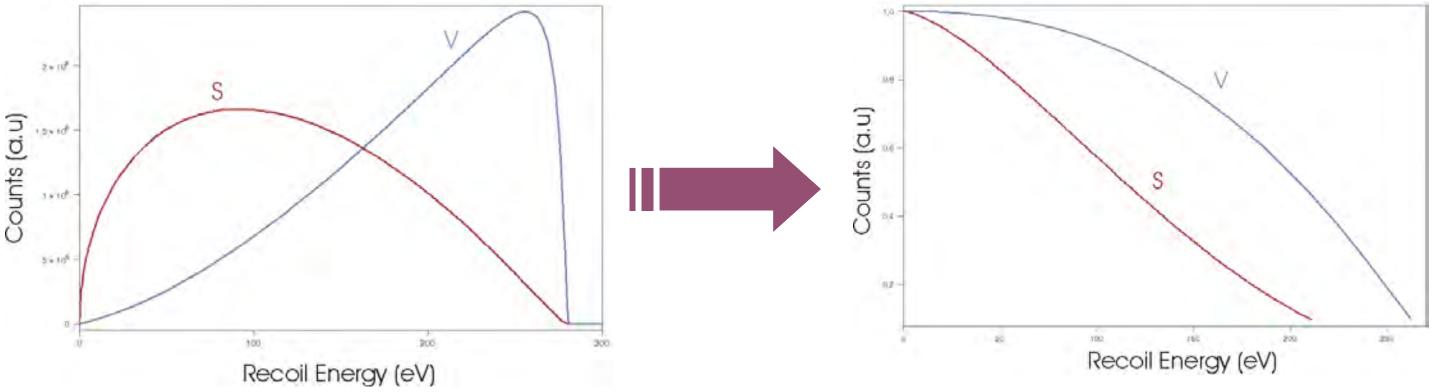



WITCH
Rextrap
pulsed
drift
tube
(78 cm)
decay
trap
(20 cm)
cooler
Trap
(20 cm)
OXFORD

# Retardation Spectrometer

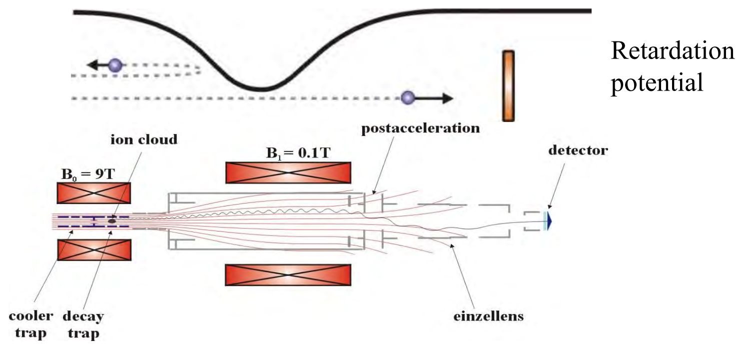


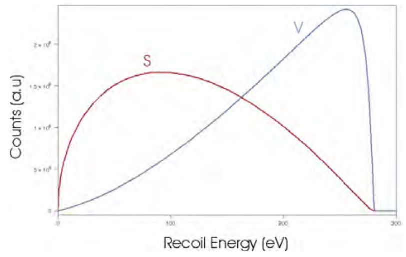



# Measurement of the recoil spectrum

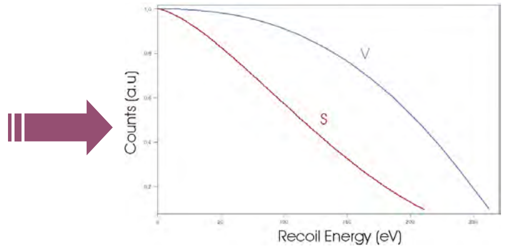
- Energy spectra of nuclei recoiling after the $\beta$-decay are measured by a combination of retardation spectrometer (probes the energy) and MCP detector (counter)
- **Retardation spectrometer**: retardation potential (barrier) blocks the ions with energy below the barrier, only ions with higher energy get further and are registered by MCP
- variation of the blocking potential ⇒ measurement of **integral** recoil spectrum




Differential recoil spectrum




Integral recoil spectrum

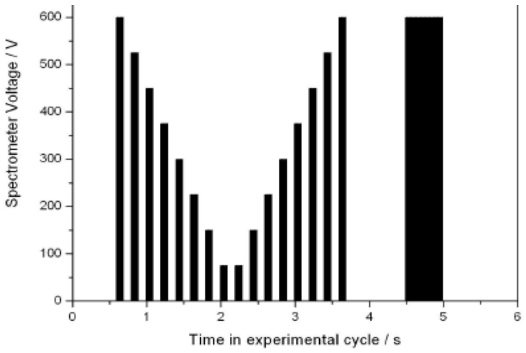



## Experiment :

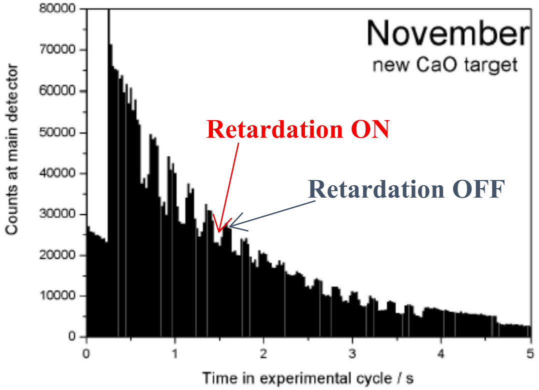
Retardation potential pattern is applied during the 5s measurement cycle after cooled bunch of studied ions were transferred to decay trap and left to decay, after each 5s cycle trap is cleaned and new cycle is started

Typical example of the experimental settings during the 2011 online experiment with $^{35}Ar$

