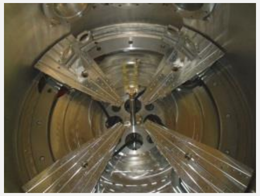


Seminar RESANET
May 10th, 2021

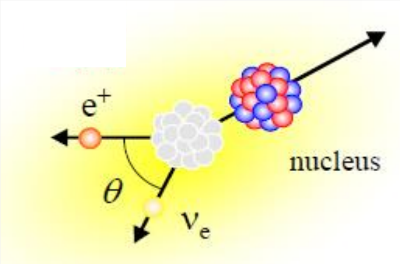
Search for New Physics beyond the Standard Model with precision measurements in nuclear β decays

- *General context and motivations*
- *LPCTrap setup and $^{6}He^{1+}$ experiment*
- *Perspectives*
  - *S & T exotic currents: WISArD & b-STILED projects*
  - *V_{ud}: measurements in mirror decays*
  - *CP violation: the MORA project*
- *Summary*

E. Liénard *LPC Caen, Université de Caen Normandie*

Nuclear β decay: a laboratory to test the Standard Model

Nuclear β decay = semi-leptonic process governed by weak interaction (WI)



⇒ possible tool to study WI

How ? Precision measurements of

- Correlations between particles momenta or momenta and spins
- "ft" values

in pure decays (F or GT) & mirrors (F + GT)

Why ?

SM structure & conditions	Possible tests
• V-A theory ($W^{\pm}$, Z_0 = mediating particles) ⇒ $C_{Scalar} = C_{Tensor} = C_{Pseudoscalar} = 0$	• Exotic "currents" beyond V-A ⇒ new mediating particles (leptoquarks…)
• Maximal Parity Violation (*MPV*): $C_i = C_i'$ • Time Reversal Invariance (*TRI*): C_i real	• Violation of fundamental symmetries: right currents, CP violation,…
• Conserved Vector Current (*CVC*) • 3 fundamental particle families	• CVC hypothesis, unitarity of CKM matrix (precise determination of V_{ud})

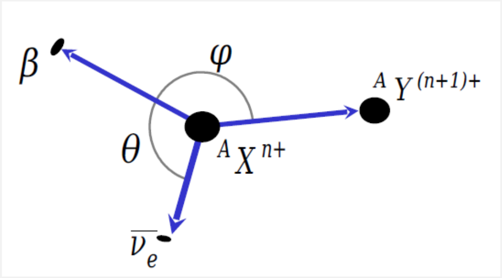
Nuclear β decay: a laboratory to test the Standard Model

Sensitive tool to test the electroweak Standard Model, complementary to high energies measurements

Hergé, "Tintin au Tibet", Ed. Casterman

Search for "traces"

low energy (q << M)



EFT makes the link!

Meet the beast

high energy (E ~ M)

González-Alonso et al PPNP104 (2019)

& Experiments to be performed clearly targeted @ LE in nuclear beta decays

Exotic currents beyond *V-A* theory

- Correlations between particles momenta

$$\omega(\langle \vec{J}\rangle \,|\, E_e,\Omega_e,\Omega_\nu)\, dE_e\, d\Omega_e\, d\Omega_\nu \;\propto\; \underbrace{F(\pm Z,\, E_e)}_{\text{Fermi function}} \;\; \underbrace{p_e\, E_e\, (E_0 - E_e)^2\, dE_e\, d\Omega_e\, d\Omega_\nu}_{\text{phase space}}$$

$$\text{x}\;\; \xi \left\{ 1 + a\,\frac{\vec{p}_e\cdot\vec{q}}{E_e E_\nu} + b\,\frac{\gamma m_e}{E_e} + A\,\frac{\ldots}{J} \ldots E_\nu) \right\}$$

β-ν correlation

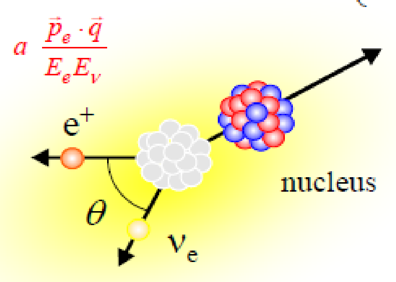
Fierz interference term (b ≡ 0 in standard model)

...try

D-...

