WISArD

Perspectives at DESIR

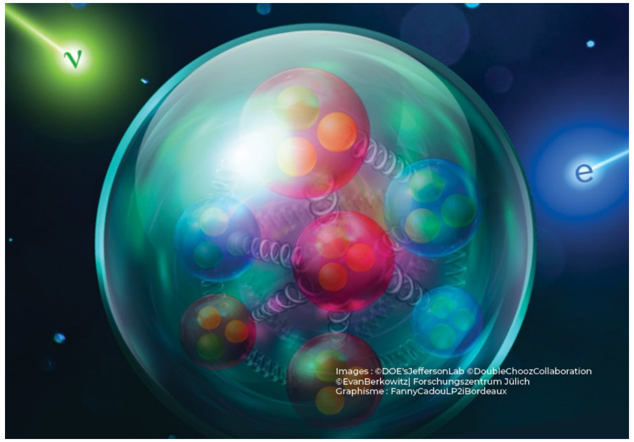
M.Versteegen

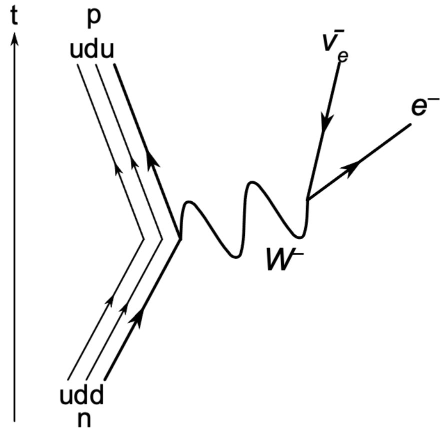
P.Alfaurt, D.Atanasov, P.Ascher, B.Blank, L.Daudin, X.Fléchard, A.Garcia, M.Gerbaux, J.Giovinazzo, S.Grévy, J.Ha, R.Lica, E.Liénard, D.Melconian, C.Mihai, C.Neacsu, A.Ortega-Moral, M.Pomorski, M.Roche, N.Severijns, S.Vanlangendonck, D.Zakoucky

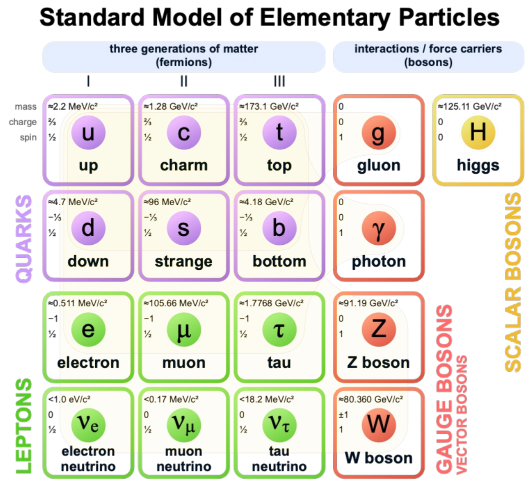
KU LEUVEN · Institute for Basic Science (IBS) · LPC Caen · Laboratoire de Physique des 2 infinis Bordeaux · NPI · CERN · ISOLDE

2024 DESIR WORKSHOP
27 Feb. – 1 March

Beyond the Standard Model







β decay

- Ft values
- β spectrum shape
- Correlation coefficients

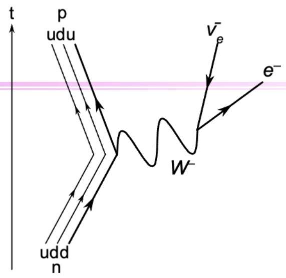
Weak interaction

- CVC hypothesis
- CKM matrix unitarity

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}.$$

- **Exotic currents**
- CP violation
- …

Exotic currents



- **Lee & Yang Lagrangian (1956) for n decay**

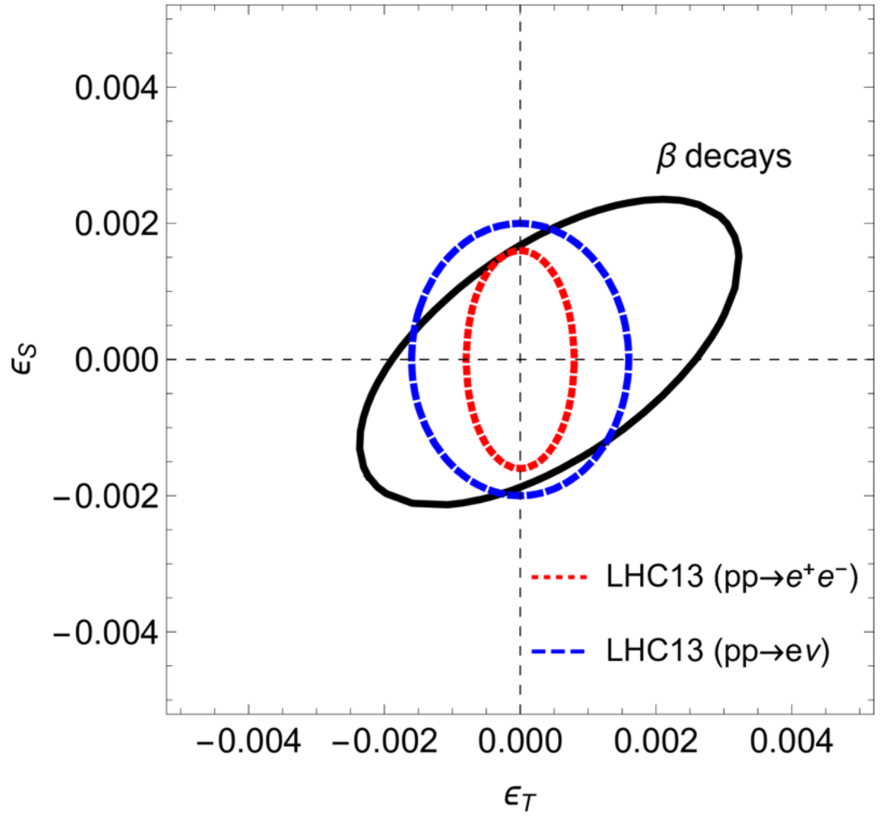
$$-\mathcal{L}_{LY} = C_V\left(\bar{p}\gamma^\mu n + \frac{C_A}{C_V}\bar{p}\gamma^\mu\gamma_5 n\right) \times \bar{e}\gamma_\mu(1-\gamma_5)\nu_e$$

SM "V-A" structure

$$+\, C_S\,\bar{p}n \times \bar{e}(1-\gamma_5)\nu_e + \frac{1}{2}\,C_T\,\bar{p}\sigma^{\mu\nu}n \times \bar{e}\sigma_{\mu\nu}(1-\gamma_5)\nu_e + hc$$

$$+\, right\text{-}handed\ \ neutrinos$$

Exotic couplings : S and T
P omitted



- **Effective Field Theories**

$$\epsilon_i \propto \left(\frac{m_W}{\Lambda}\right)^2 \sim 10^{-3}$$

TeV NP scale ↲

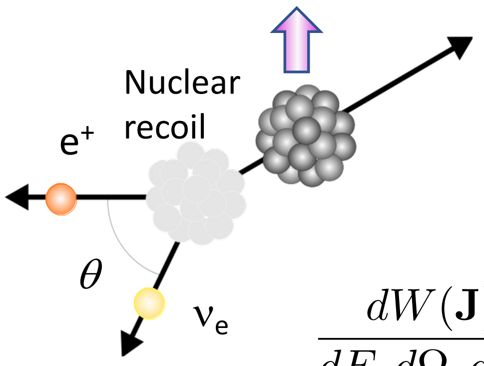
EFT

$$\overline{C}_V + \overline{C}'_V = 2\,g_V\,(1+\epsilon_L+\epsilon_R)$$
$$\overline{C}_A + \overline{C}'_A = -2\,g_A\,(1+\epsilon_L-\epsilon_R)$$
$$\overline{C}_S + \overline{C}'_S = 2\,g_S\,\epsilon_S$$
$$\overline{C}_P + \overline{C}'_P = 2\,g_P\,\epsilon_P$$
$$\overline{C}_T + \overline{C}'_T = 8\,g_T\,\epsilon_T$$

M. González-Alonso, Colloque GANIL (2019)
T.Lee, C-N Yang Phys. Rev. 104 (1956)
M. González-Alonso, O. Naviliat-Cuncic, N. Severijns Prog. Part. Nucl. Phys. (2019)
A. Falkowski, M. González-Alonso, O. Naviliat-Cuncic JHEP04 (2021)

Nuclear beta decay

- **Decay rate distribution for polarized nuclei**



Nuclear polarization

$$\frac{dW(\mathbf{J})}{dE_e d\Omega_e d\Omega_\nu} = dW_0 \times \xi \left\{ 1 + a\frac{\mathbf{p}_e \cdot \mathbf{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + \frac{<\mathbf{J}>}{J} \cdot \left(A\frac{\mathbf{p}_e}{E_e} + B\frac{\mathbf{p}_\nu}{E_\nu} + D\frac{\mathbf{p}_e \times \mathbf{p}_\nu}{E_e E_\nu} \right) \right\}$$

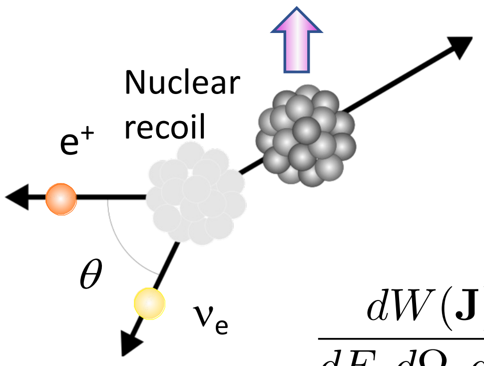
Fermi Function
Phase space factor

β and
ν momenta

J.D Jackson, S.B Treiman, H.W Wyld Nuclear Phys 4 (1957)

Nuclear beta decay

- **Decay rate distribution for polarized nuclei**



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β–ν correlation coefficient
CP conserving
Access to C_S and C_T quadratically

Fierz interference term
CP conserving
Access to C_S and C_T linearly

« D » coefficient
CP violating
Access to C_A, C_A', C_V, C_V' linearly

Angular correlation measurements
Beta spectrum shape measurements

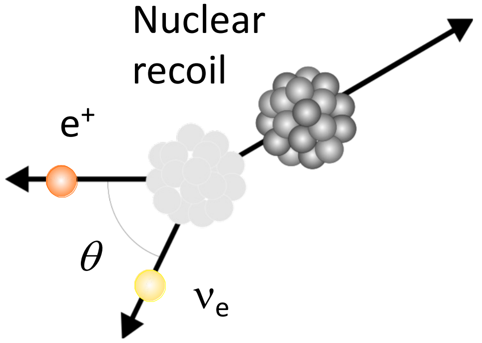
J.D Jackson, S.B Treiman, H.W Wyld Nuclear Phys 4 (1957)