V-shaped retardation voltage pattern

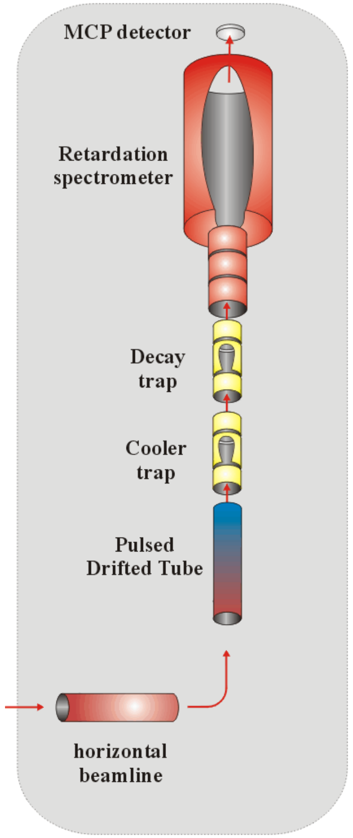


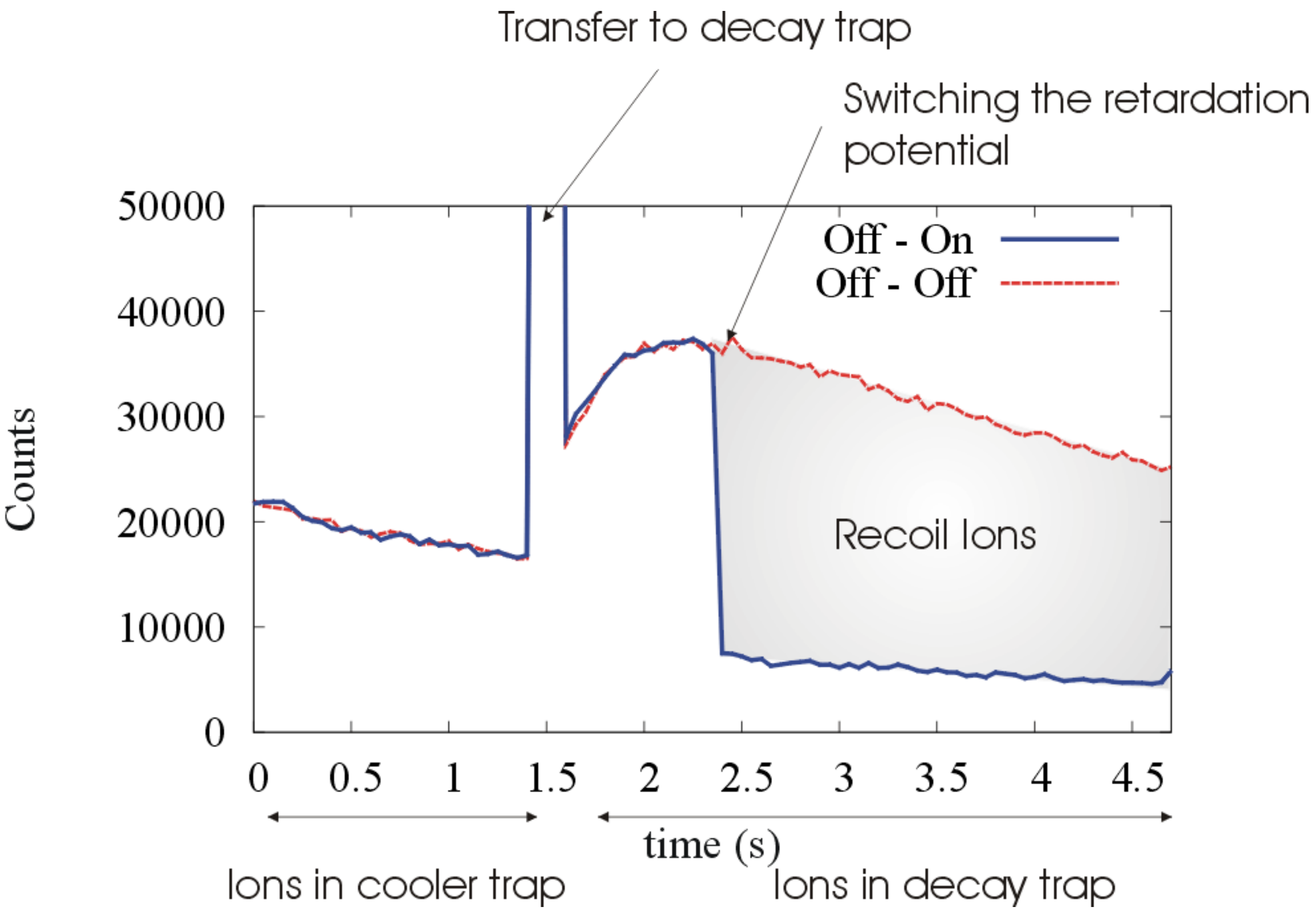

Count rate in MCP detector



# WITCH proof-of-principle experiment

## (recoil spectrum of $^{124}In$)

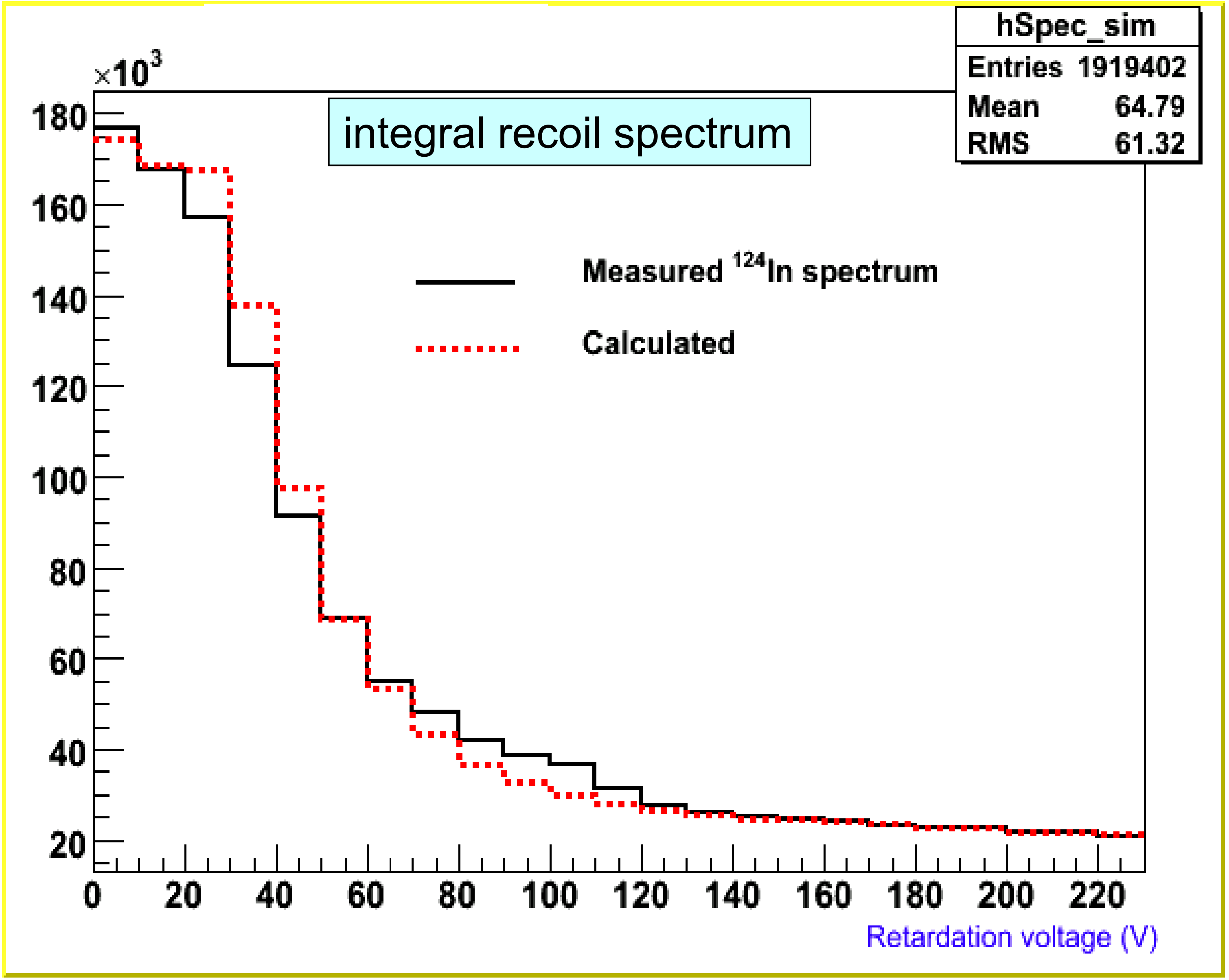



Retardation barrier 400V **On**: recoil ions cannot reach the detector

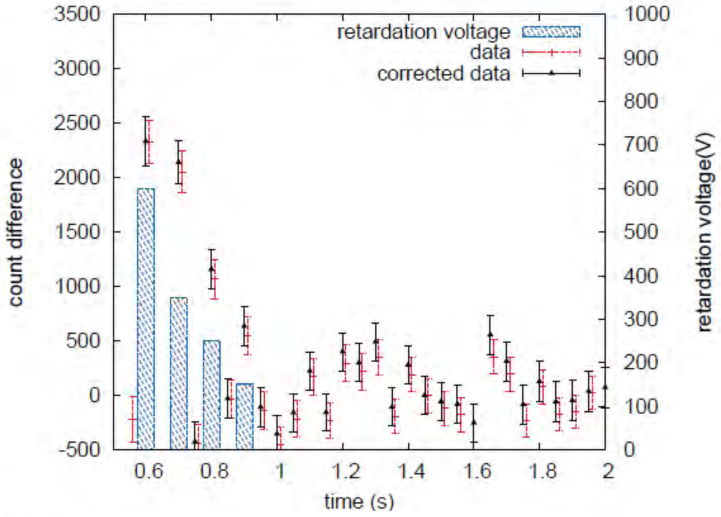
**Off**: all recoil ions can reach the detector

# WITCH proof-of-principle experiment (recoil spectrum of $^{124}$In)

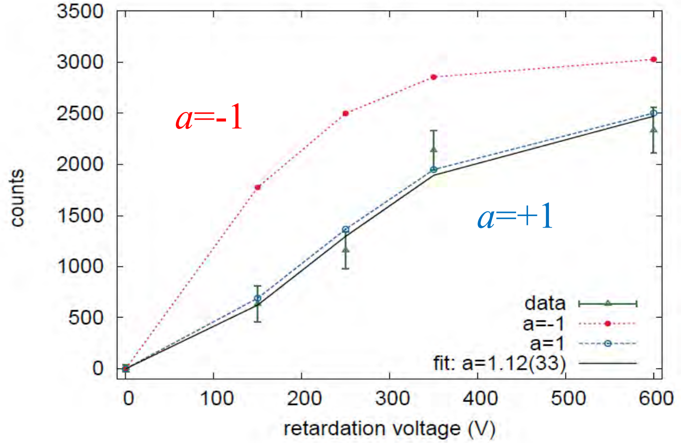


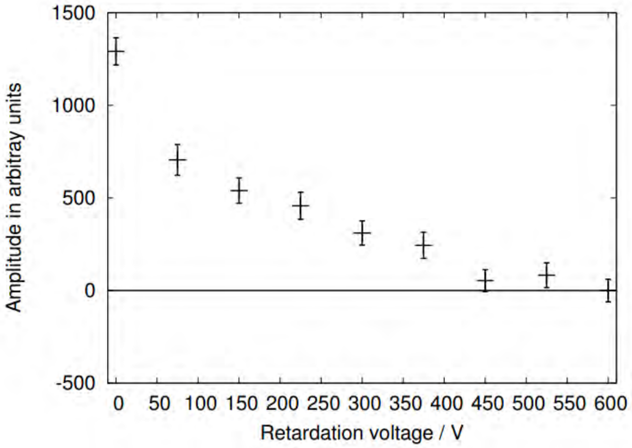
# Results of 2011 online experiment with $^{35}$Ar

Difference in retardation spectra and non-retarded spectra




Experimental data together with the simulated spectra for **a=1** and **a=-1**



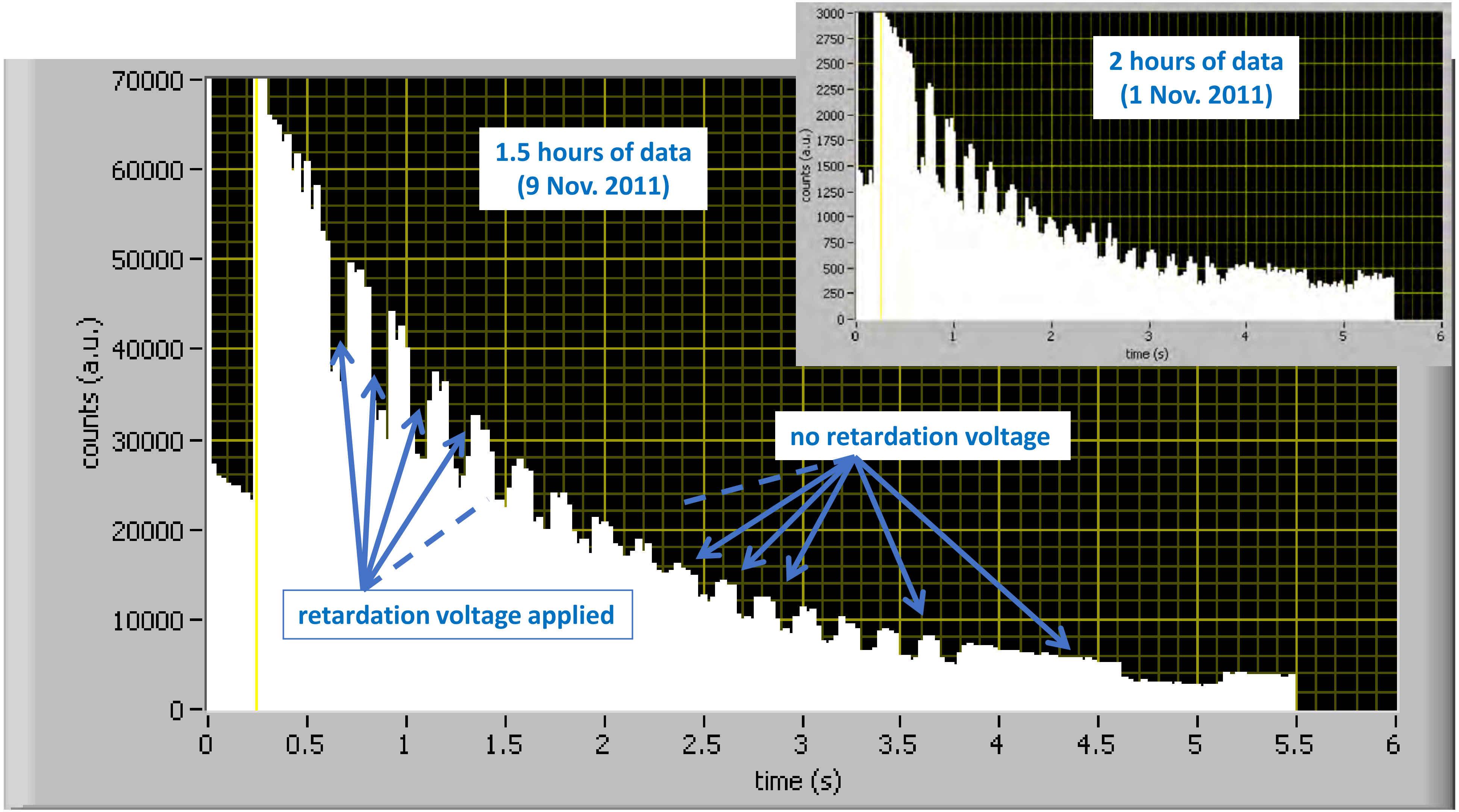

Experimental integral recoil spectrum of $^{35}$Ar

- **First successful online experiment with $^{35}$Ar** catching and cooling $^{35}$Ar ions, decay of scattering-free cool radioactive source (at rest), measurement of the recoil spectrum
- Statistics still low – both ISOLDE beam and WITCH setup need to be optimized

- **Result:** $a$ = 1.12(33)
- Standard Model: a=0.9004(16)
- First determination of ***a*** by the WITCH experiment

# First high-quality data $^{35}Ar$ from WITCH experiment

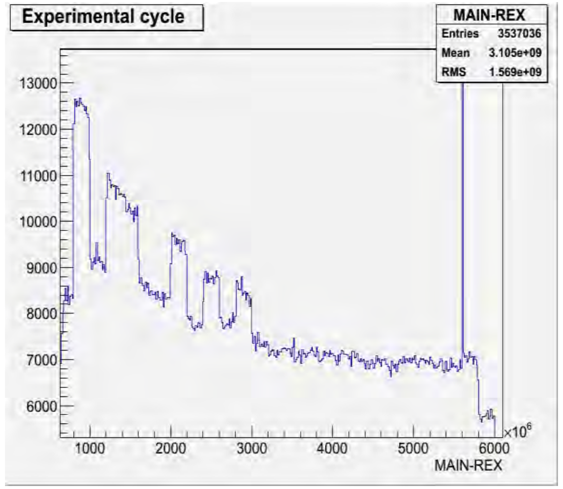
Count rate is high when no retardation of the recoil ions leaving the Penning trap is applied, and low when a retardation voltage is applied. Voltage settings are shown in the inset.
The decay of the count rate reflects the $^{35}Ar$ half-life of 1.78 s.