T odd

Non polarized nuclei



J,D, Jackson, S.B. Treiman, H.W. Wyld, Nucl. Phys. 4 (1957) 206

a & b depend on possible coupling constants: *C_i & C_i' with i=V, A, S & T*

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

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

Exotic currents beyond *V-A* theory

- Correlations between particles momenta

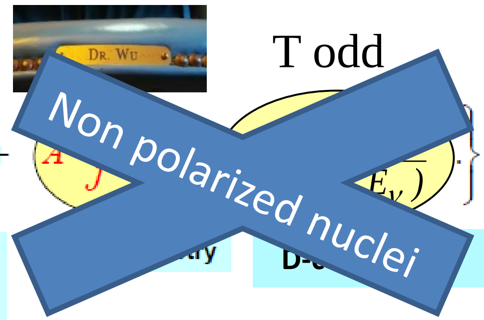
$$\omega\left(\langle \vec{J}\rangle \mid E_e,\Omega_e,\Omega_\nu\right) dE_e\, d\Omega_e\, d\Omega_\nu \;\propto\; \underbrace{F(\pm Z,\, E_e)}_{\text{Fermi function}} \;\; \underbrace{p_e\, E_e\, (E_0-E_e)^2\, dE_e\, d\Omega_e\, d\Omega_\nu}_{\text{phase space}}$$

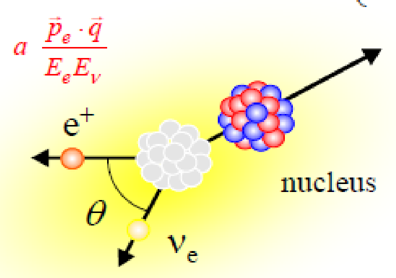
$$\text{x}\;\; \xi \left\{ 1 + a\frac{\vec{p}_e\cdot\vec{q}}{E_e E_\nu} + b\frac{\gamma m_e}{E_e} + A \ldots \right\}$$

β-ν correlation

Fierz interference term (b ≡ 0 in standard model)

T odd





J,D, Jackson, S.B. Treiman, H.W. Wyld, Nucl. Phys. 4 (1957) 206

- measurement of coefficient a: → sensitivity to recoil energy

⚠ b is present and experiments give access to: $\hat{a} = a + \alpha b$

where α depends on experiment   *González-Alonso & Naviliat-Cuncic PRC94 (2016)*

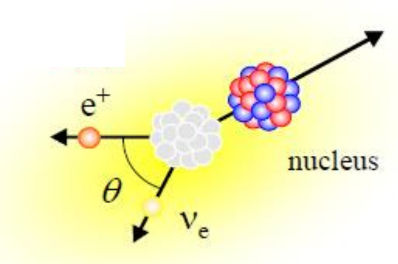
- measurement of coefficient b: → beta energy spectrum shape

or *ft*_value: $f \sim \int W(p_e)(1 + b\frac{m_e c^2}{E_e})dp_e$

Correlations measurements: which precision is relevant?

Between particles momenta $a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu}$ P, T conserving

Vector	Parity	Time
p ***J***	**- *p*** ***J***	**- *p*** **- *J***



F	GT	Mirror
$-1 < a \leq 1$ Exotic Scalar currents	$-1/3 \leq a < 1/3$ Exotic Tensor currents	$a\ (\rho)$ where ρ = GT/F

Test of V - A theory

< 0.1% to stay competitive
with HE physics

in V - A frame
determination of ρ

~ 0.5 % is sufficient

González-Alonso et al PPNP104 (2019)

High precision experiments !