Angular correlation measurement

- **Decay rate for unpolarized nuclei : integrating over J**

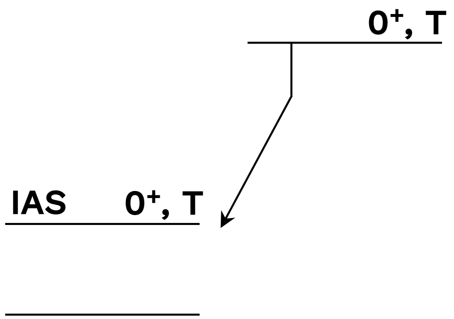
$$dW = dW_0 \times \xi \left(1 + a\frac{\mathbf{p}_e \cdot \mathbf{p}_\nu}{E_e E_\nu} + b\frac{m}{E_e}\right)$$

a > 0 : θ =0° favored and large recoil
a < 0 : θ =180° favored and small recoil



- **Angular correlation measurement = recoil measurement**

$$\tilde{a} \sim \frac{a}{1 + b < \frac{m_e}{E_e} >}$$

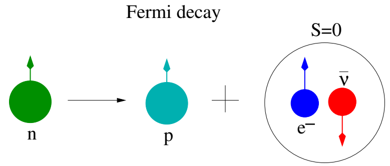


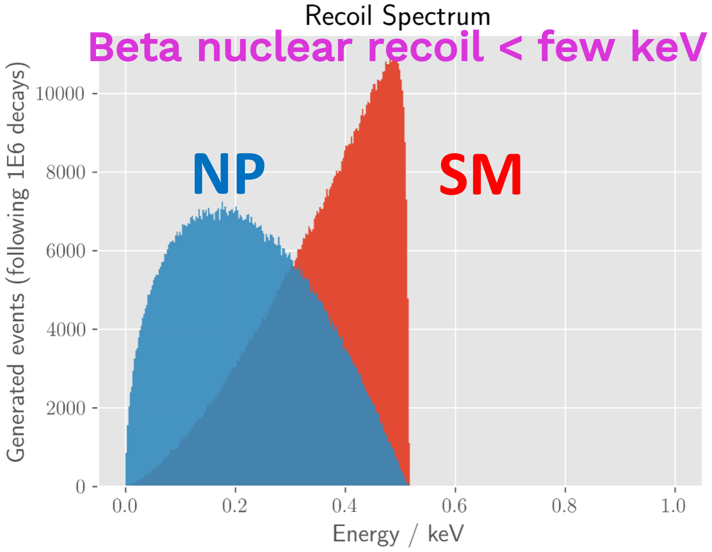
Pure Fermi transition ΔJ=0 S=0

Vector Coupling

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

$$b_F \approx \pm Re\left(\frac{C_S + C'_S}{C_V}\right)$$ **= 0**

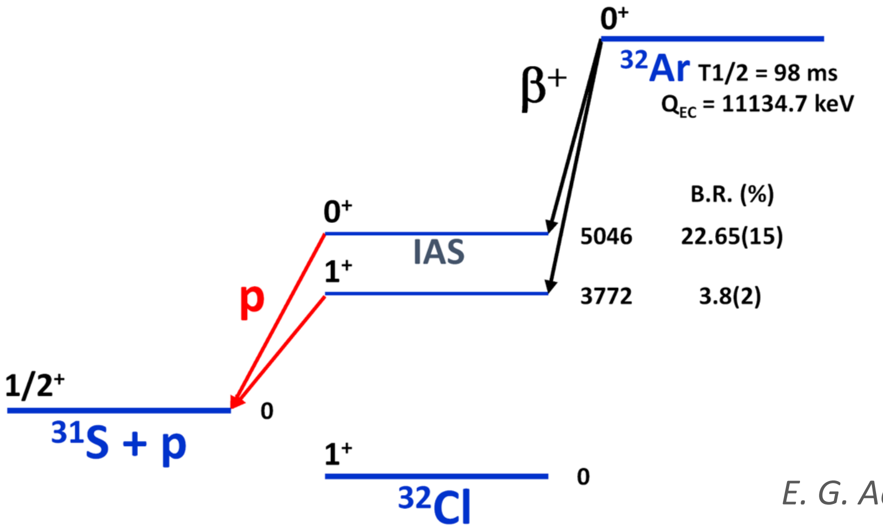


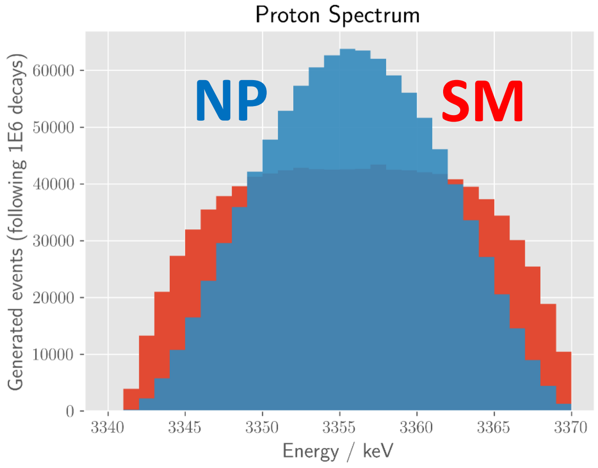


WISArD Weak Interaction Studies with ^{32}Ar Decay

- β-delayed proton emission in ^{32}Ar
  - Fermi $0^+ \longrightarrow 0^+$ transition from GS to IAS
  - Recoil ~640 eV
  - Beta delayed p emission IAS ~3.35 MeV
  - IAS : Γ ~ 20 eV ⇔ $T_{1/2}$ ~ 10^{-17} s

  ➪ p emission in flight from the recoil





E. G. Adelberger et al. Phys. Rev. Lett. 83 (1999)

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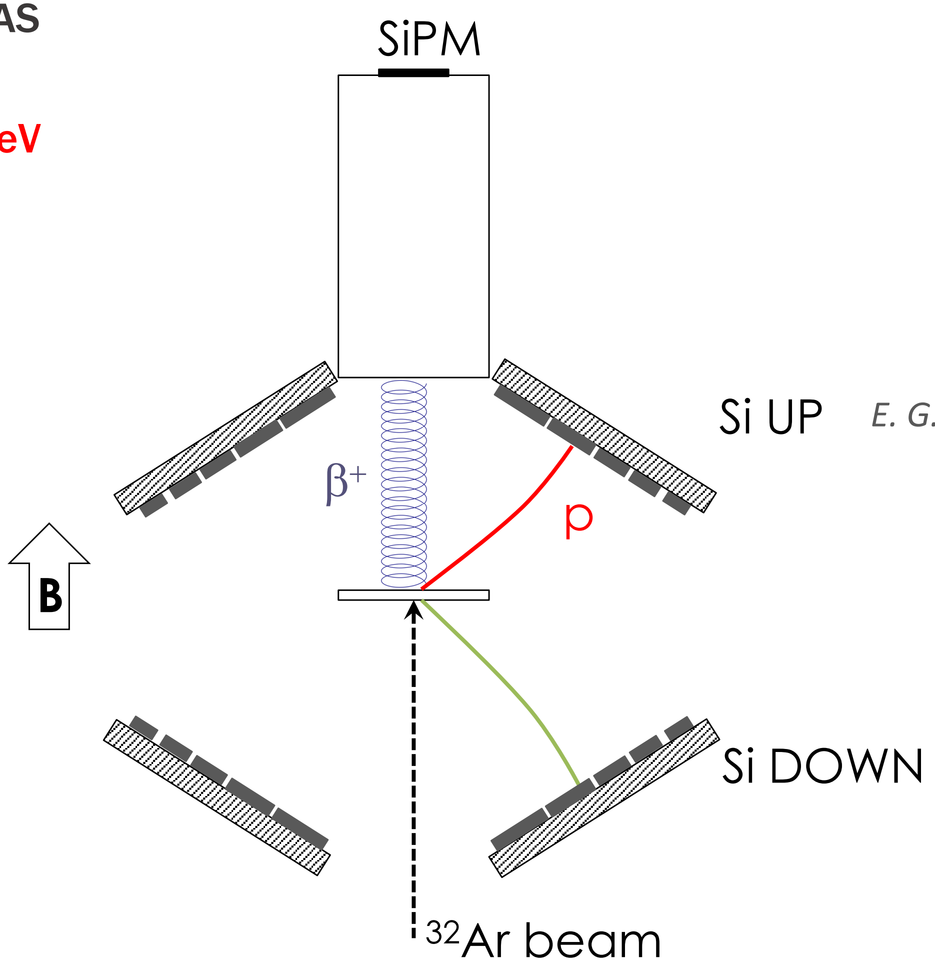
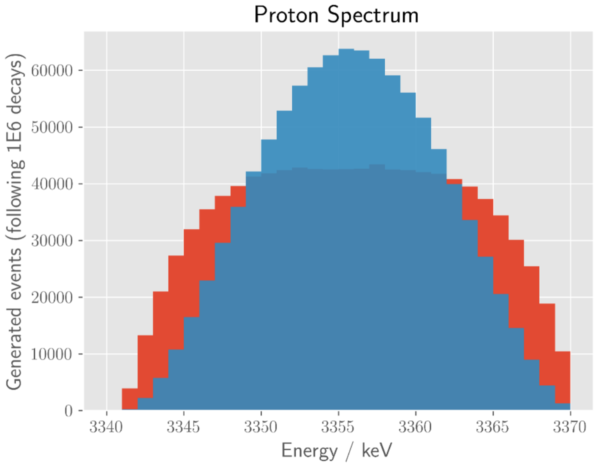
  ➪ p emission in flight from the recoil

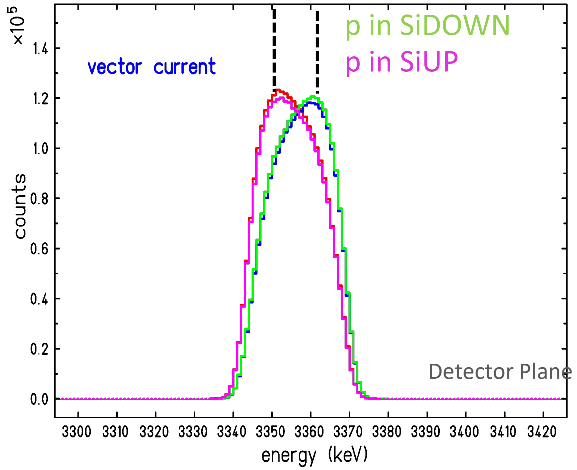
- β-p coïncidence measurement
  - Strong magnetic field
  - Catcher foil
  - 2 symmetrical p detectors
    - high resolution
    - high solid angle
  - Beta detector
    - low detection threshold