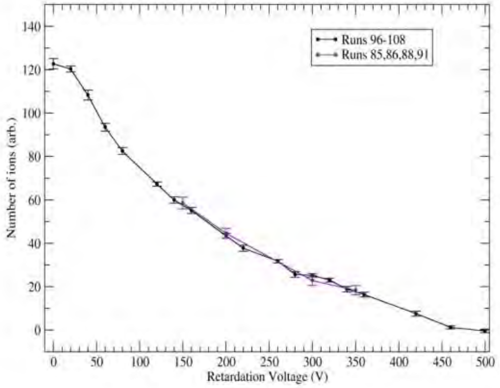
# Online data from $^{35}$Ar experiment – autumn 2012

- More intensive and cleaner beam from ISOLDE
- Better diagnostics, measurement system, transmission, new DAQ (more info in data, dead-time negligible)
- Only few levels of retardation potential measured in each measurement, from time 3s ions blocked and background measuered – realtime monitoring of background
- Statistics ~10x higher than in 2011
- Raw retardation spectrum extracted, systematic effects still studied/simulated, offline tests still necessary to correct for some systematic effects
- Data analysis in progress

20 min measurement of the retardation spectrum of recoiling ions $^{35}$Ar




Extracted retardation spectrum



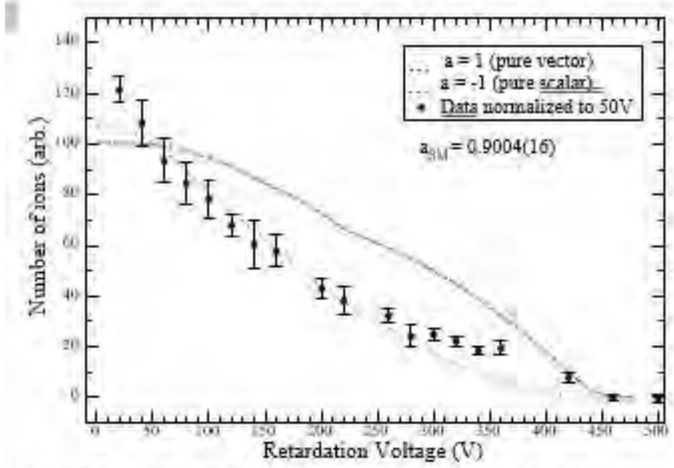



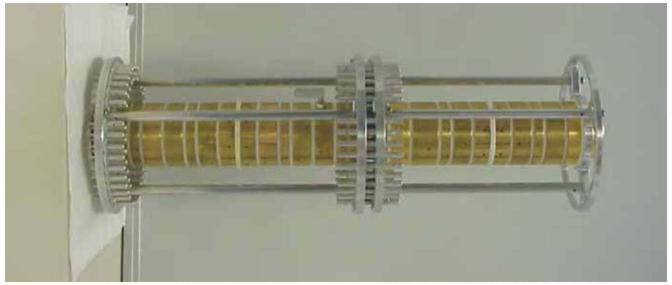

**Fig. 13.** (Colour online) Experimental recoil-ion intensities normalized to 50 V (black circles), and simulated values assuming pure vector (red dashed line) and pure scalar (red dotted line) interactions. The standard model value for the $\beta$-$\nu$ correlation parameter in $^{35}$Ar decay is 0.9004(16) [32]. The error bars for the experimental data reflect statistical uncertainties only. These data result from the analysis described in

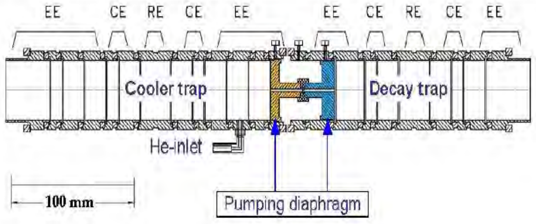
# Ions clouds in traps - Simbuca simulations

**Ion cloud in WITCH:**

- Ion bunch from REXTRAP (energy 30keV) is slowed down by PulsedDriftTube to ~$10^1$ eV, stopped in "cooler trap" and in He buffer gas cooled down (~<$10^{-1}$eV) and compressed
- Cooled ions are then transferred into the "decay trap" through narrow diaphragm (∅=2mm – necessary to avoid leaking of buffer gas from cooler to decay trap)
- Selfinteractions (Coulomb) of ions cannot be neglected for high ion densities

WITCH Penning trap structure

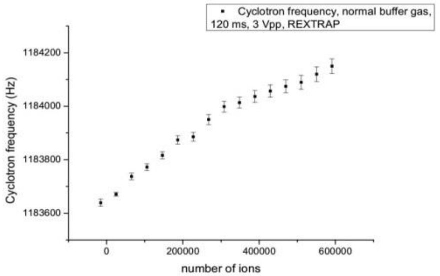




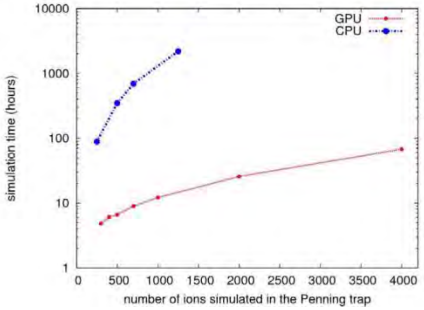

**Simbuca : simulations of the ion cloud behaviour in ion traps (even for large numbers/densities of ions)**

- **GPU paralellization essential** : longrange Coulomb interactions mean that each ion interacts with each other ⇒ standard calculations (using CPU) unrealistic for ~>$10^3$ ions
- Simulations of **space charge effects** : change of cyclotron and magnetron resonant frequency, change of the cloud shape and energy in traps due to selfinteraction of ions, ..
- Ion selfinteractions (with high densities) seriously change the size and energy of the ion cloud ⇒ without these simulations our understanding of cloud properties wrong
- Results interesting for whole ion trap community

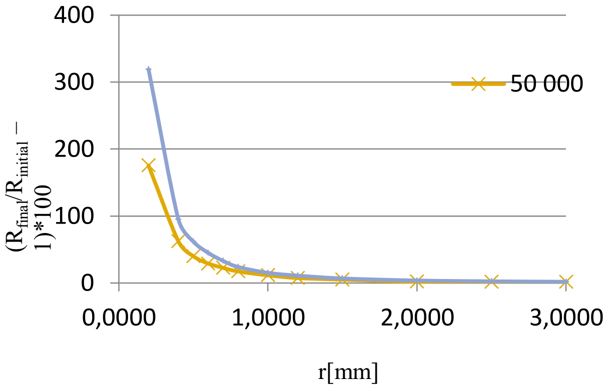
Change of cyclotron frequency with No., of ions



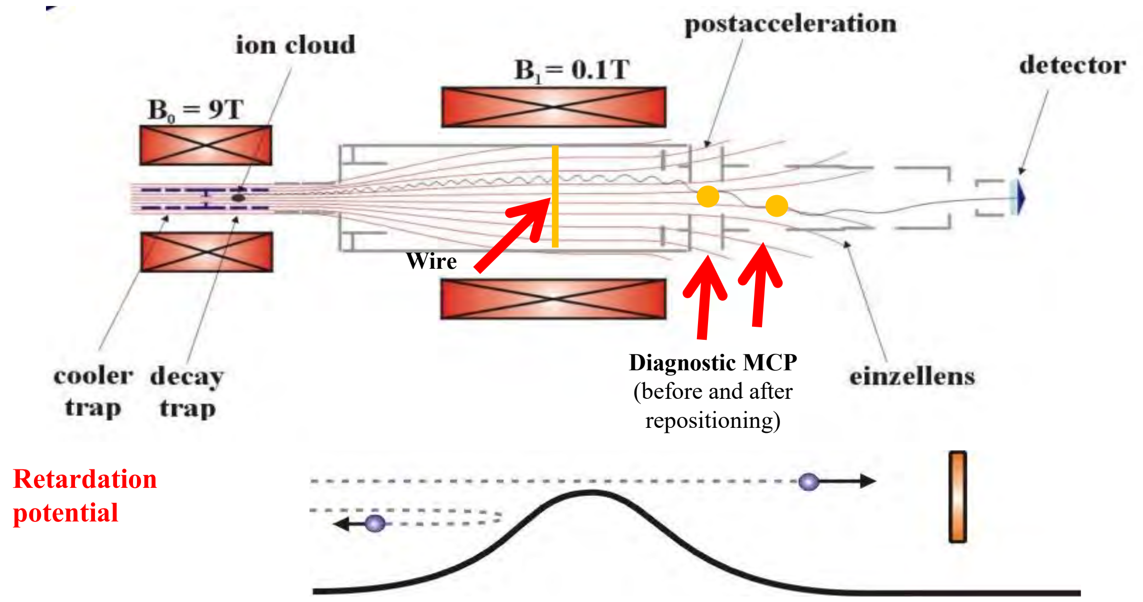

Comparison of the speed of calculations on CPU and GPU




Ions kept for 200 ms in „cooler trap" : relative increase of the cloud size [%] depending on the initial cloud radius [mm] and number of ions (50 000, 5 000 000)



# Trajectories of recoiling ions - simulations SimWitch




**Monte Carlo simulations of ion trajectories**

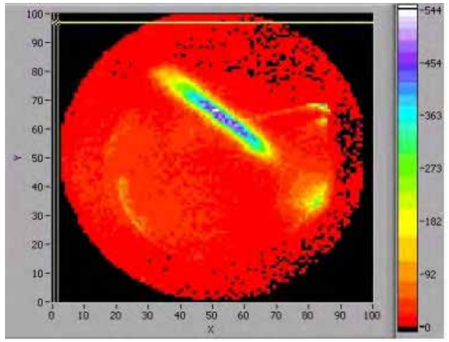
from the decay trap through the spectrometer to the MCP detector

- Ion transport simulated for various retardation voltages (0 V – 450 V) and various $^{35}Ar$ charge states ($1^+$, $2^+$, $3^+$, $4^+$, $5^+$)
- originally 2D (cylindrical symmetry), now upgraded to 3D (due to several components breaking the symmetry – small diagnostic MCP, anti-ionization wire)
- Simulations either for optimalisation of parameters before the experiment or for analysis and correction of measured experimental data