Needs:

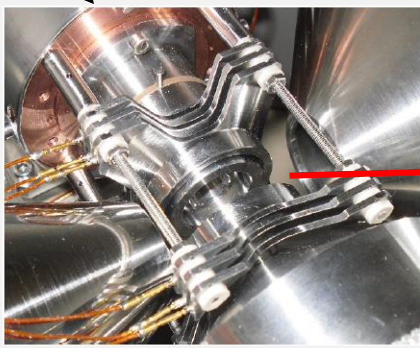
- Sources as clean as possible in vacuum (very low energy recoil ions)
- High stats: → Intense radioactive beams
  → high solid angle
  → Fast DAQ
- Deep knowledge of experimental setup (systematic effects)

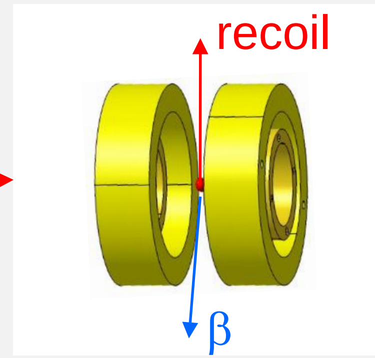
- Traps
- New generation of facilities (example: GANIL/SPIRAL)
- Setup arrangement
- New generation DAQ system
- Realistic simulations

The LPCTrap setup

- Decay source confined in a transparent Paul trap

beam



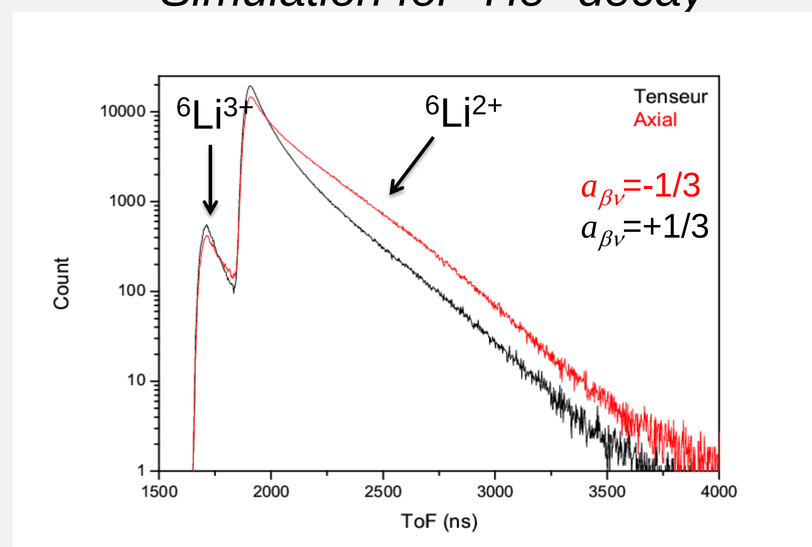


- β - recoil ion detection in coincidence
- a deduced from recoil time-of-flight distribution