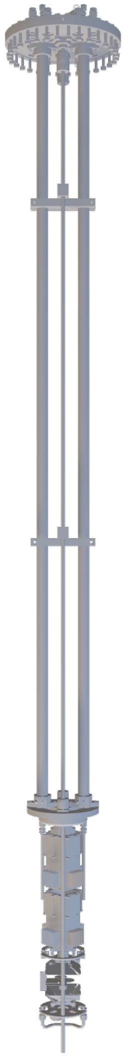


E. G. Adelberger et al. Phys. Rev. Lett. 83 (1999)

ΔE : linear with ã

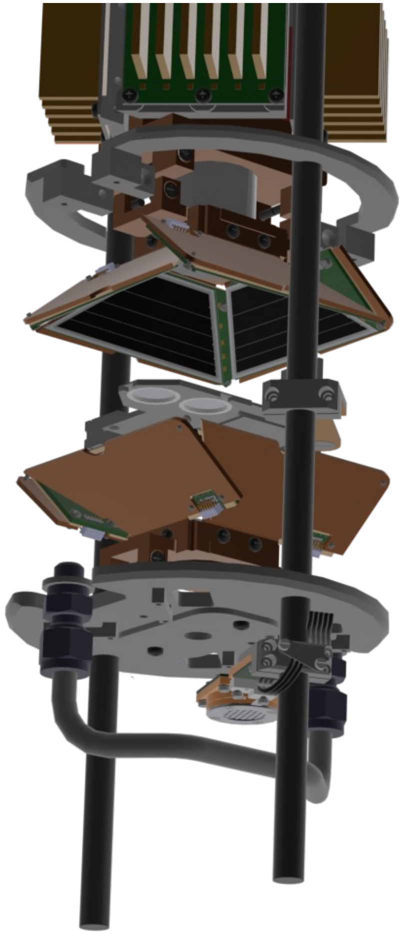


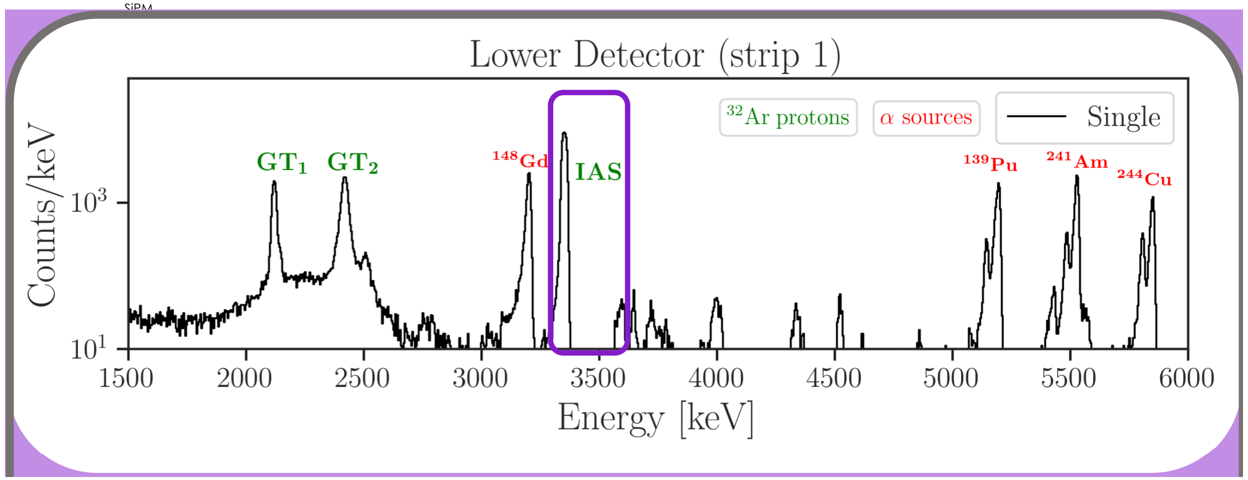
WISArD Weak Interaction Studies with ^{32}Ar Decay

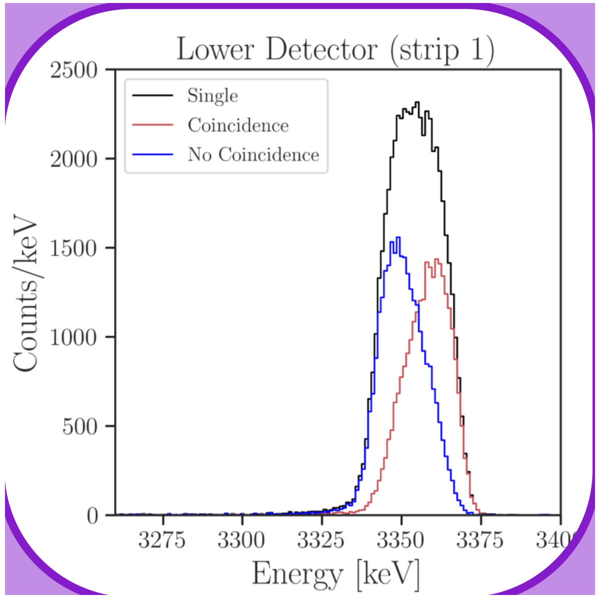


V. Araujo-Escalona et al. Phys. Rev. C 101 (2020)
D. Atanasov et al. NIM A 1050 168159 (2023)
Exclusion plot from D. Atanasov

WISArD Weak Interaction Studies with ^{32}Ar Decay



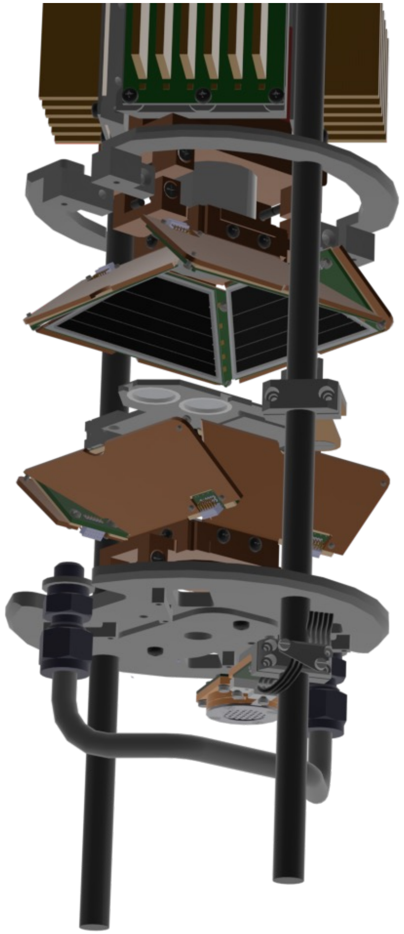


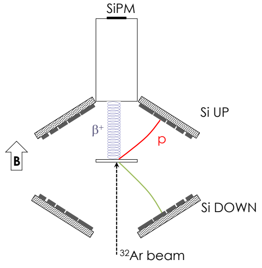


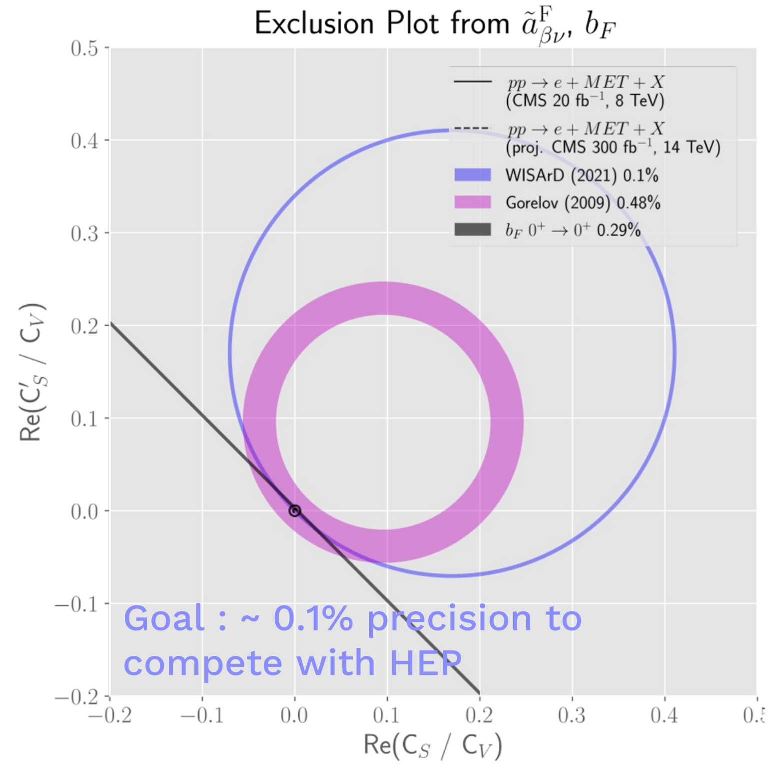
Samuel Lecanuet
2021 dataset

POSTER

WISArD Weak Interaction Studies with ^{32}Ar Decay







- 2018 Proof-of-Principle Δa/a ~ 4%

$$\tilde{a}_F = 1.007(32)_{stat}(25)_{syst}$$

- 2021 : See Poster S. Lecanuet
- 2024 : new data taking early June 2024

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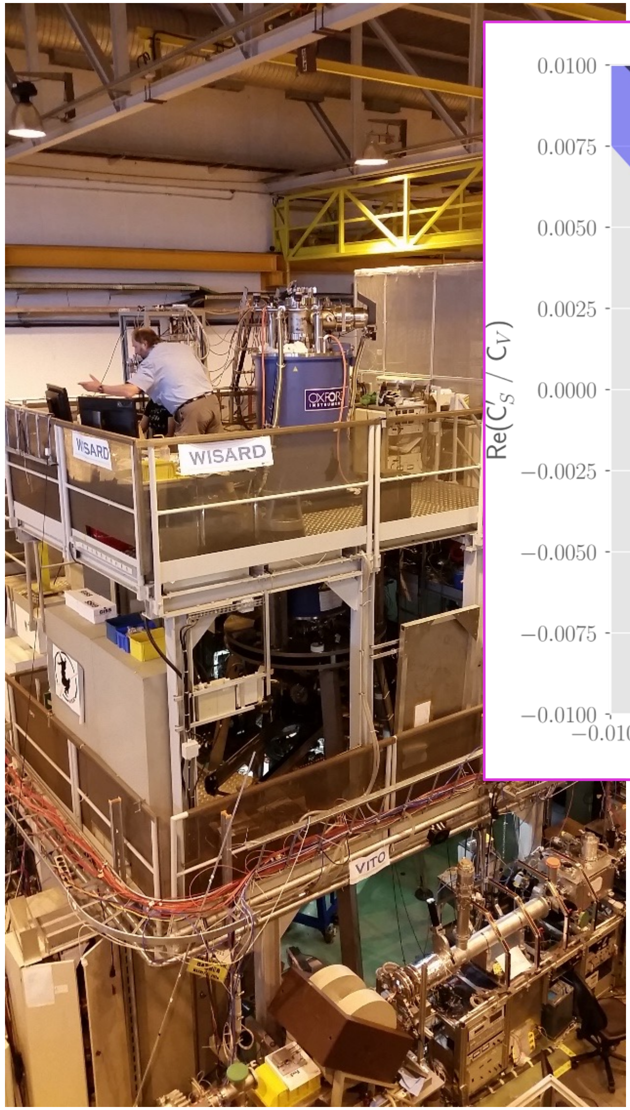