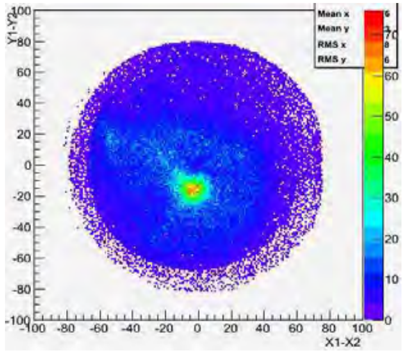
**Breaking of cylindrical symmetry:**

- Ions travelling from decay trap through the spectrometer and detected by main MCP detector (asymmetry caused by the presence of diagnostic MCP deforming electric field configuration)
- Reproduced by simulations

**Before MCP repositioning**



**After MCP repositioning**

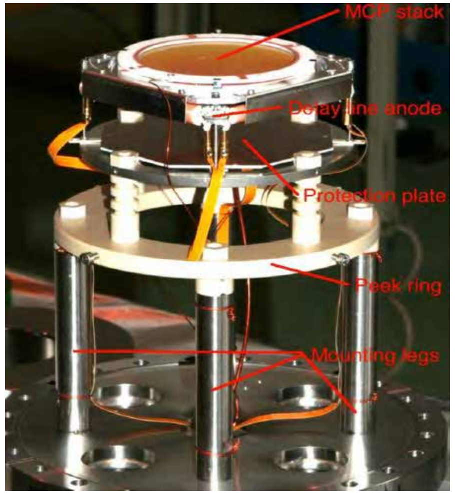


# MCP detector

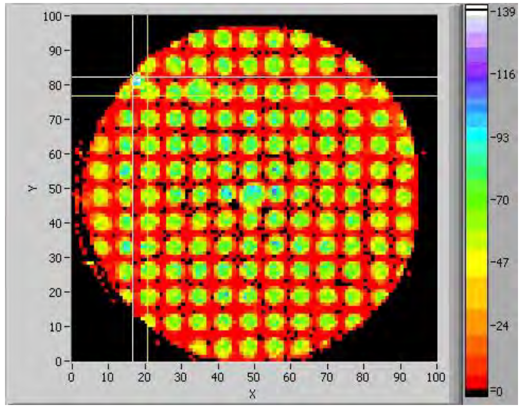
**MCP detector for registration of recoil nuclei :**

- ∅=8cm,
- position sensitive (delay lines) – position resolution 0.2mm
- detection efficiency 40(11)% - **should be energy (and position) independent**

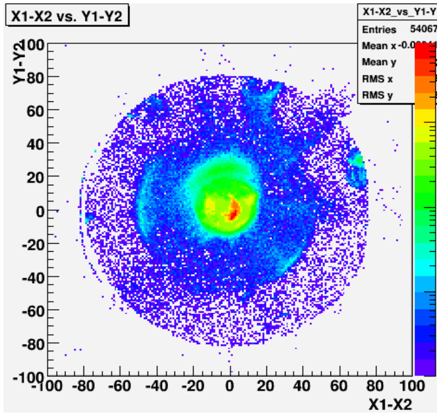
Position sensitive MCP detector




Test of resolution and efficiency of the MCP detector with perforated absorption mask and α-particles $^{241}$Am




Ions from Decay-trap transmitted through the retardation spectrometer and detected by the MCP detector

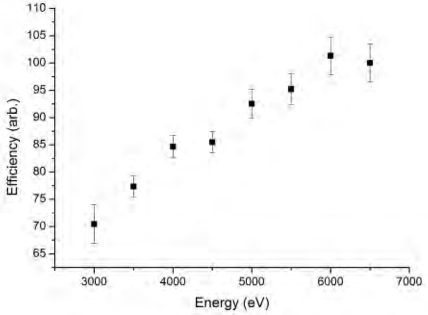



**BUT: Shape of the extracted experimental retardation spectrum in autumn 2012 experiment is strange (after all corrections)– deformation due to the unaccounted systematic effect ?**

⇒ **Study of the energy dependence of MCP detector efficiency for $Na^+$ ions in energy range 0 – 6.5 keV**

- **Result :** efficiency of our MCP detector increases with ion energy in region 3-6keV - **crucial systematic efffect , need to be corrected** (higher charge states of decay products have higher energy due to reacceleration in front of the main MCP ⇒ energy dependent efficiency deforms the charge state population)
- More detailed tests planned, necessary for precision correction of experimental data

Efficiency of the MCP detector for $Na^+$ ions



# First run with $^{35}$Ar

**failed due to:**

- **isobaric contamination with stable $^{35}$Cl** - ratio Cl/Ar = 400, after optimisation 25, but reduced yield – ISOLDE target group solving this (change cleaning!!)

  **!! lesson : always try to check even the things which are obvious !!**

- **losses of $^{35}$Ar due to charge exchange in REXTRAP** - improvements planned
- **losses of $^{35}$Ar due to charge exchange in WITCH** - we couldn't cool the ion cloud, because the ions were neutralized before being cooled - vacuum upgrade necessary
- **'secondary ions', not created by beta decays (**noise/discharges/..)

## Necessary improvements

- Reduce charge exchange in the traps – purity, vacuum (pumps, NEG, no teflon, all metal buffer gas,…) – vacuum $O(10^{-10}$mbar) reached
- Reduce the secondary ionisation (redesign, (electro) polish electrodes,..)
- Install magnetic shielding and RFQ → be independent from the other experiments (stray field of WITCH influencing other setups)

# WITCH history & status

- 2006 first recoil spectrum measured $^{124}$In
  - Some discharges, electrodes could not be operated as intended
- 2007 physics run $^{35}$Ar
  - Discharges (ions and electrons are created and released at certain times)
  - Trap-halflife of $^{35}Ar^{+}$ only 8 ms, stable $^{35}Cl^{+}$ domination in the beam ⇒ purity !
- 2008 WITCH ⇒ UHV
  - Vacuum, metal buffer gas system, dry pumps, NEG material, redesign & electropolish electrodes, ..
- 2009
  - $^{35}$Cl contamination, charge exchange, discharges – all solved , low-level ionization
- 2010
  - test runs investigate systematics - $^{144}$Eu (EC decay) to measure the response function of the system
- 2011

  2 runs with $^{35}Ar^{+}$ , measuring recoil spectra, taking statistics
- 2012

  online run with higher statistics

  spectrum extracted, systematic effects still not fully accounted for, studies of main MCP energy-dependent efficiency
- Future
  - improvements of the diagnostics, measurement systems and transmission
  - new data acquisition system from LPC Caen - more information in the datastream, dead time issue solved
  - solve high rates of background ionization - caused by unwanted Penning traps formed at undesirable locations due to the combination of magnetic and electric fields

# WITCH results & status

**Experimental setup WITCH works :**

- we are able to catch and cool $^{35}Ar$ ions in Penning traps, keep them in traps with minimal energy (<~ $10^{-1}$eV) for long enough time (~>1s) with negligible losses, probe the energy of recoiling nuclei after the β–decay by means of retardation spectrometer and MCP detector
- Penning traps proved to be well suited to provide scattering-free RA sources for low energy spectrometry, MAC-E filter retardation spectrometer showed its suitability for studies of very low energies particles high precision and efficiency

**Results**

- Several online measurements of $^{35}Ar$ were performed at ISOLDE
- Retardation (recoil) spectra of ions produced in β–decay of $^{35}Ar$ were extracted
- 1st pilot experiment from 2011 with low statistics was fully analyzed and the value of angular β-ν correlation coefficient ***a*** was determined by the WITCH experiment
- 2nd online experiment from autumn 2012 with much higher statistics, improved beam quality and measurement conditions was analyzed, raw retardation spectrum extracted and systematic effects studied
- SimWITCH-3D code successfully models systematics of the ion tracking, including axial symmetry breaking
- Simbuca code successfully simulates ion cloud evolution in the traps and transfer between traps, including space-charge effects
- MCP efficiency crucial for extracting the β-ν correlation coefficient, further study needed -> experimental studies of main MCP energy-dependent efficiency
- High rates of background ionization (background level) - caused by unwanted Penning traps formed at undesirable locations due to the combination of magnetic and electric fields

# WISArD

# Probing the structure of weak interactions

D.Zakoucky, P.Alfaurt, V.Araujo-Escalona, P.Ascher, D.Atanasov, B.Blank,
L.Daudin, X. chard, M.Gerbaux, J.Giovinazzo, S. vy, T. Kurtukian-Nieto,
E. nard, G.Qu ner, M.Roche, N.Severijns, S.Vanlangendonck, M.Versteegen

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

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

CENBG Bordeaux KU Leuven ISOLDE,CERN LPC Caen NPI Rez

# Motivation, sensitive variables

**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

study **recoil nuclei instead of neutrinos -** measurement of the shape of p-spectrum from **β-delayed proton decay** (WISArD)

measurement of recoil energy spectrum → 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

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

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

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

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%

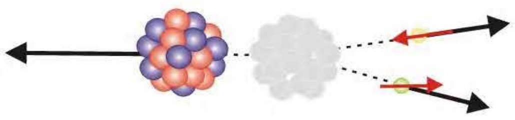
WISArD: measuring $\tilde{a}$ , sensitive to both *a & b*

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

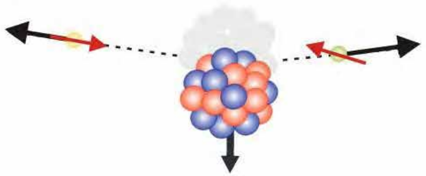
measuring recoil nucleus energy⇒ ratio Scalar/Vector

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



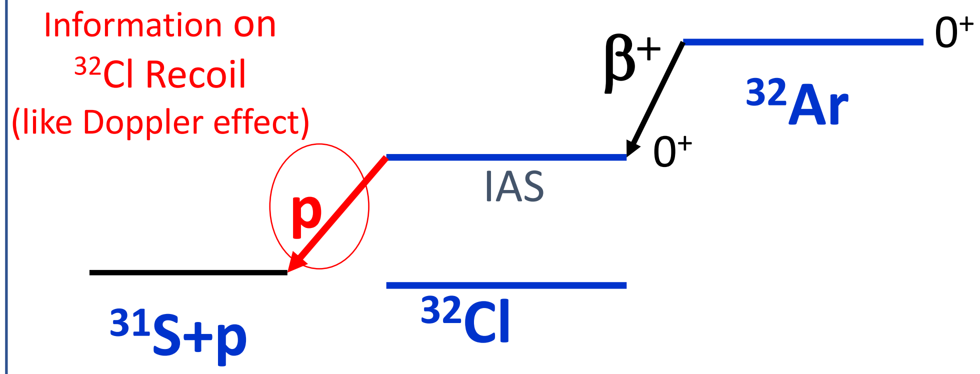
**Scalar interaction** (beyondSM)
Very small energy of recoil nucleus

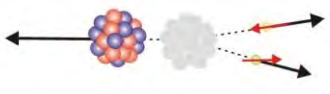


# Principle of the experiment

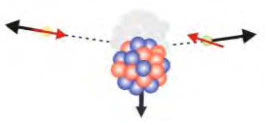
- **Inspired by the 'Adelberger experiment' from 1999 : kinematic proton E broadening**