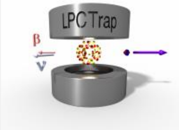
- ^{6}He: Good candidate

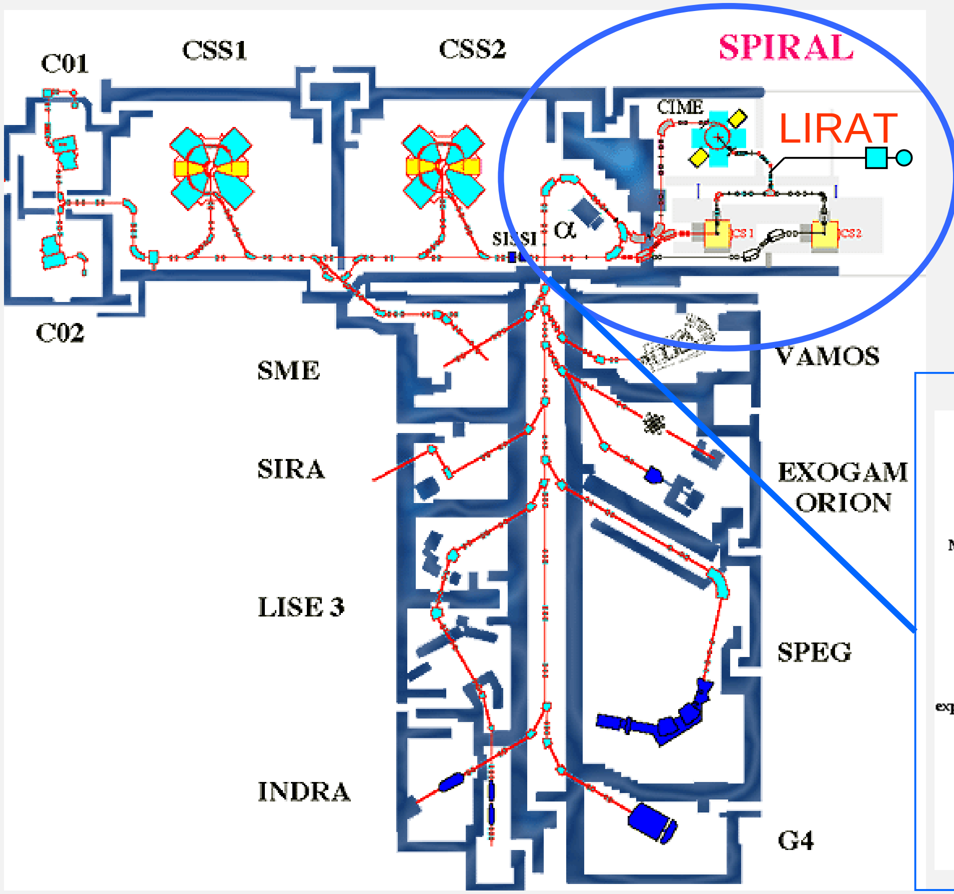
  - Pure GT transition: T vs A
  - 100% G.S. to G.S.
  - Reasonable $T_{1/2}$ = 806.7 ms
  - High Q_β = 3.51 MeV, T_{max} = 1.4 keV
  - High production rate: 2 10^8 ions/s