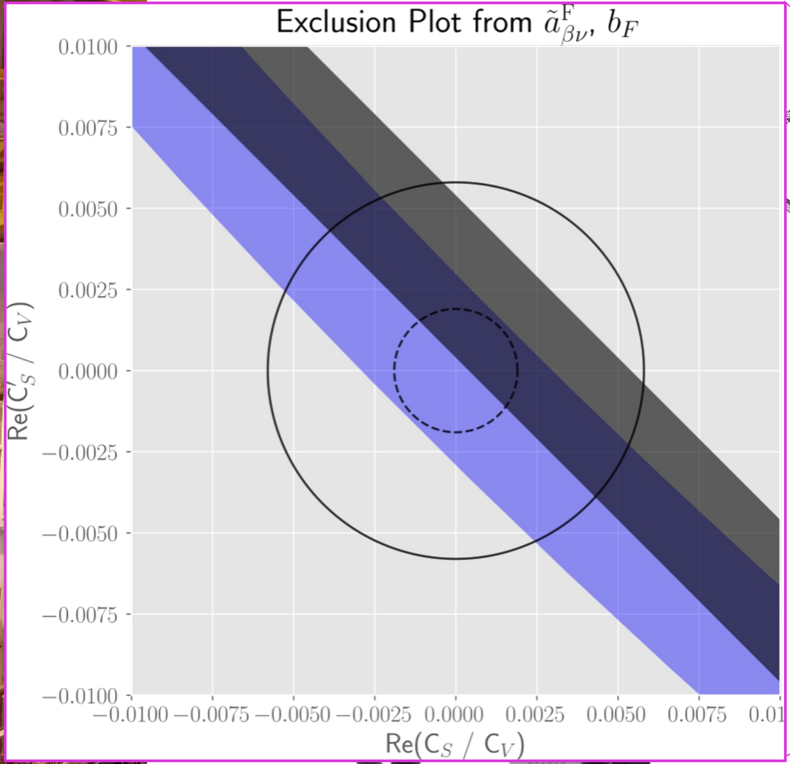

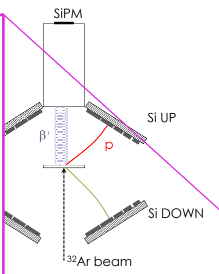

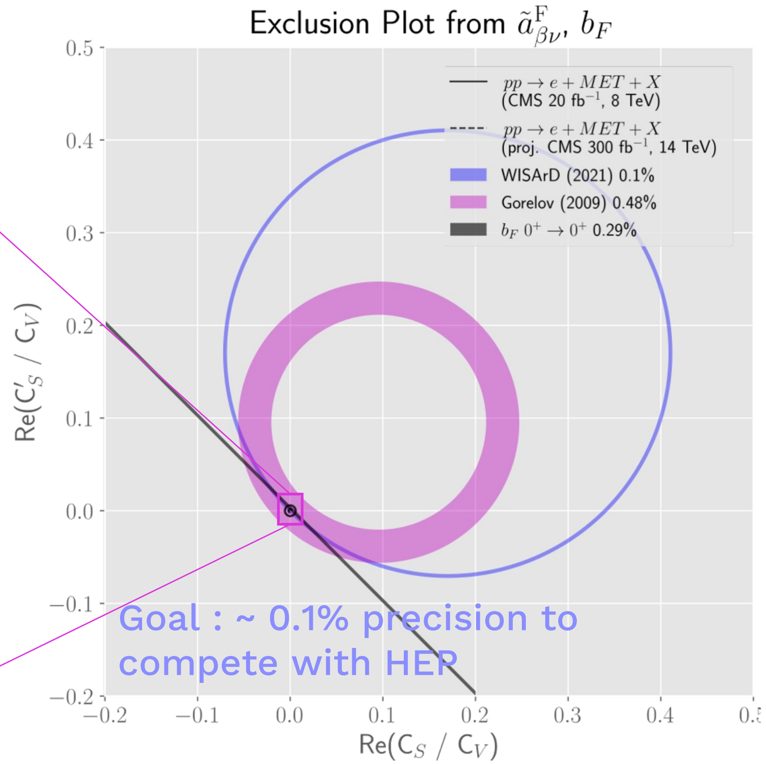

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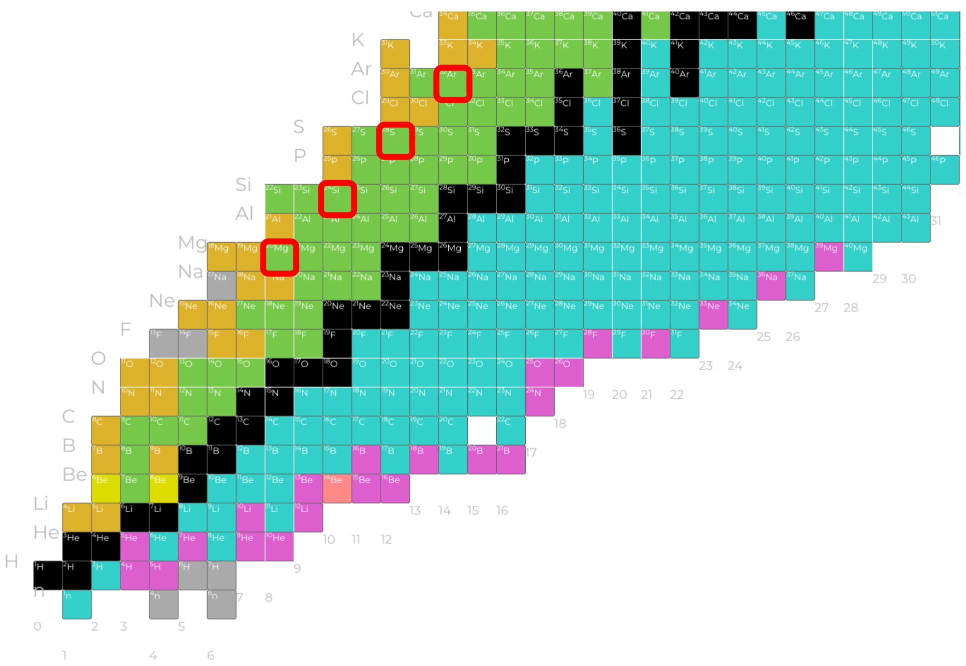
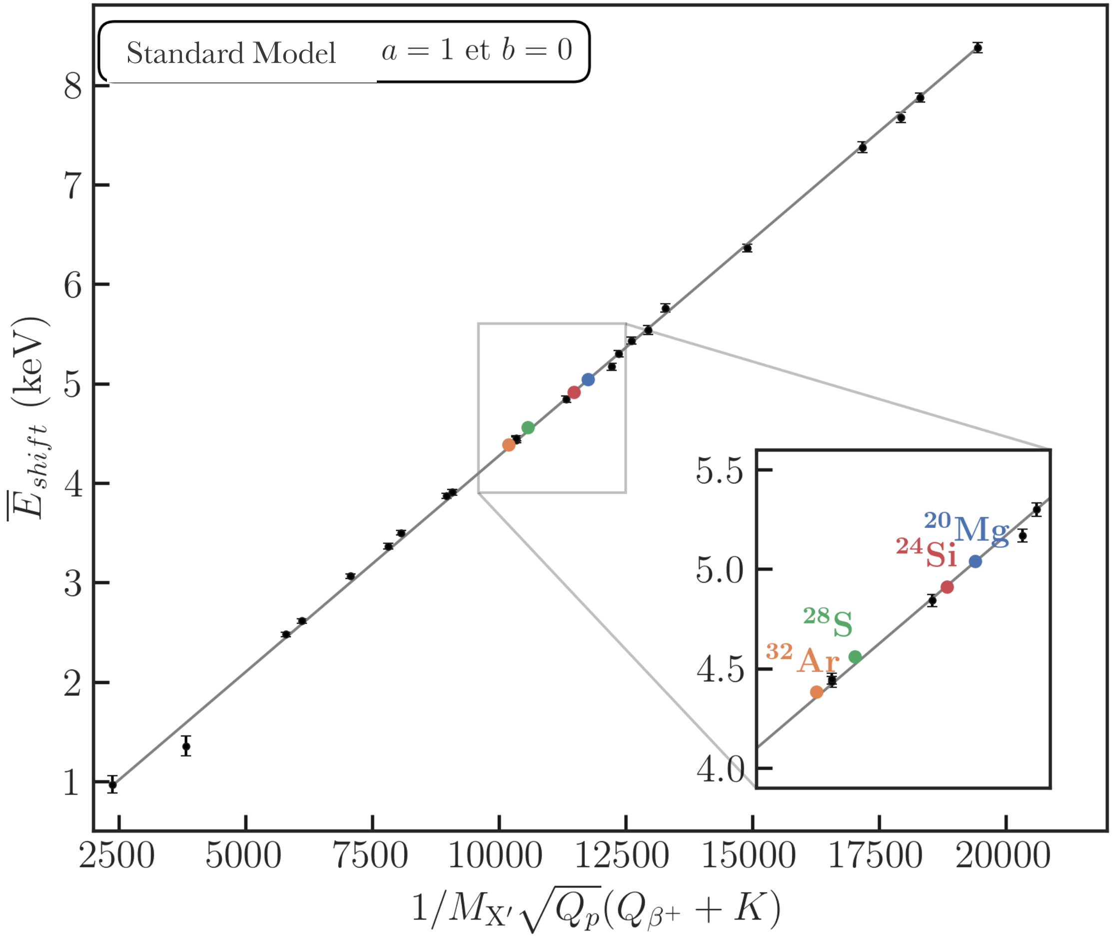
D. Atanasov et al. NIM A 1050 168159 (2023)
Exclusion plot from D. Atanasov

Other β-p candidates

- 14 β-p emitters with pure Fermi transition
- Kinematic shift :
  - ∝ 1/M’ of daughter nucleus
  - ∝ $\sqrt{Q_p}$ proton kinetic energy
  - ∝ Q_β endpoint
- 3 exotic nuclei lighter than ^{32}Ar

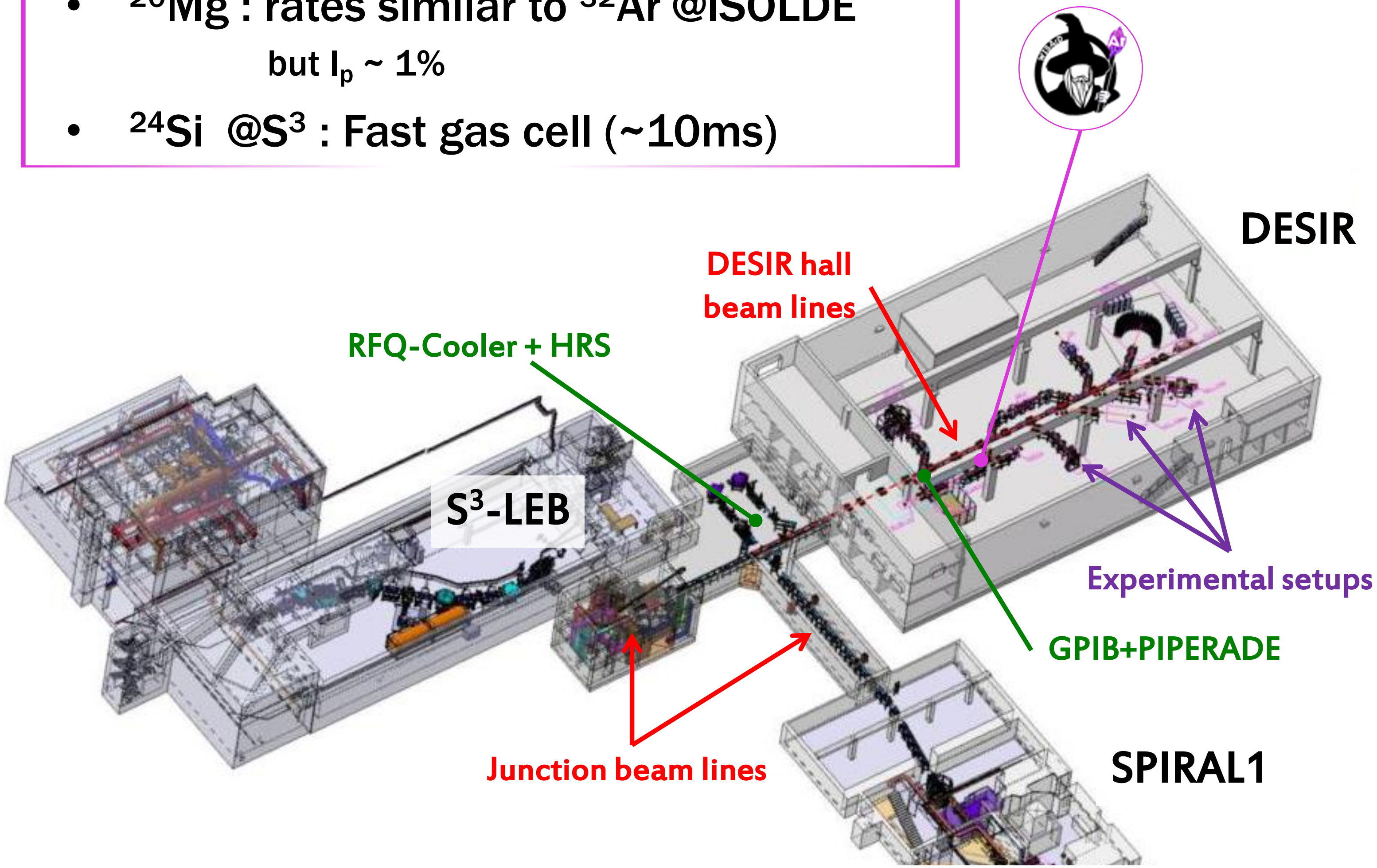


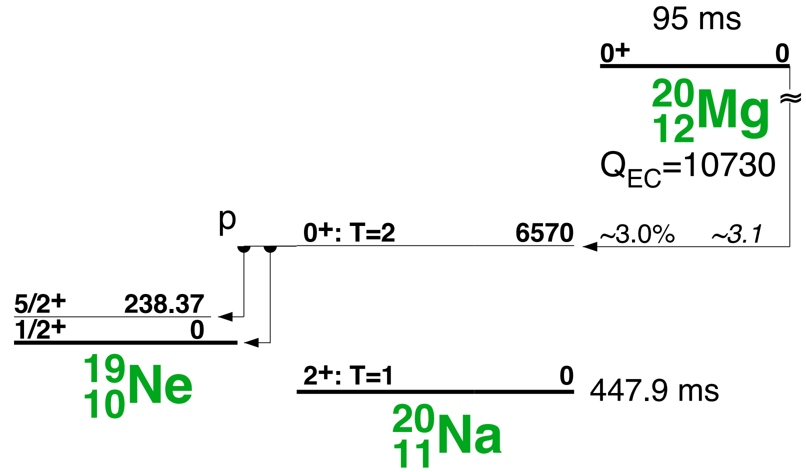


S. Lecanuet – M2 Internship

^{20}Mg at DESIR

- Contaminant : ^{20}Na ➪ PIPERADE
- ^{20}Mg : rates similar to ^{32}Ar @ISOLDE
  but I_p ~ 1%
- ^{24}Si @S^3 : Fast gas cell (~10ms)