Adelberger 1999 CERN-ISOLDE



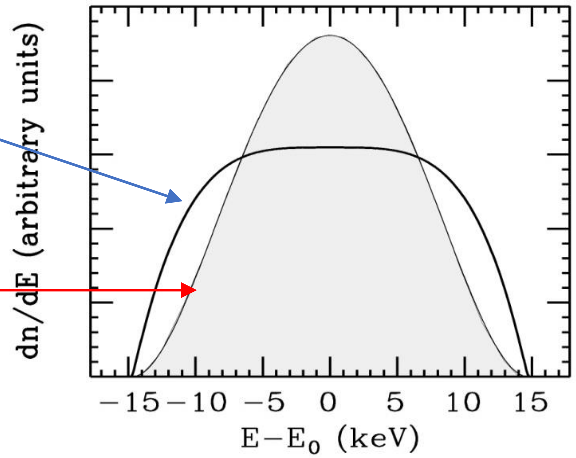



Vector, $a$=1
high recoil energy
large broadening



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

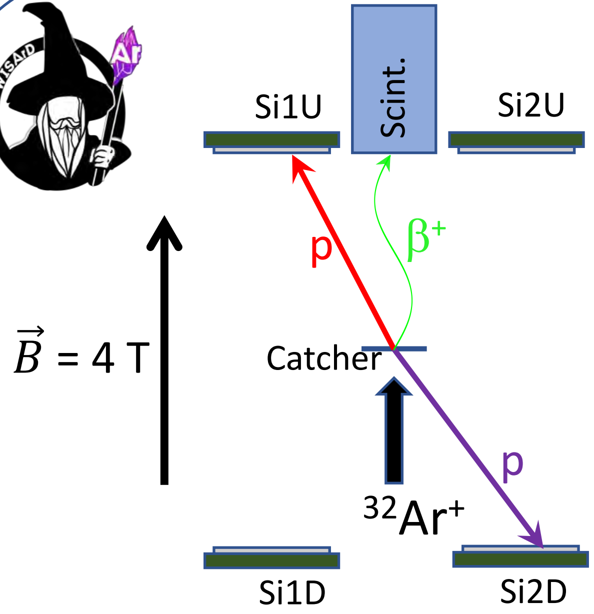
Proton peak shape



# Principle of the experiment

- New idea (initialy proposed in 2001! )

Detect ***in coincidence*** **protons & beta particles** to increase the sensitivity

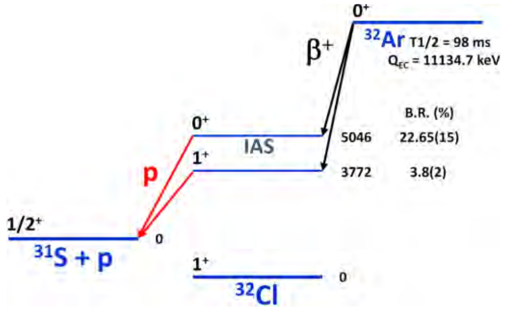



- **We measure the proton energy shift** for same & opposite emission directions **This shift is a linear function of *ã***

- Higher sensitivity on ***ã*** (**~ x 2.5**)
- Even higher sensitivity on ***b*** (**~ x 4.5**)
- Do not depend on ***p*** detector response function
- Do not depend on ***p*** peak intrinsic shape
- *New systematics due to beta particle detection…*

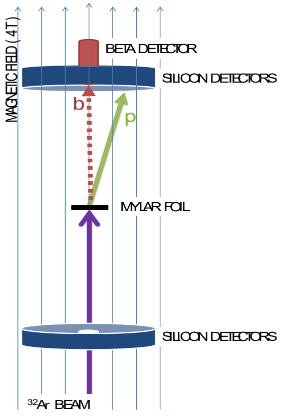
# WISArD (Weak-Interaction Studies with $^{32}$Ar Decay) experiment

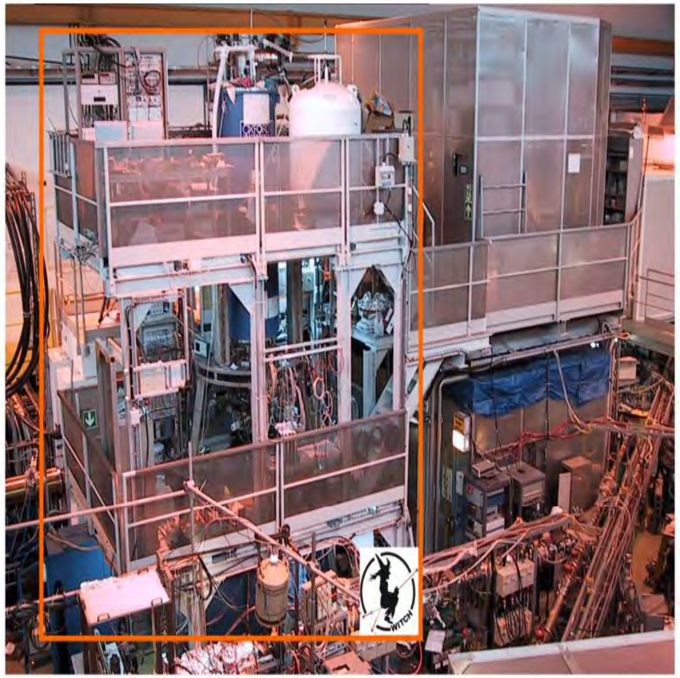
WISArD – measuring β-delayed proton decay of $^{32}$Ar
in β-p coincidence measurement we measure the proton energy shift for same & opposite β emission directions which is a linear function of $\tilde{a}$

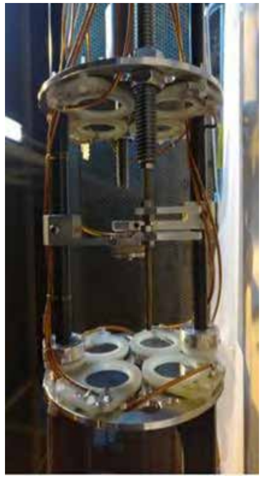


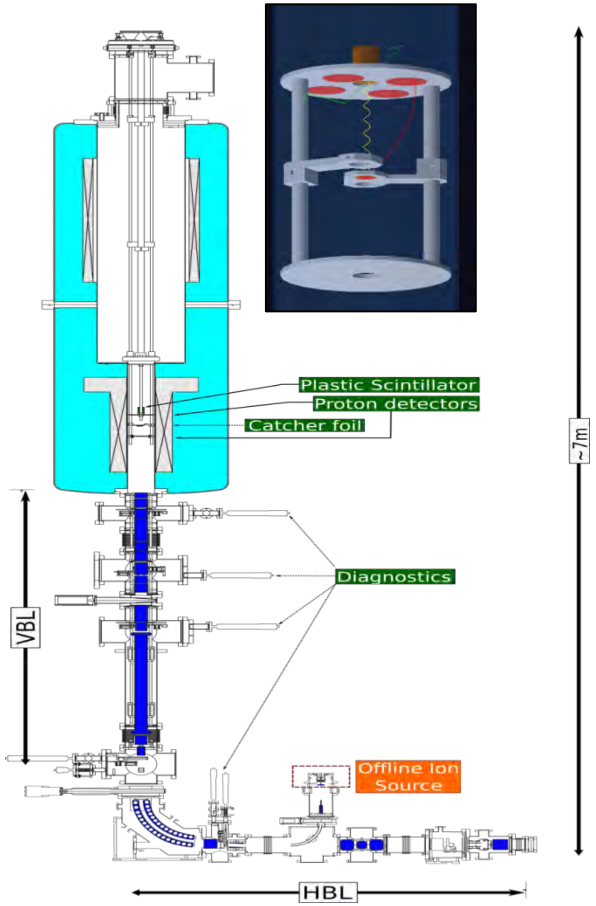

Super-allowed Fermi β-decay $^{32}$Ar→ $^{32}$Cl to Isobaric Analog State is followed by the proton decay $^{32}$Cl → $^{31}$Si;
Protons are emitted from the moving nucleus $^{32}$Cl recoiling after previous β-decay ⇒ energy of protons is Doppler shifted: high recoil energy, Vector interaction, $a$=1 low recoil energy, Scalar, $a$=-1

Whole setup in the magnetic field 4T (up to 9T))
$^{32}$Ar ions implanted into the mylar foil
Positrons from the β-decay detected by the narrow forward 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







# ‘test experiment’ setup at ISOLDE

**Experimental hall of ISOLDE**
**(9T former WITCH magnet)**

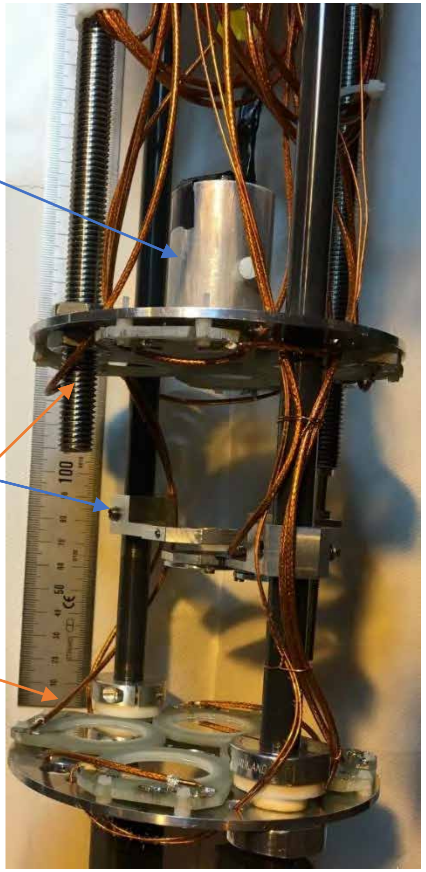

**Detection setup**
(putting together old detectors…)

β detector: plastic scintillator and SiPM

6 μm mylar Catcher
(32Ar implantation)