Simulation for $^6He^+$ decay

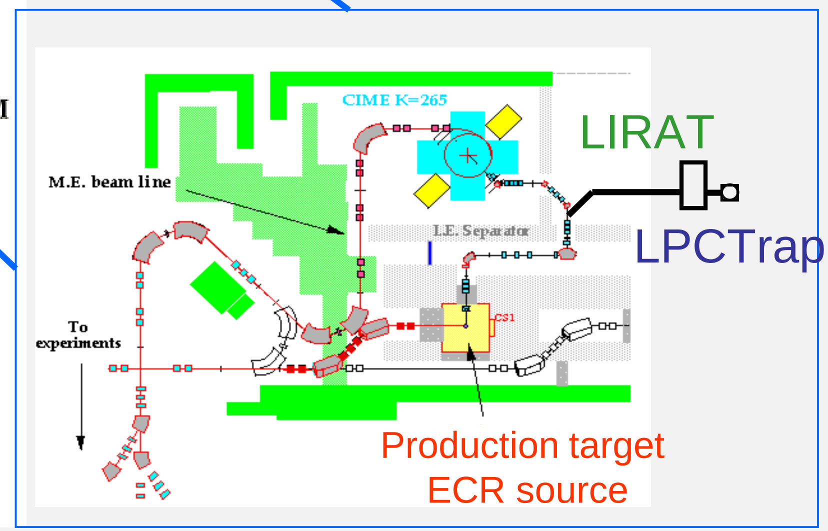


LPCTrap @ GANIL





Beams characteristics:
- 10-30 keV, 80 π mm mrad
- rate: 10^7 - 10^8 ions/s

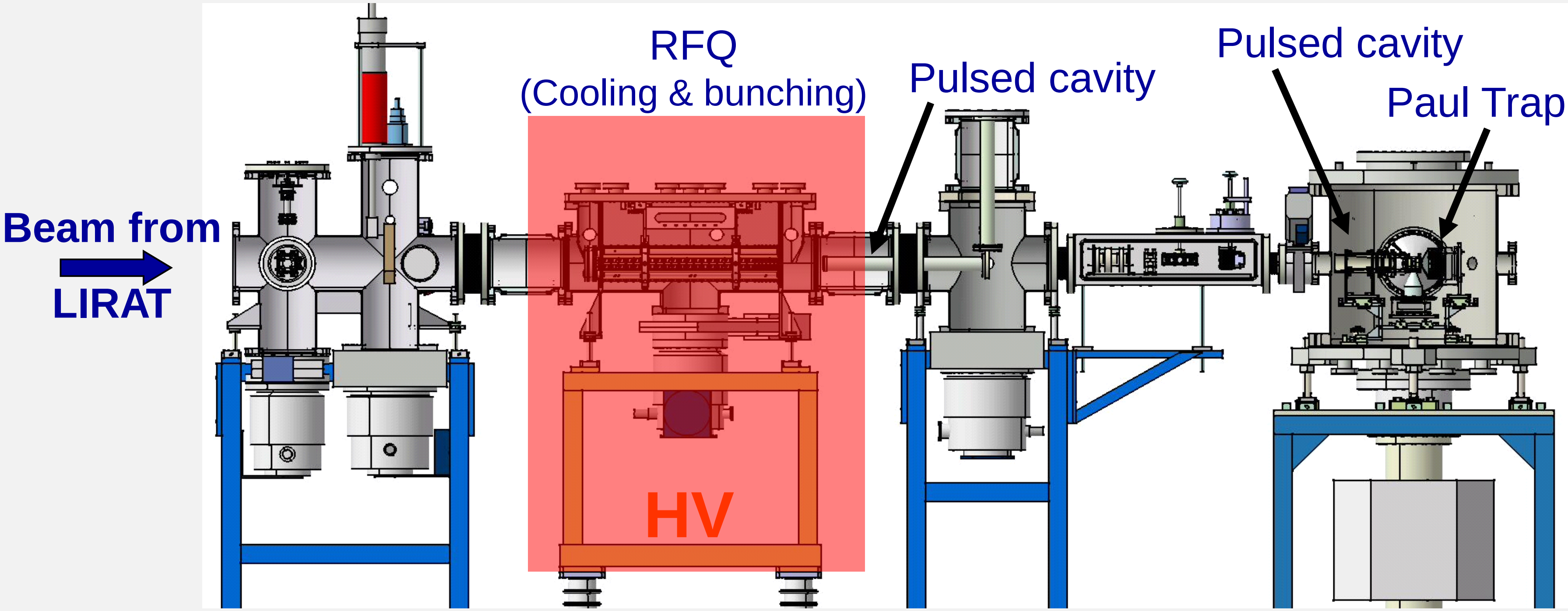


SPIRAL beam:
10-30 keV
ΔE ~ 20eV

?