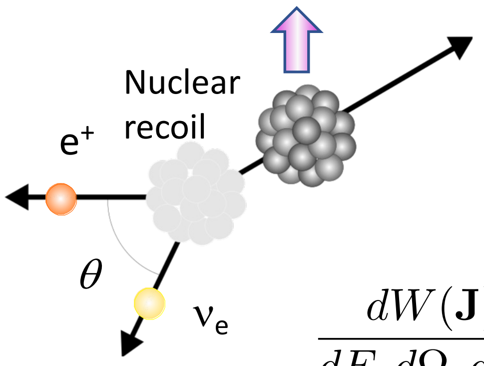


M.V. Lund et al, Eur. Phys. J. A (2016) 52: 304

	$T_{1/2}$ (ms)	rate ISOLDE (ions/µC)	rate DESIR (pps)
^{20}Mg	90	-	1500-3600 (SP1) / 300-500 (S3)
^{24}Si	143	-	420 (S3)
^{28}S	125	-	?
^{32}Ar	100	~ 3000	2300 (SP1)

Nuclear beta decay

- **Decay rate distribution for polarized nuclei**



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β–ν correlation coefficient
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Access to C_A, C_A', C_V, C_V' linearly

Angular correlation measurements
Beta spectrum shape measurements

J.D Jackson, S.B Treiman, H.W Wyld Nuclear Phys 4 (1957)

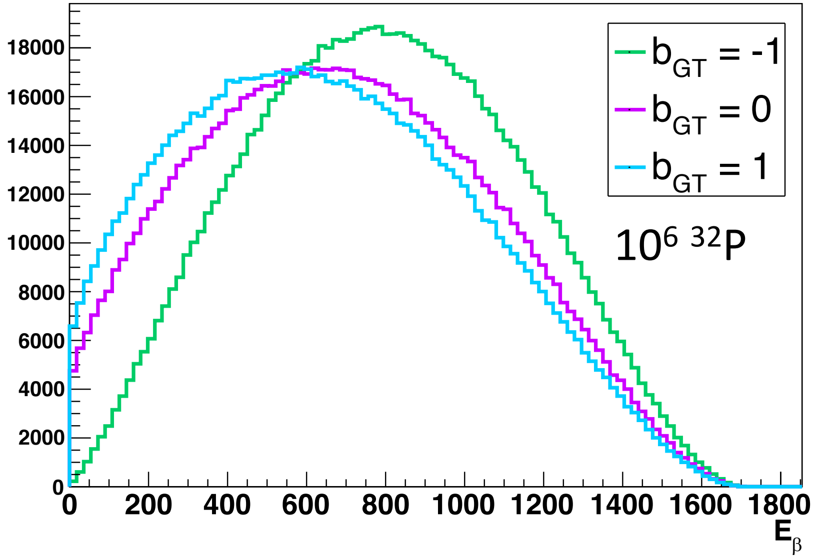
β-spectrum shape measurement

- **Decay rate for unpolarized nuclei : integrating over all angles**

$$dW = dW_0 \times \xi \left(1 + b\frac{m}{E_e}\right)$$

Pure Gamow-Teller transition

$$b_{GT} \approx \pm Re\left(\frac{C_T + C'_T}{C_A}\right)$$



- **Going down to 1‰ level of uncertainty**

$$W = \frac{m}{E_e} + 1$$

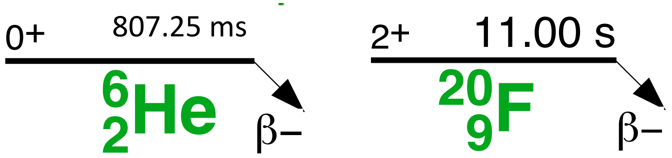
$$N(W)dW = \frac{G_V^2 V_{ud}^2}{2\pi^3} F_0(Z,W)L_0(Z,W)U(Z,W)D_{FS}(Z,W,\beta_2)R(W,W_0)R_N(W,W_0,M)$$
$$\times Q(Z,W)S(Z,W)X(Z,W)r(Z,W)C(Z,W)D_C(Z,W,\beta_2)pW(W_0 - W)^2 dW$$

$$N(W)dW \propto pW(W_0 - W)^2 \times \left(1 + \frac{\gamma m_e}{W} b_{GT} \pm \frac{4W}{3M} b_{wm}\right) dW$$

J.D Jackson, S.B Treiman, H.W Wyld Nuclear Phys 4 (1957)
L. Hayen et al, Rev. Mod. Phys. 90 (2018)

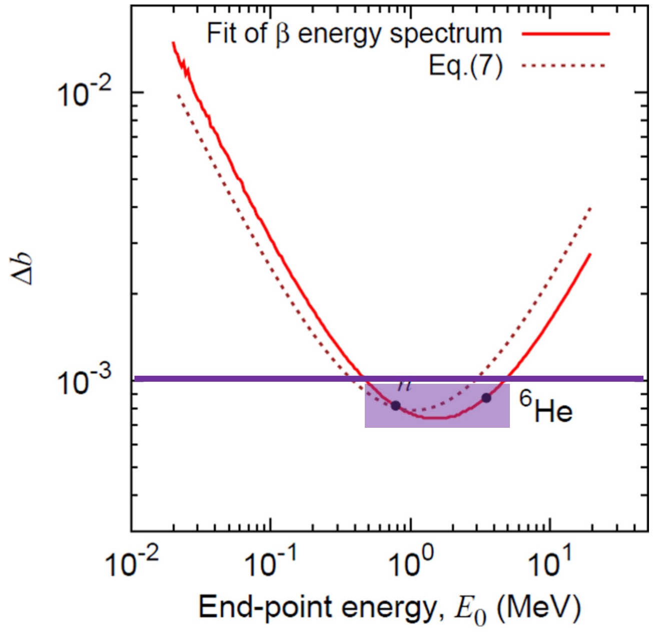
Choosing the best candidate

- **Theoretical constraints**
  - Radiative corrections under control
  - Recoil order corrections : b_{WM}
  - Simple shape : allowed transition
  - Simple decay scheme
- **Sensitivity**

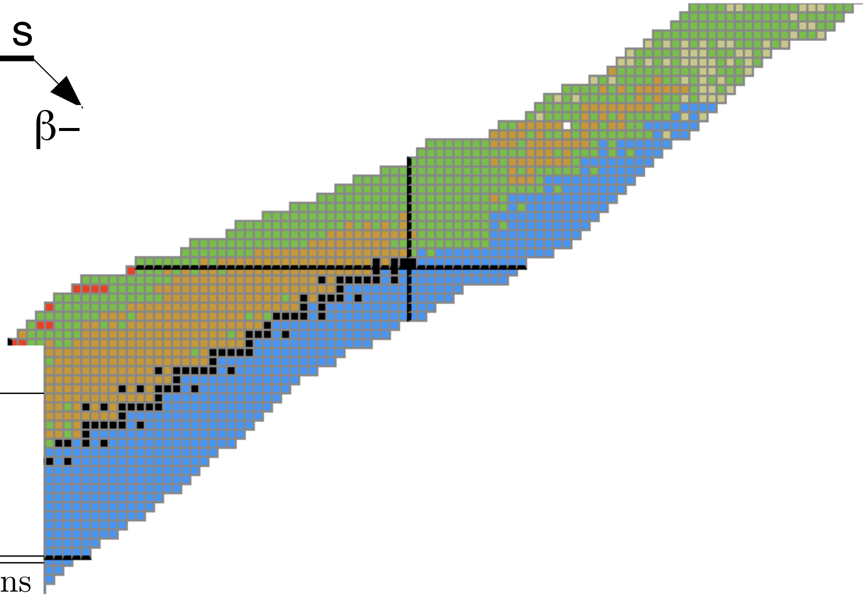


$Q_{\beta-}$ 3507.8 $Q_{\beta-}$ 5392

E_0 between 1 and 3 MeV



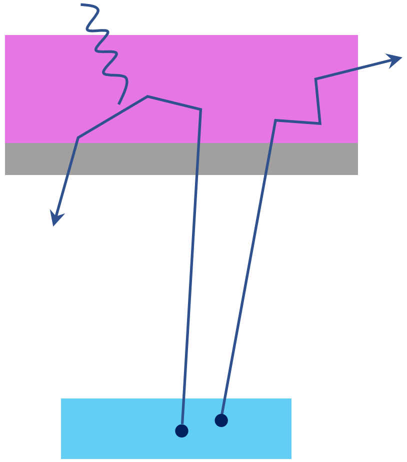
	$T_{1/2}$	E_0 [MeV]
^{63}Ni	101.2 y	0.066945(5)
^{45}Ca	162.61 d	0.2558(8)
^{32}P	14.3 d	1.71066(4)
^{114}In	71.9(1) s (49.51(1) d)	1.9886(6)
		Mirror transitions
^{11}C	20.364(14) m	0.9604(10)
^{13}N	9.965(4) m	1.1985(3)
^{15}O	122.24(16) s	1.7320(5)
^{17}F	64.385(53) s	1.73847(25)
^{25}Al	7.183(12) s	3.2547(5)
		$T = 1$ triplet
^{18}F	109.77(5) m	0.6335(6)
^{10}C	19.3016(24) s	2.92968(7)
^{6}He	806.7(1) ms	3.5078(11)
^{30}P	2.498(4) m	4.2324(3)
^{20}F	11.163(8) s	5.39086(8)



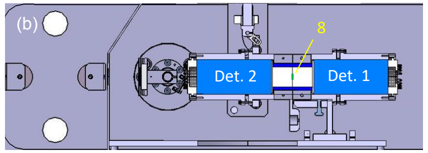
. González-Alonso, O. Naviliat-Cuncic Phys. Rev. C 94 (2016)
L. Hayen et al, Rev. Mod. Phys. 90 (2018)

Experimental challenges

- Partial energy deposit
  - Backscattering
  - Out-scattering
  - Bremsstrahlung
- Energy loss
  - Source localization
  - Detector dead layer
- Tracking simulations accuracy