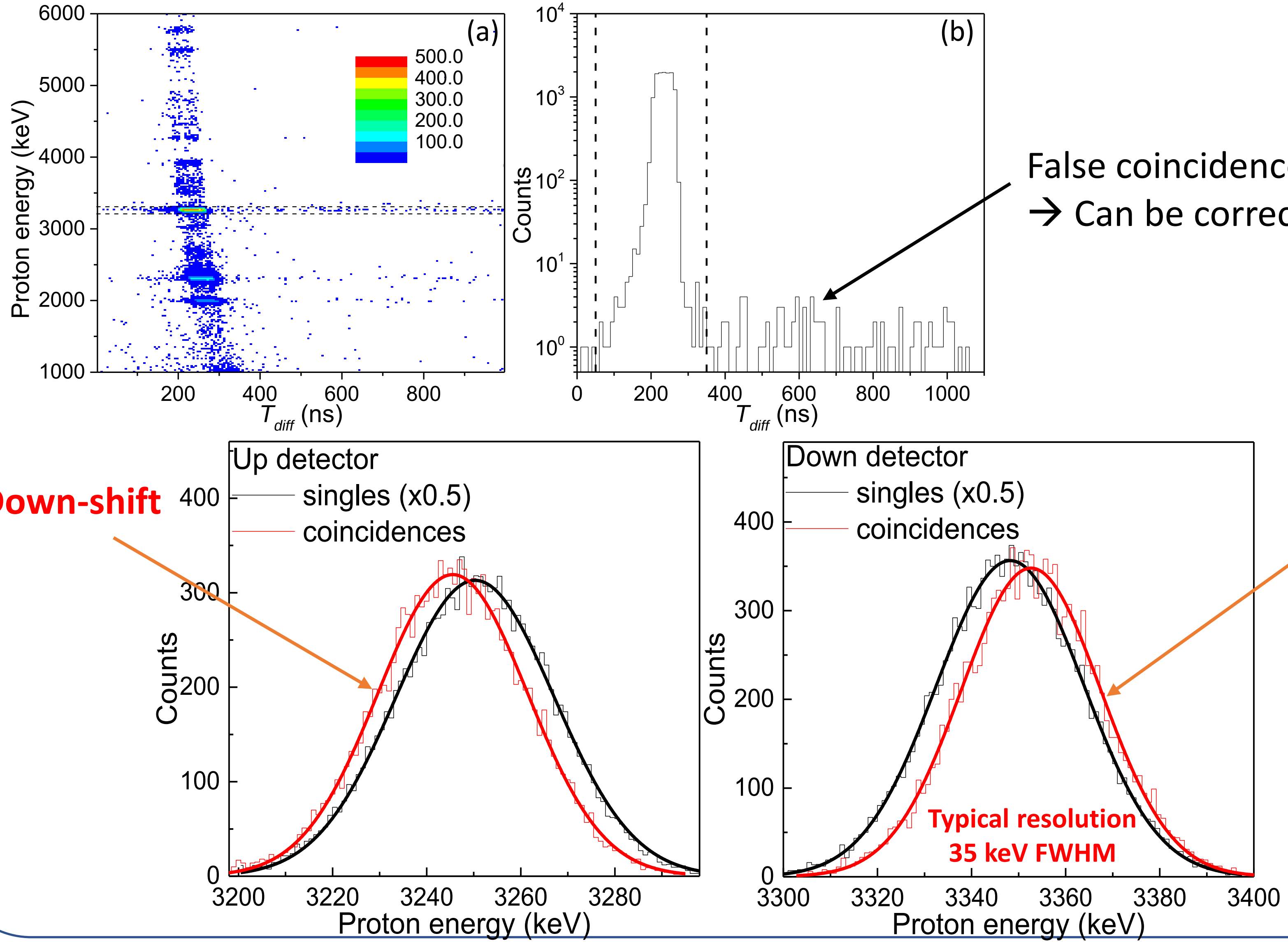
8 proton detectors
(300 μm Si Detectors)

+ FASTER DAQ



$\vec{B}$ = 4 T

# First results (Nov. 2018)




False coincidences (<0,3%)
→ Can be corrected

**Down-shift**

**Up-shift**

# Results, outlook

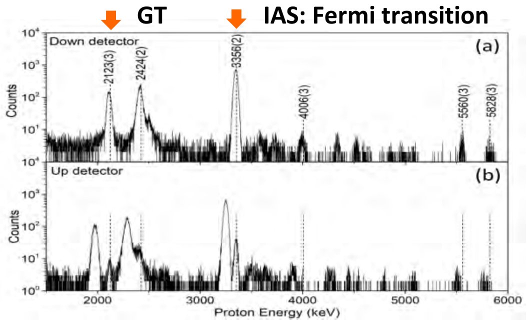
**WISArD online proof-of-principle experiment**

Nov 2018, latest run before the CERN shutdown

Readily available beta and proton detectors

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

~ 35h of beamtime



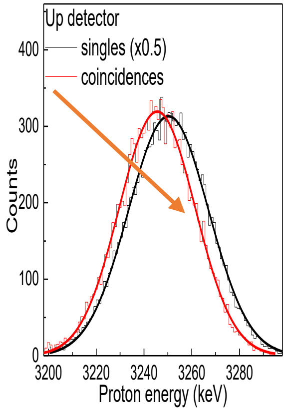

Systematic error budget (in ‰) :

| | 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 $\mu$m | 5 |
| | mylar thickness | 0.15 $\mu$m | 3 |
| positron | detector backscattering | 15% | 2 |
| | catcher backscattering | 15% | 21 |
| | threshold | 12 keV | 8 |
| total | | | 24 |

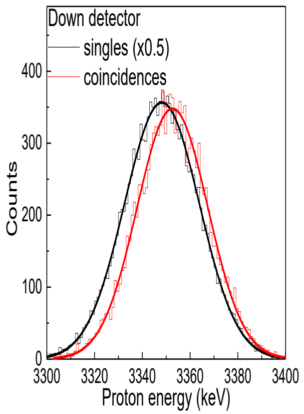
-unknown detectors dead layer
-source profile poorly known
→Can be easily reduced by factor ~10

→Must be reduced by factor >20

Down-shift




Up-shift




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)*

Statistical error reduced below 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

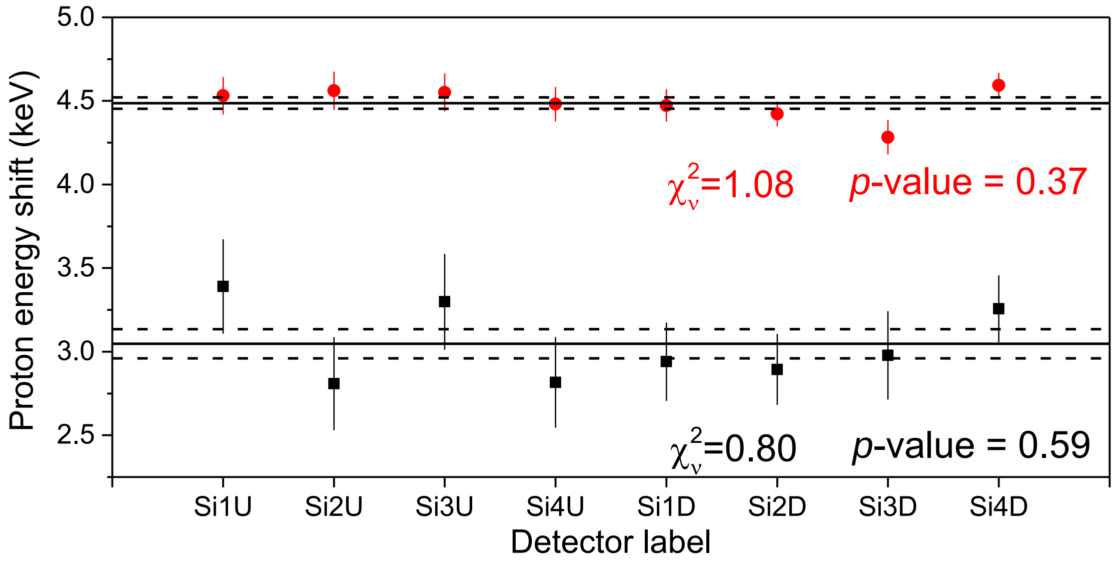
**- ⇒ ~0.9 ‰ (F), ~1.4 ‰ (GT)**

# First results (Nov. 2018)

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

**Fermi (IAS): 4.49(3) keV**

**GT: 3.05(9) keV**




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

  - with decay involving different values of *a* (-1, -1/3 ,0 ,1 /3, 1)

    → ***ã* = α x $E_{shift}$ + Cst**

  - varying instrumental parameters in MC → **Systematic errors estimation**

$$\tilde{a}_{\beta\nu}^{F} = \mathbf{1.01(3)_{(stat)}(2)_{(syst)}} \qquad \tilde{a}_{\beta\nu}^{GT} = \mathbf{-0.22(9)_{(stat)}(2)_{(syst)}}$$

***V. Araujo-Escalona et al., arXiv:1906.05135 [nucl-ex]***

# Systematic errors (Nov. 2018)

- **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 $\mu$m | 5 |
| | mylar thickness | 0.15 $\mu$m | 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**

# WISArD detectors

**2018**

**2021**

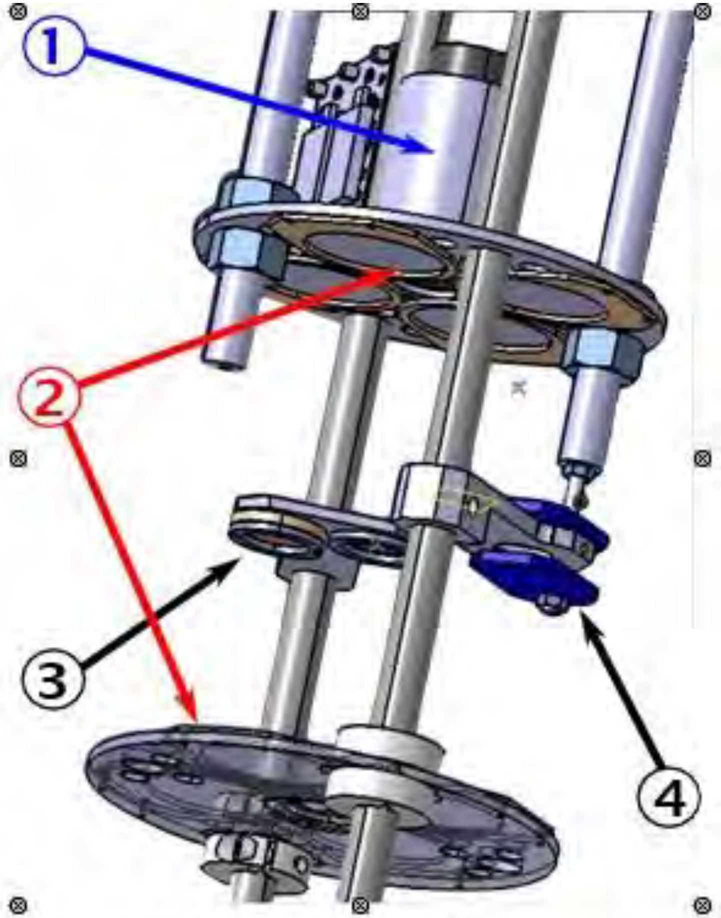



Figure 3: CAD drawing of the Nov2018 detectors system.

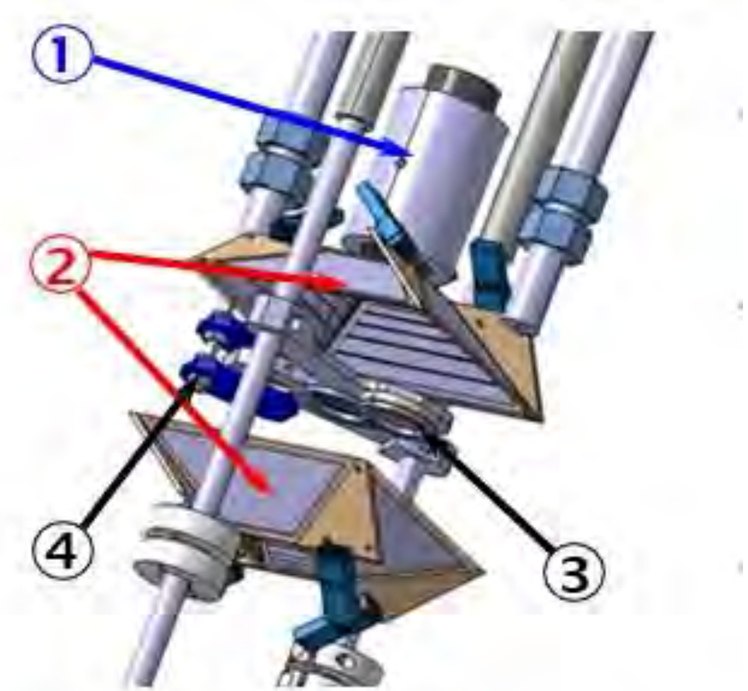



Figure 6: The new design of the detector assembly of WISArD. (1) Housing of the plastic scintillator coupled to the SiPM array for detecting beta particles. (2) Two pyramid-like hemispheres of eight silicon detectors to detect the beta-delayed protons. (3) Arm to hold the Mylar foil used for implantation of the ISOLDE RIB and a beam diagnostics, i.e. MCP or Faraday Cup. (4) Arm holding the calibration alpha source placed in the parking position.

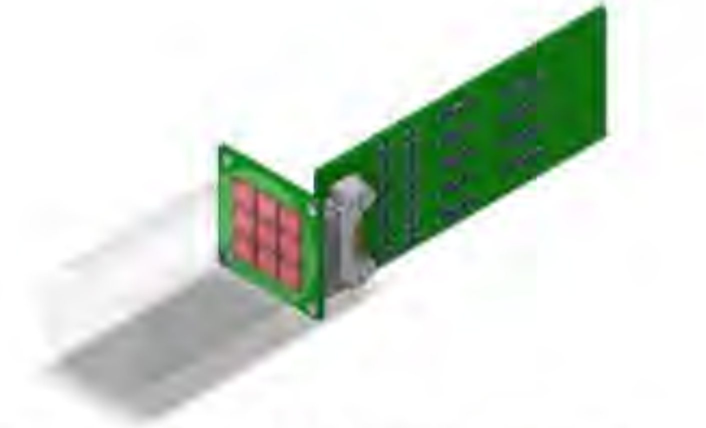
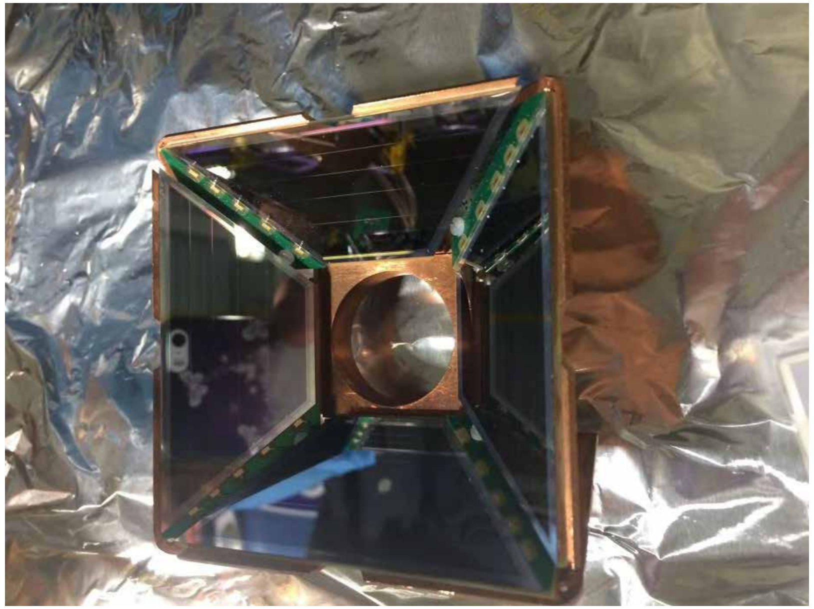
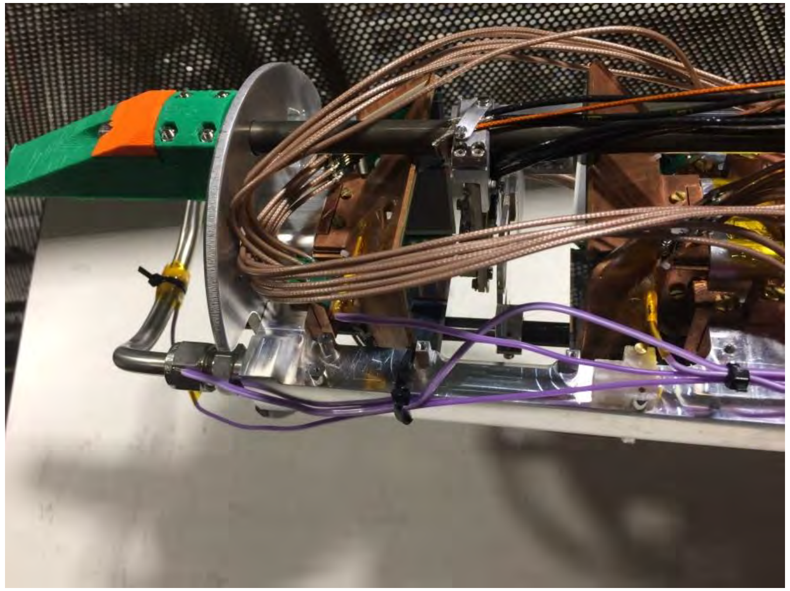


Figure 7: CAD drawing of the SiPM array seen through the plastic scintillator. Nine individual SiPMs are visible on the back side of the scintillator. Furthermore, one can see the front-end electronics composing the high and low gain amplification stages (see text for details).

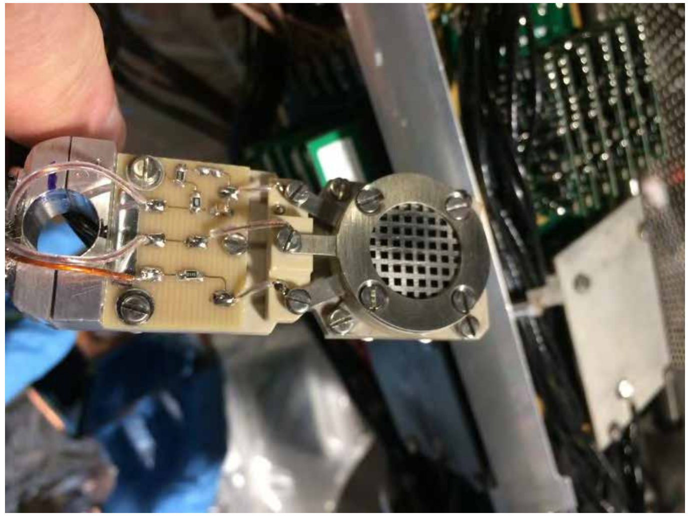
# WISArD detectors, diagnostics

Si detector

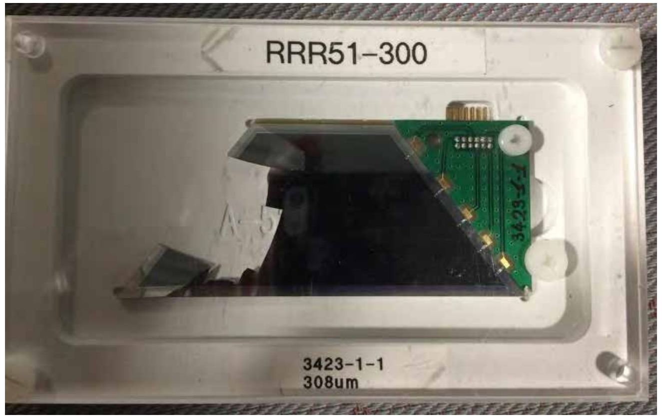





MCP detector

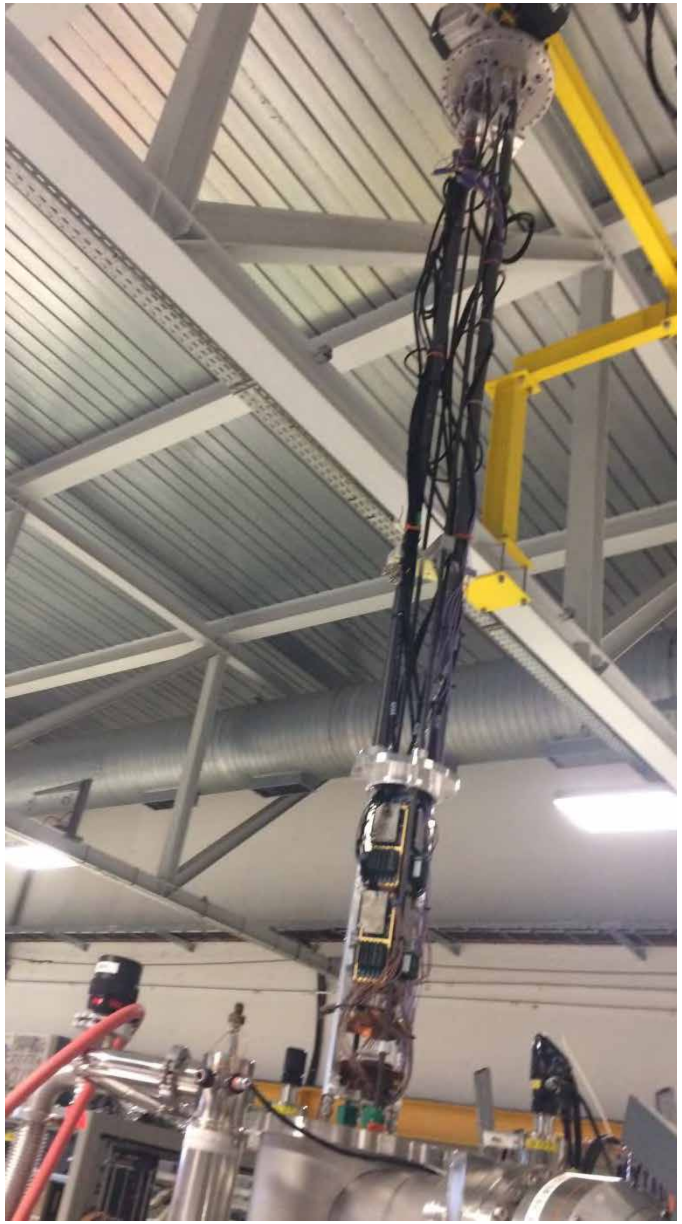


Broken Si detector




Segmented FC

# WISArD detection tower



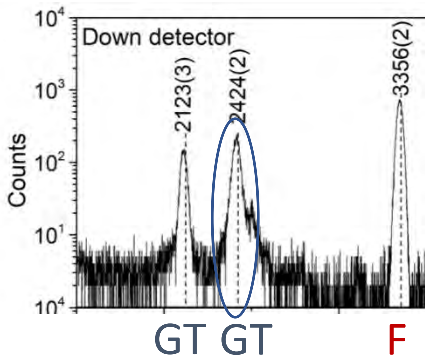
# Perspectives (2021-?)

- **First data taking in 2021 (1 week):**
  - Statistical error reduced below 1 ‰

    -production + transmission + time → x ~50 in decay statistics

    -new detection setup → x ~5 in sensitivity

    ~0.9 ‰ (F)




~1.4 ‰ (GT)

  - Systematic errors:

    -no real show stopper to reduce to the ~1 ‰ level

- **Longer term:**
  - Several campaigns @ ISOLDE with successive upgrades
  - Other nuclei (test theoretical corrections, higher sensitivity)?
  - Other facilities ? → DESIR (GANIL)

# Summary

- **Nuclear Orientation:**
- Technical - reliable detectors working at low temperatures and in high magnetic fields
- Simulations - GEANT4 code handling electron scattering and detector response with a few % accuracy
- Physics: Most precise β-asymmetry parameter A determined for nuclear decay.