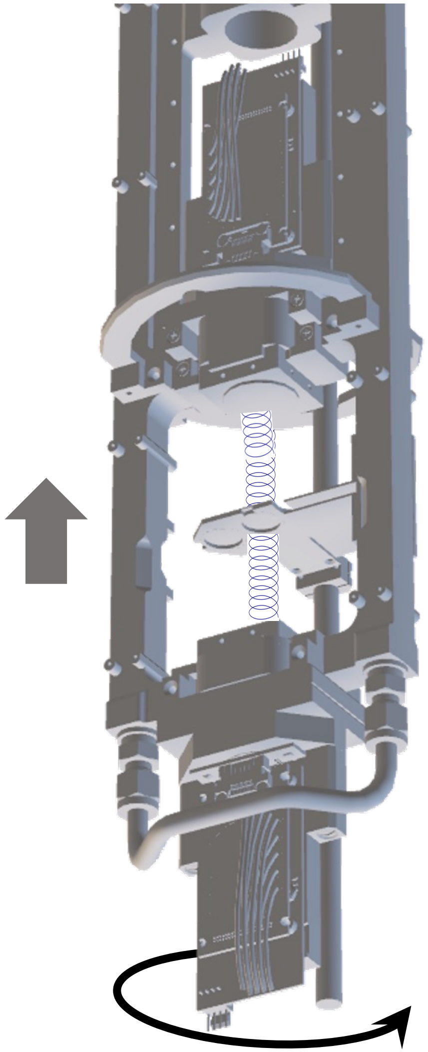


- Traps : LPCTrap, WITCH, TAMUTRAP…
- 4π calorimetry
  - b-STILED, ^{20}F@MSU…



- Tracking with MWDC
  - MiniBETA

- New techniques
  - ^{6}He-CRES
  - Recoil measurement with superconducting tunnel-junctions



G. Soti et al., NIMA 728 (2013)
M. Kanafani, Phys. Rev. C **106**, 045502 2022
D.Rozpedzik arXiv:2208.09971
S. Friedrich et al., Phys. Rev. Lett. 126, 021803 (2021)

InESS at WISArD

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^{45}Ca	162.61 d	0.2558(8)
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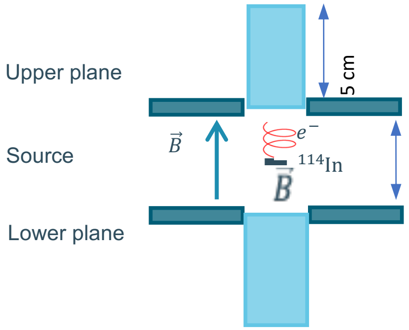
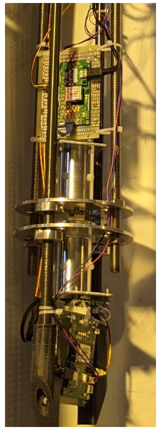
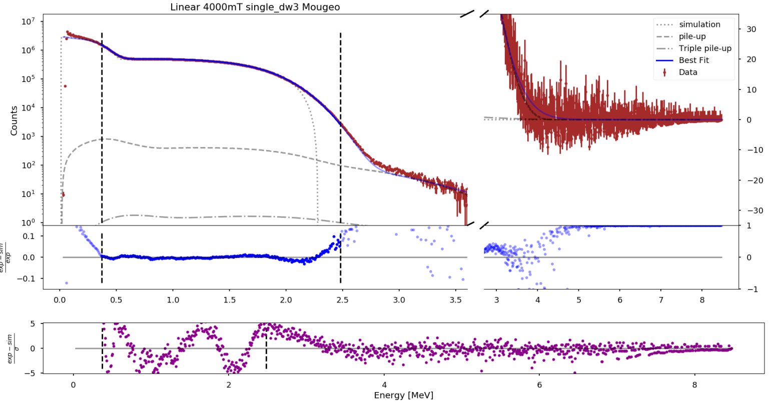
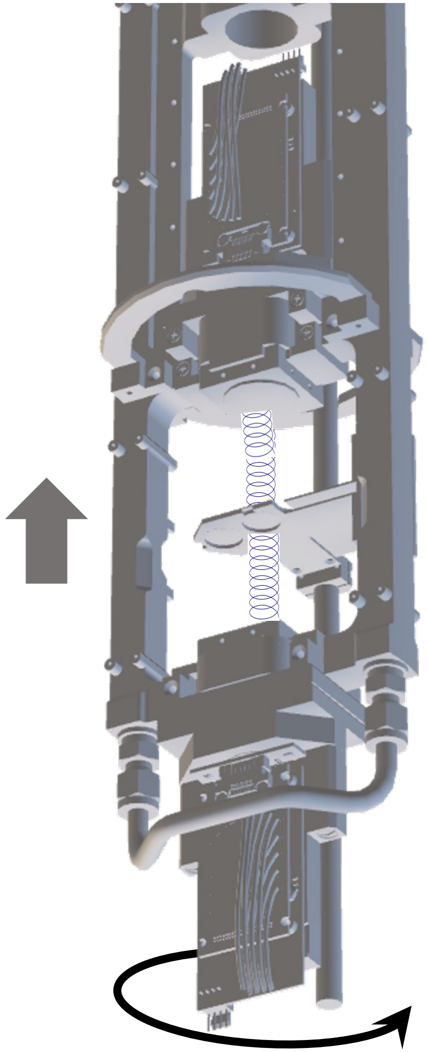
^{114}In	71.9(1) s (49.51(1) d)	1.9886(6)
		Mirror transitions
^{11}C	20.364(14) m	0.9604(10)
^{13}N	9.965(4) m	1.1985(3)
^{15}O	122.24(16) s	1.7320(5)
^{17}F	64.385(53) s	1.73847(25)
^{25}Al	7.183(12) s	3.2547(5)
		$T = 1$ triplet
^{18}F	109.77(5) m	0.6335(6)
^{10}C	19.3016(24) s	2.92968(7)
^{6}He	806.7(1) ms	3.5078(11)
^{30}P	2.498(4) m	4.2324(3)
^{20}F	11.163(8) s	5.39086(8)







S. Vanlangendonck, PhD (2023)



β-spectrum shape at DESIR

	$T_{1/2}$	E_0 [MeV]
^{63}Ni	101.2 y	0.066945(5)
^{45}Ca	162.61 d	0.2558(8)
^{32}P	14.3 d	1.71066(4)
^{114}In	71.9(1) s (49.51(1) d)	1.9886(6)
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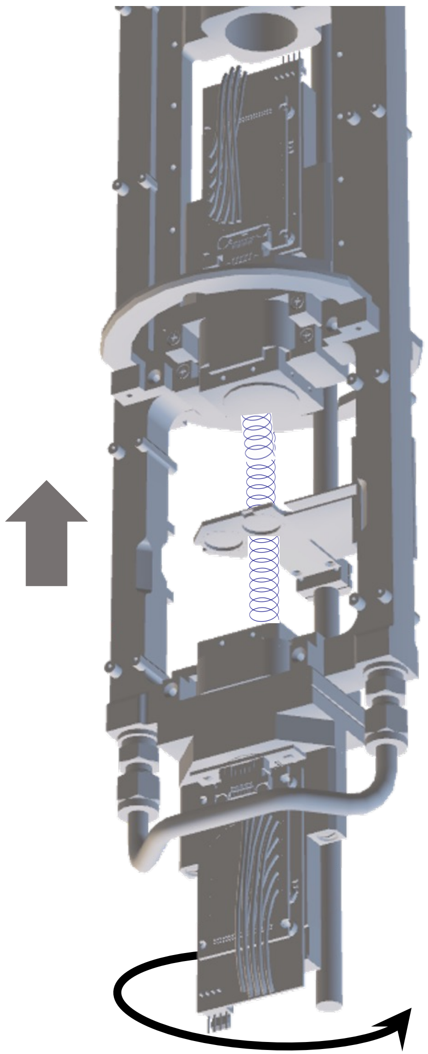
^{30}P	2.498(4) m	4.2324(3)
^{20}F	11.163(8) s	5.39086(8)

Source measurement ➪ b_{WM}

Mirror transitions

Isospin triplet : b_{WM} determined from CVC hypothesis ➪ b_{GT}

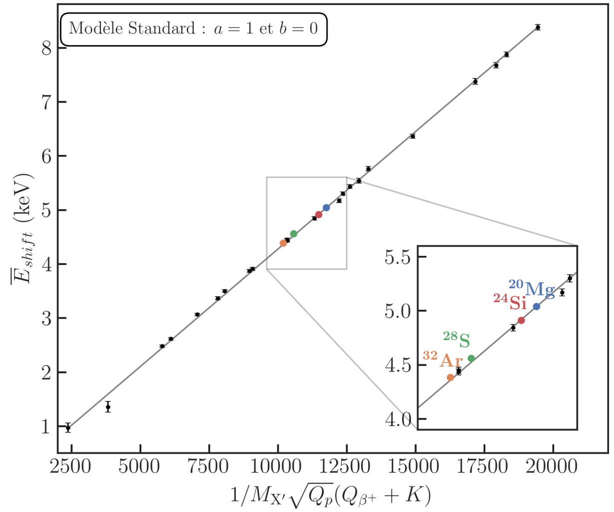


Conclusion

- **WISArD**
  - **High magnetic field**
  - **Angular correlation measurement with β-p emission : ^{32}Ar**
  - **β spectrum shape measurement : ^{114}In**

  - **^{8}Li β-delayed α break-up for exotic T currents**
  - **^{14}O BR measurement with β spectrum shape for Ft values**

- **WISArD @DESIR**
  - **New setup with more compact superconducting magnet**
  - **^{20}Mg for exotic S currents**
  - **^{30}P β spectrum shape**



	$T_{1/2}$	E_0 [MeV]
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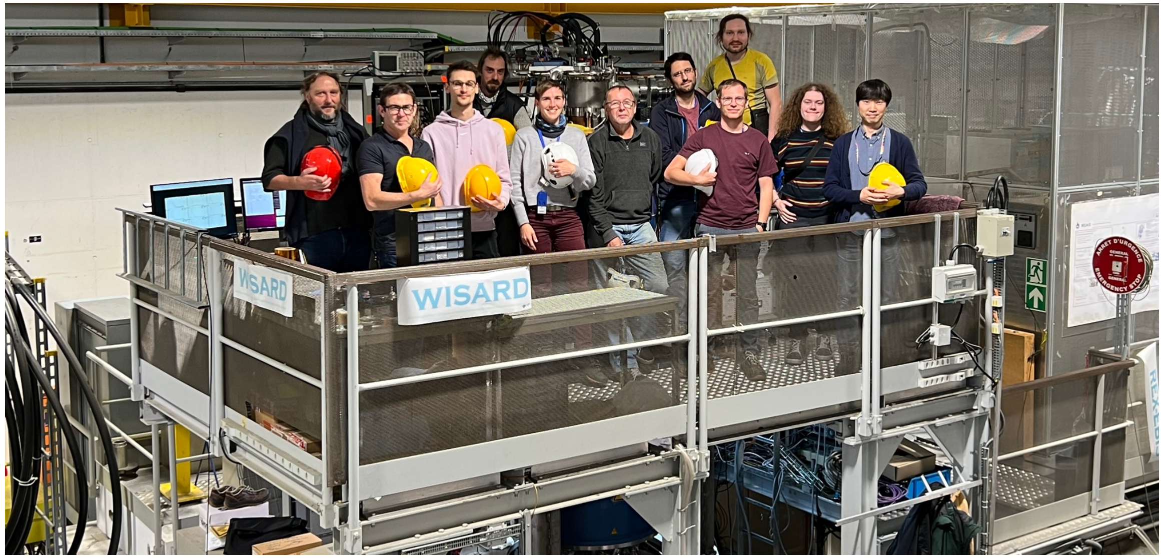
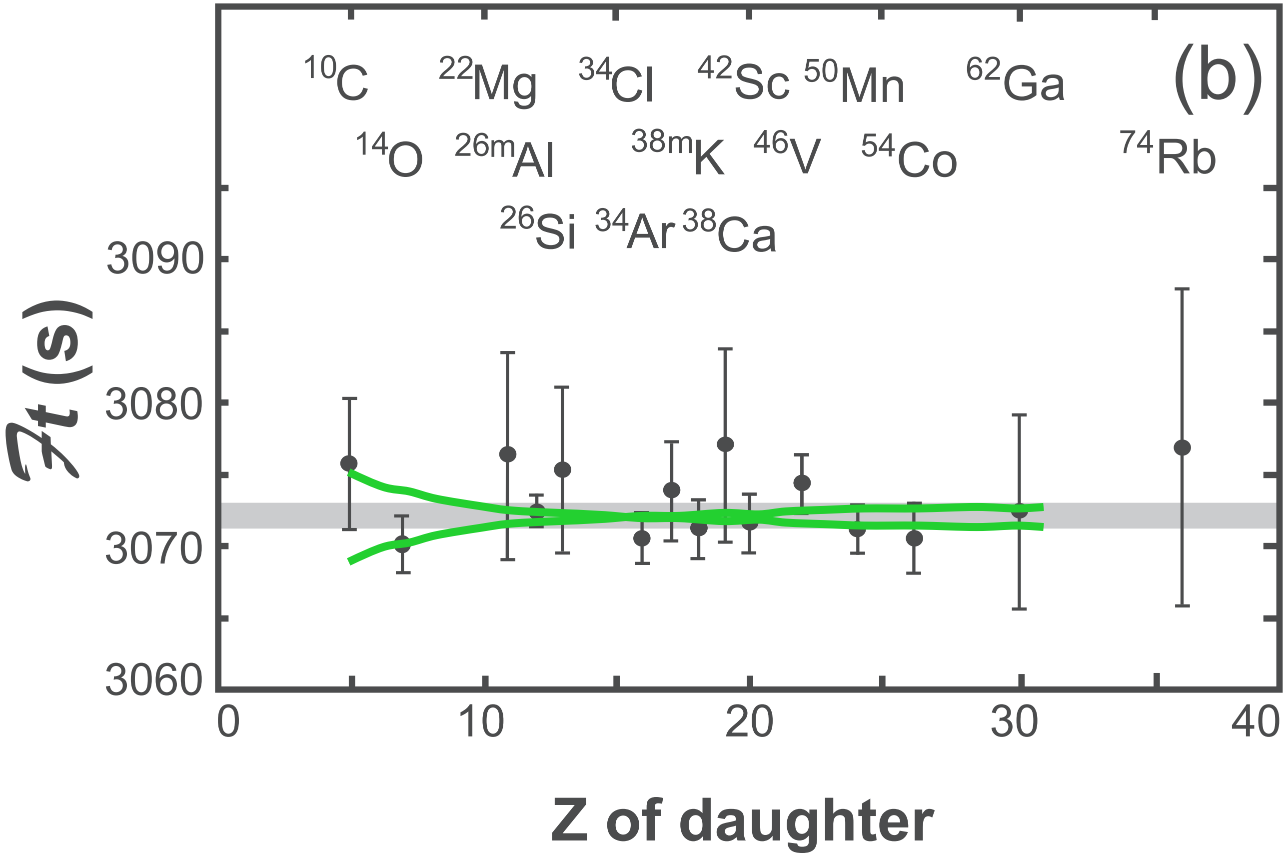
^{20}F	11.163(8) s	5.39086(8)

Thank you



P.Alfaurt, D.Atanasov, P.Ascher, B.Blank, L.Daudin, X.Fléchard, A.Garcia, M.Gerbaux, J.Giovinazzo, S.Grévy, J.Ha, R.Lica, E.Liénard, D.Melconian, C.Mihai, C.Neacsu, A.Ortega-Moral, M.Pomorski, M.Roche, N.Severijns, M. Versteegen, S.Vanlangendonck, D.Zakoucky

^{14}O : BR from beta spectrum shape



$\mathcal{F}t$

$=$ **Statistical rate function** $f \propto \int dW_0$ $\times$ **Partial half-life** $t = \frac{t_{1/2}}{BR}(1+P_{EC})$ $\times$ **Corrections: Radiative < 1% Structure < 1%**

Trap : Q_{EC}
$\Delta m \sim 10^{-8}$

Beta counting and Ge with calibrated ε :
$t_{1/2}$ and BR
$\Delta\varepsilon \sim 0.2\%$

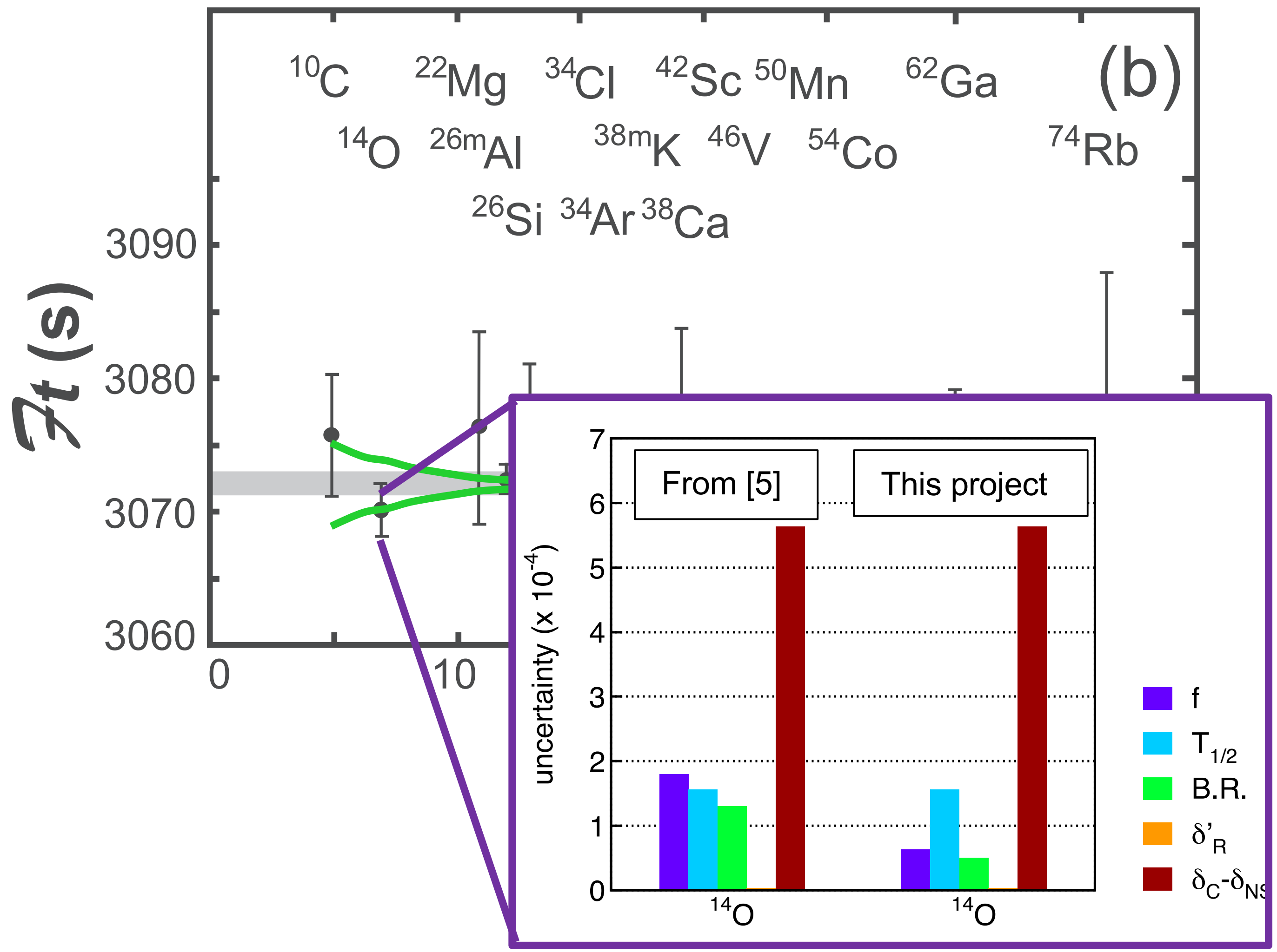
Theoretical Calculations
uncertainties < 0.1%
(except ^{62}Ga&^{74}Rb)

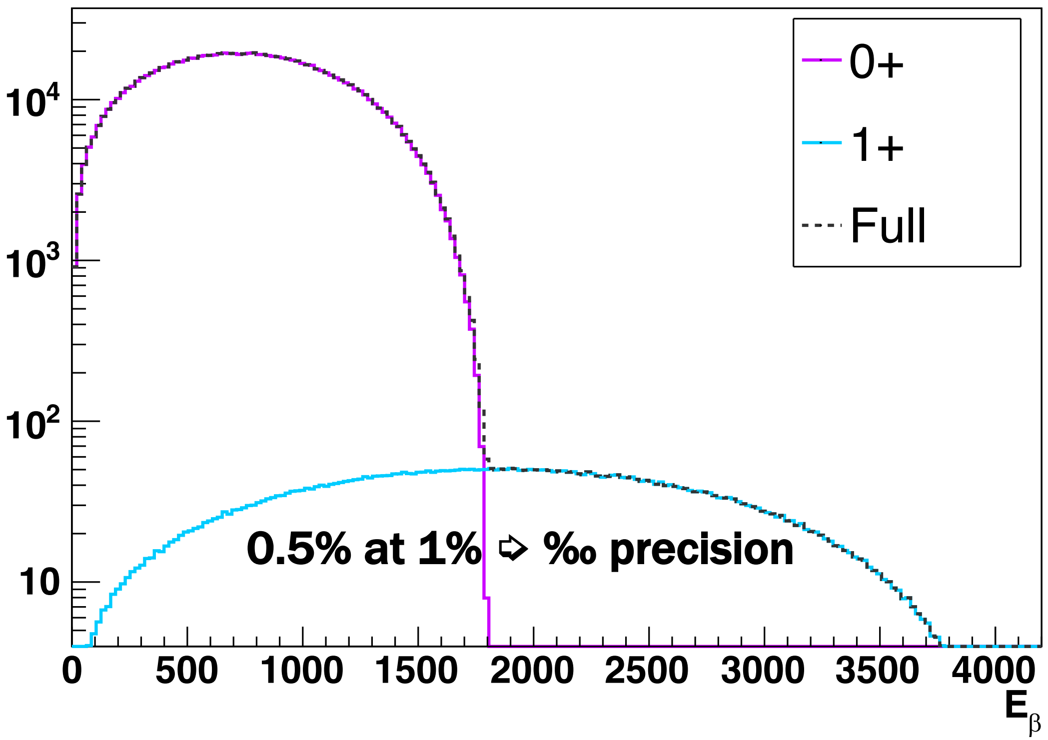
$$= \frac{K}{2G_F^2 V_{ud}^2 (1+\Delta_R^V)}$$