  Limits on $C_T^{(')}$ comparable to those coming from other single experiments, not yet strict enough to significantly change to overall limits

  Our 2 % precision is a competitive result for the β-asymmetry correlation parameter, approaching 1 % precision (accuracy) on A needed to extract good weak interaction tensor current physics

- **WITCH:**
- took data for main physics case ($^{35}Ar$)
- Argon ions can be trapped, cooled and stored in the cooler trap (negligible losses during storage time of ~0.5s)
- Energy distribution of ions in the trap reduced to about 0.2eV FWHM
- First recoil spectra measured, full data analysis done, systematic effects under investigation
- Unfortunately combination of faulty MCP detector and presence of radioactive beam-related background prevented us from further continuation

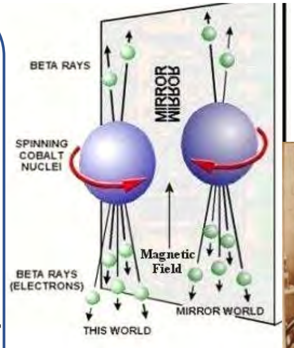
- **WISArD:**
- First proof-of-principle experiment in 2018 , already 3rd most precise measurement of $\tilde{a}_F$
- 2021 precise experiment with improved setup, errorbars significantly improved
- installation of further upgrades, ready for beamtime in 2023

# Backup

# Search for exotic currents in the electroweak sector of the SM

*Precision measurements in nuclear beta decay* → *very sensitive tools to test the electroweak interaction and its fundamental symmetries:*

- Discovery of ***Parity violation*** (asymmetry coefficient $A_\beta$ in $^{60}Co$ decay) & *V-A* form of the weak interaction
- Today: test ***unitarity of CKM*** quark coupling matrix, search for new sources of ***CP violation***, ***look for exotic couplings***




- **Current structure** (SM) : *V-A* theory (based on previous observations)
  - Vector - Axial Vector interaction with couplings : $C_V \equiv 1$ & $C_A = -1.27$ (from n-decay)
  - Maximal parity violation (only left-handed neutrinos): $C_V' = C_V$ & $C_A' = C_A$
  - No Scalar (S) or Tensor (T) components : $C_S = C_S' = C_T = C_T' = 0$
  - No Time reversal violation : all Couplings are real

***How true are those hypothesis?***

- **New Physics ?**
  - Experimental upper limits for $\left|C_S/C_V\right|$ & $\left|C_T/C_A\right|$ at the % level (*n* & nuclear β-decay)

**Link with HEP:**

- Extending the limit to per mil level allows setting lower limits on new boson (mass ~ 2.5 TeV)

$$C_i \propto \frac{M_W^2}{M_{new}^2}$$

# Present limits & Projects for $\tilde{a}$

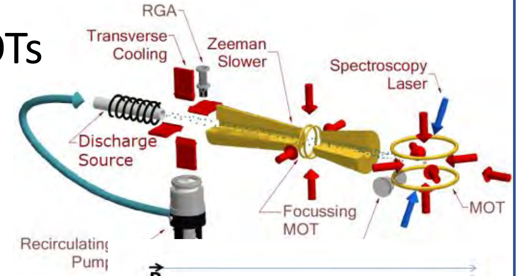
| Parent | type | Technique | Team | $\tilde{a}$ | | Year |
|---|---|---|---|---|---|---|
| $^{6}$He | GT | Spectro | ORNL | -0.3308(30) | 0.9% | 1963 |
| $^{32}$Ar | F | *p* recoil | UW, ISOLDE | 0.9989(52)(39) | 0.65% | 1999 |
| $^{38m}$K | F | MOT | SFU, TRIUMF | 0.9981(30)(34) | 0.45% | 2004 |
| $^{21}$Na | M | MOT | Berkeley, BNL | 0.5502(38)(46) | 1.1% | 2008 |
| $^{6}$He | GT | Paul Trap | LPCC, GANIL | -0.3335(73)(75) | 3,1% | 2011 |
| $^{8}$Li | GT | Paul Trap | ANL | -0.3342(26)(29) | 1.2% | 2015 |
| $^{6}$He | GT | Paul Trap | LPCC, GANIL | Analysis under way (<1%) | | |
| $^{35}$Ar | M | Paul Trap | LPCC, GANIL | Analysis under way (<1%) | | |
| $^{19}$Ne | M | Paul Trap | LPCC, GANIL | Analysis under way (~3%) | | |
| $^{6}$He | GT | MOT | ANL,CENPA, LPCC | Analysis under way (~1%) | | |
| $^{6}$He | GT | EIBT | Weizman, SOREQ | In preparation | | |
| Ne | M | MOT | Weizman, SOREQ | In preparation | | |
| $^{32}$Ar | F & GT | Penning | Texas A&M | In preparation | | |
| $^{38m}$K | F | MOT | SFU, TRIUMF | In preparation | | |
| $^{32}$Ar | F & GT | *p* recoil | WISArD | In preparation (prelim 3.6%) | | |

GT: ~ 1% precision

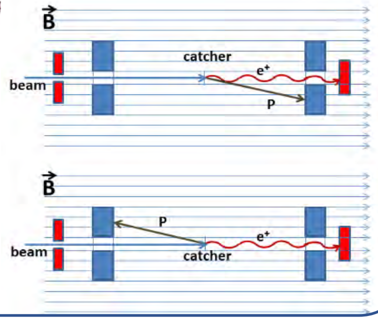
F: ~ 0.5% precision

Ion traps

MOTs



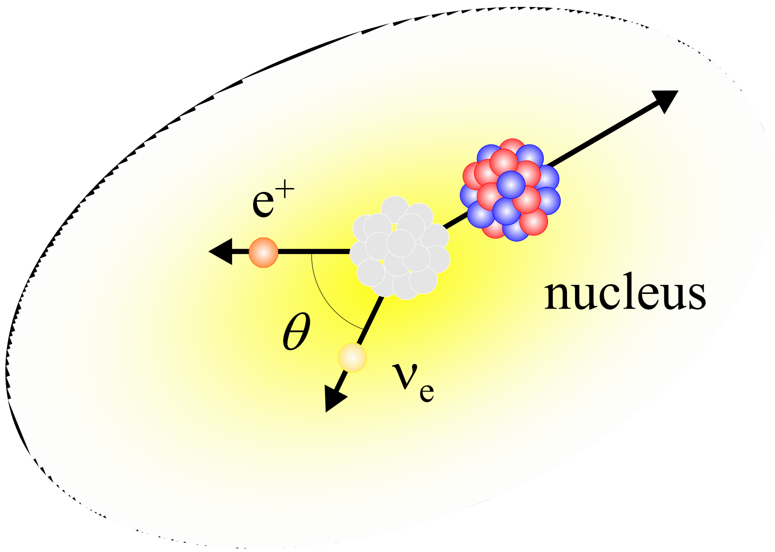

Doppler shift

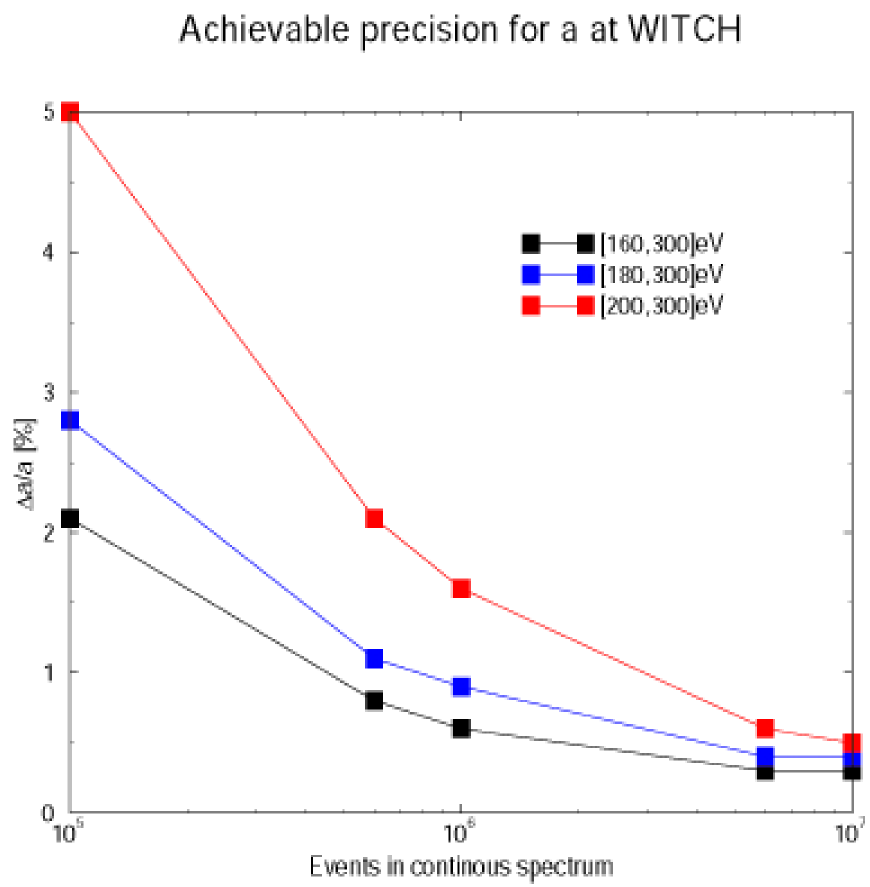



All new projects aim at 0.1% precision level…

**precision :**

for recoil ion endpoint energy of 300 eV




$$\Delta a = 0.5\% \Rightarrow C_S / C_V < 0.09, \quad CL = 95\%$$

$$\Delta a = 0.2\% \Rightarrow C_S / C_V < 0.06, \quad CL = 95\%$$

# Correlation measurements in nuclear β decay

- Correlation parameters $a$ & $b$ depend on all possible weak interaction coupling constants: $C_i$ & $C_i'$ with i=V, A, S & T

Pure F $\quad a_F \cong 1 - \frac{|C_S|^2 + |C'_S|^2}{|C_V|^2}$ (= 1 in SM) $\quad b_F \cong \pm\gamma\left(\frac{C_S + C'_S}{C_V}\right)$ (= 0 in SM)

Pure GT $\quad a_{GT} \cong -\frac{1}{3}(1 - \frac{|C_T|^2 + |C'_T|^2}{|C_A|^2})$ (= -1/3 in SM) $\quad b_{GT} \cong \pm\gamma\left(\frac{C_T + C'_T}{C_A}\right)$ (= 0 in SM)

$$\gamma = \sqrt{1 - (\alpha Z)^2}$$

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

In pure F transition **measurement** : $\tilde{a}_F$ → *limits on* $C_S$ & $C_S'$

**In pure GT transition measurement:** $\tilde{a}_{GT}$ → ***limits on*** $C_T$ & $C_T'$

- $\tilde{a}$ independent of nuclear matrix elements (in pure F or GT transitions)
- Recoil corrections & Radiative corrections: from ~$10^{-3}$ **to ~$10^{-2}$**