15 transitions with
uncertainties < 0.3%

$$b_F = -2\frac{C_S}{C_V} \neq 0 \Rightarrow \mathcal{F}t(< 1/W >)$$

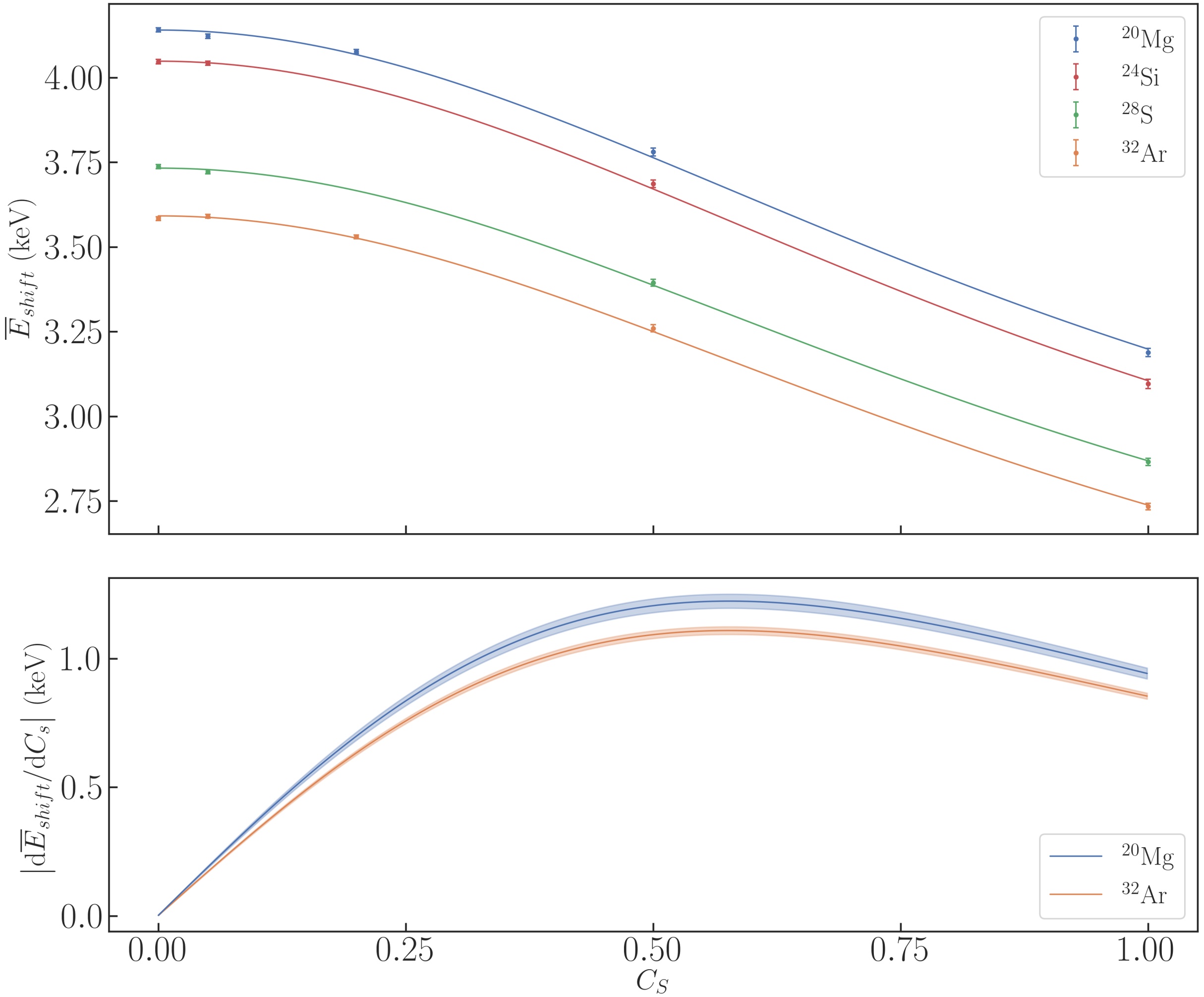
^{14}O : BR from beta spectrum shape



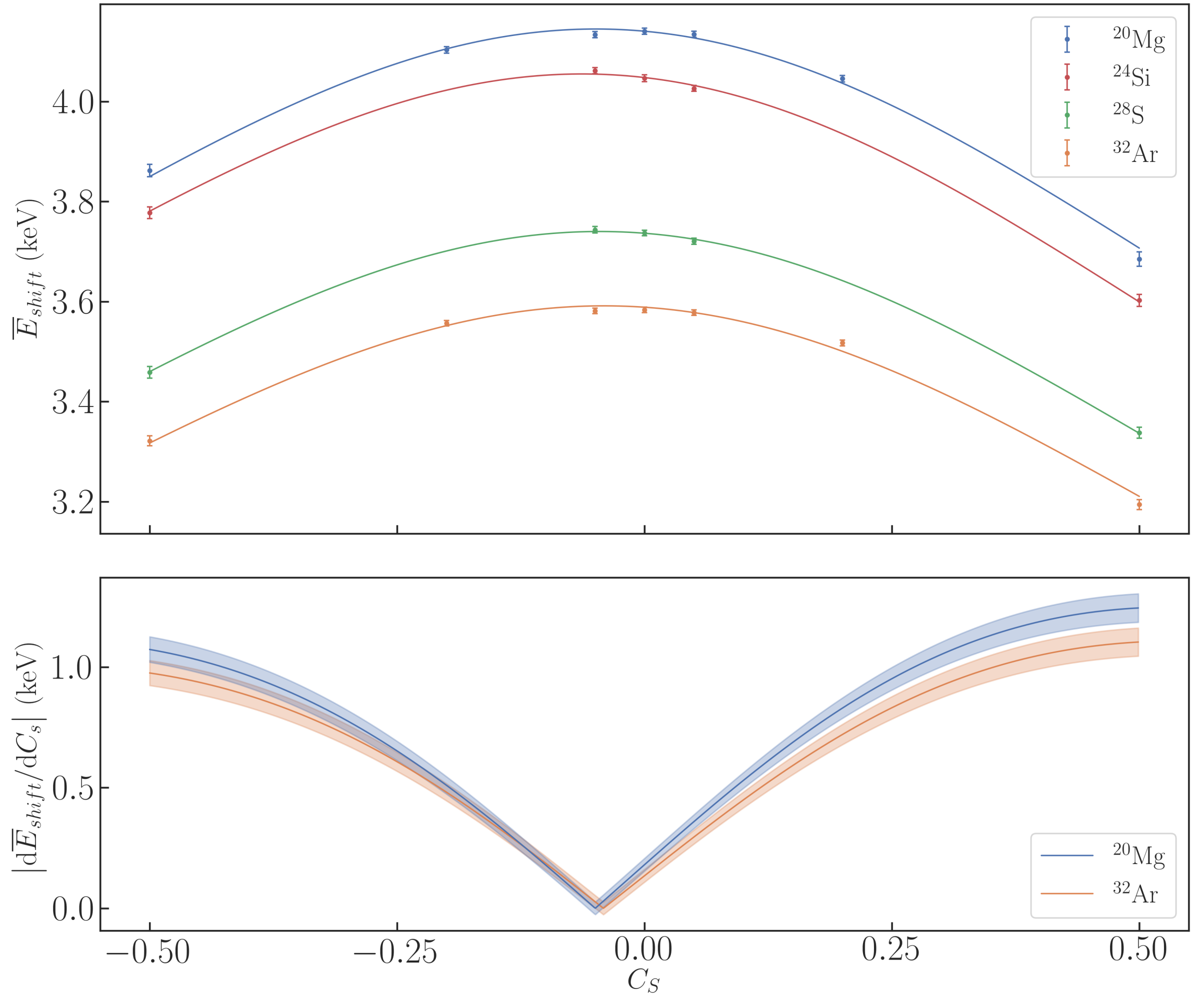


Sensitivity to scalar currents

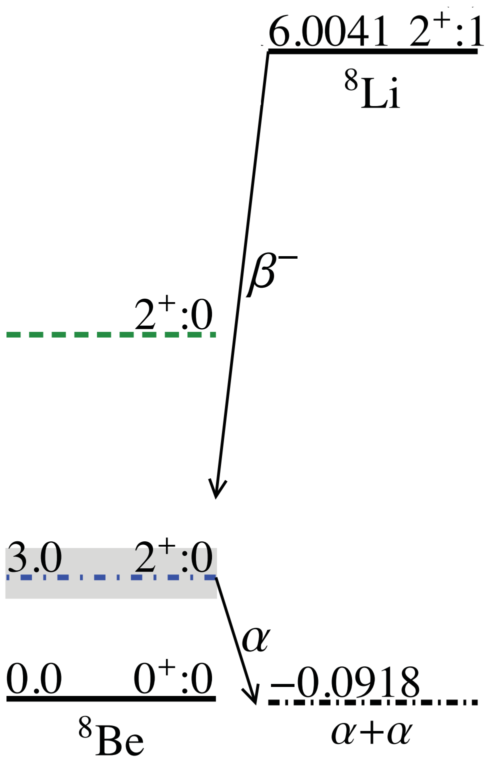
- Scalar right-handed currents : $b_F=0$

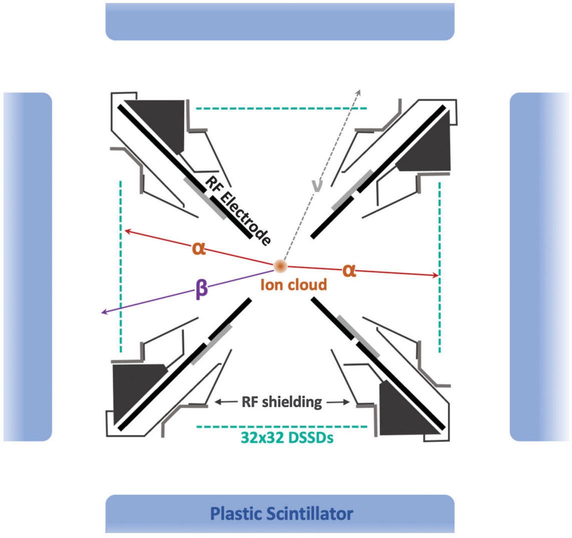


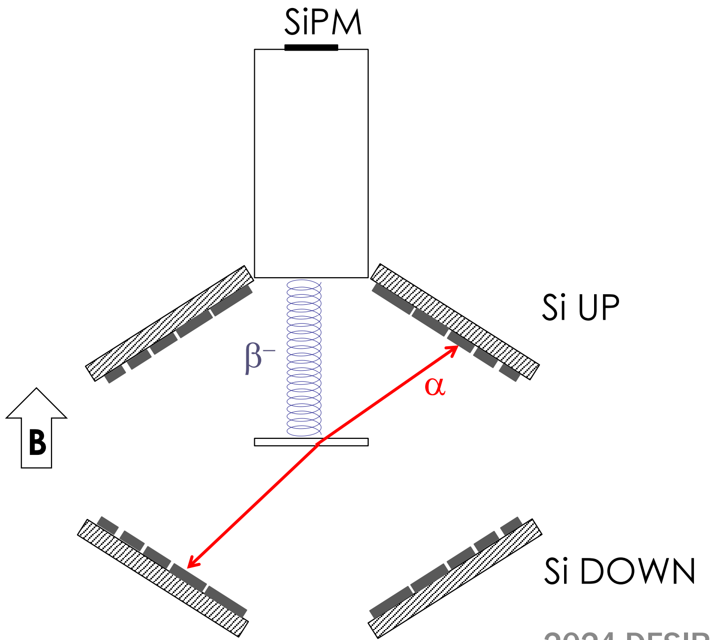
- Scalar left-handed currents : $b_F\neq0$



^{8}Li : β-delayed α break-up





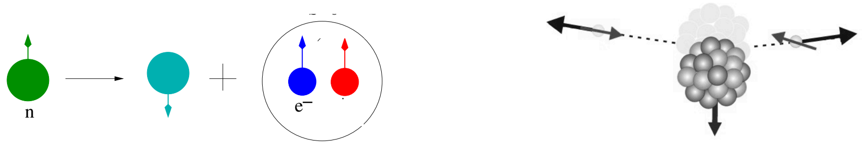


Pure Gamow-Teller transition **ΔJ=0 or 1 S=1**

Axial-Vector Coupling

$$a_{GT} \cong -\frac{1}{3}\left(1 - \frac{|C_T|^2 + |C'_T|^2}{|C_A|^2}\right)$$ **= -1/3 standard model**

$$b_{GT} \approx \pm Re\left(\frac{C_T + C'_T}{C_A}\right)$$ **= 0**



- **Argonne : Paul Trap (BPT)**

  $a_{\beta\nu} = -0.3325 \pm 0.0013_{\text{stat}} \pm 0.0019_{\text{syst}}$

  $|C_T/C_A| < 0.087$ at the 95.5% C.L.
- **WISArD sensitivity ?**
  - **Geometry**
  - **Energy loss in the catcher and dead layers**

M.T. Burkey et al. Phys. Rev. Lett. 128 (2022)