Paul trap:
Effective potential:
2-3 V

LPCTrap @ LIRAT



KE

KE_{ion}: 10 keV | 100 eV - <1 eV | 1 keV | 100 eV | 0 eV

ΔKE: ~20 eV | ~1 eV | ~0.1 eV

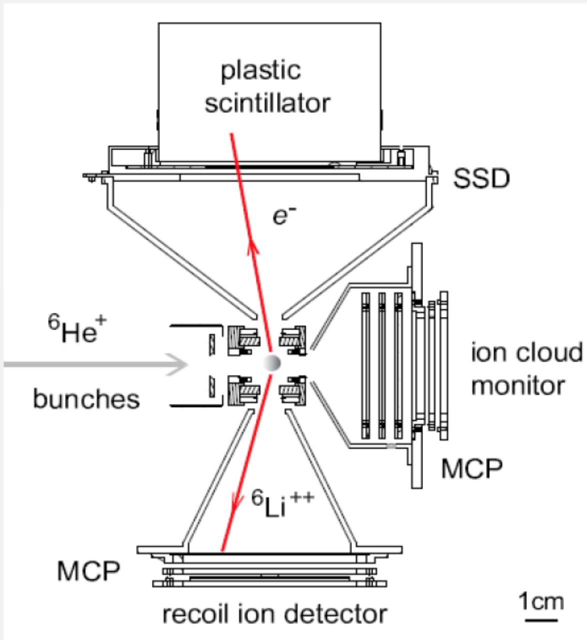
~1.5 10^8 $^6He^+$/s

- Buffer-gas: H_2 (He for heavier nuclei)
- Accumulation: 200ms (cycle: 160 + 40)

~4 10^4 $^6He^+$ /cycle
Total efficiency: ~ 10^{-3}

LPCTrap: The detection setup

- < 2010



E. Liénard et al., NIMA551(2005)

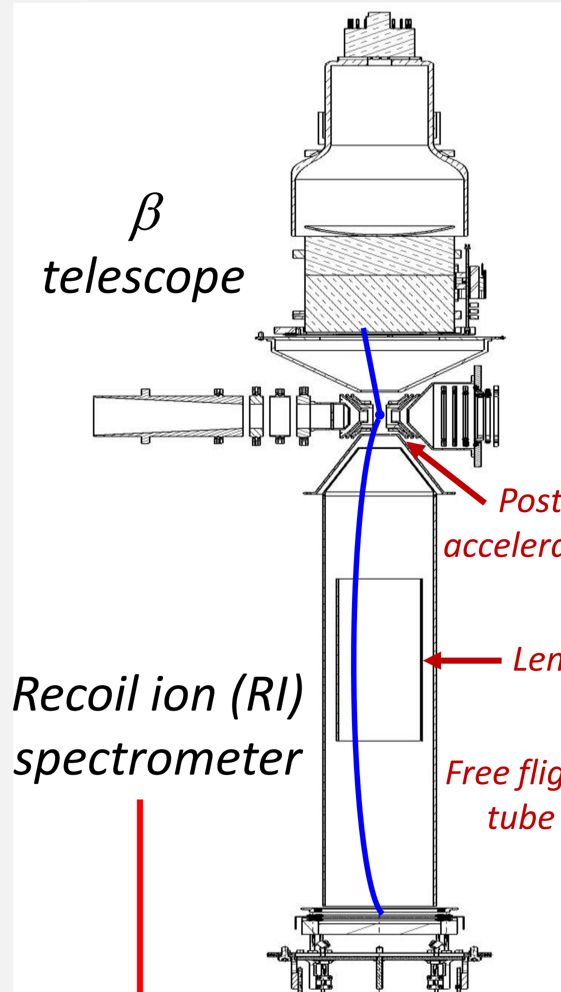
Trigger: β scintillator

Parameters:

- β energy
- β position
- recoil ion ToF
- recoil ion position

+ timestamp in cycle
  & trap RF phase

- ≥ 2010

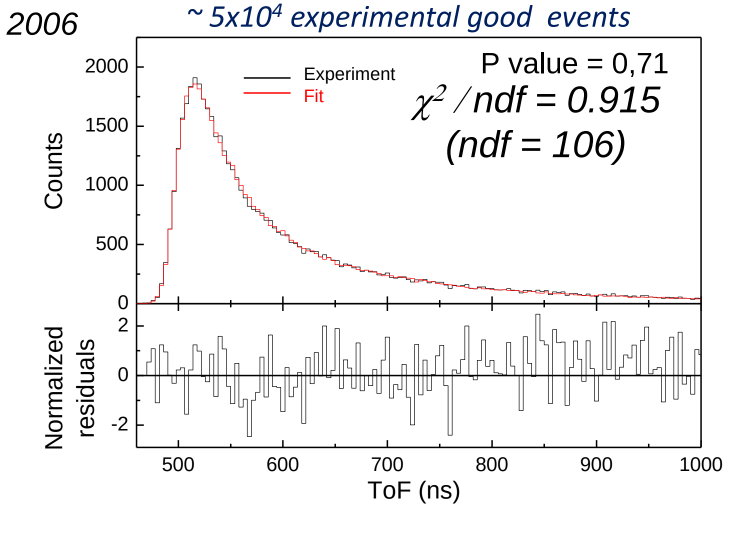


RI charge state distribution (shakeoff)

- *Time of flight of RI*
- *BG suppression*
- *Control of systematic effects*
- *Control of results consistency*

First experiment with LPCTrap: the $^{6}He^{1+}$ case

- Pure Gamow-Teller decay → Exotic Tensor currents ($a_{\beta\nu} \neq -1/3$)?



$a_{\beta\nu}$ **= - 0.3335 (73)** $_{\textbf{stat}}$ **(75)** $_{\textbf{syst}}$

Fléchard et al., J.Phys.G 38 (2011)

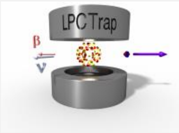
- Best precision on a_{GT} using coincidence technique ($\Delta a/a$ = 3%)
- Good control of experimental & simulation parameters

Systematic error budget

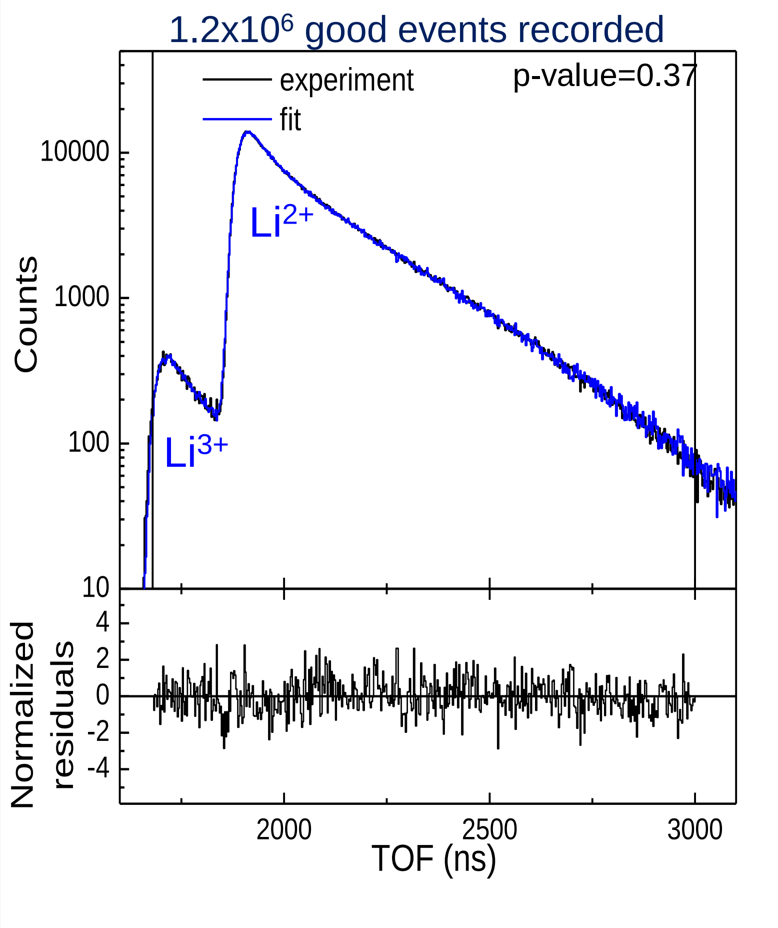
Source	Uncertainty	$\Delta a_{\beta\nu}$ (x 10^{-3})	Method
Cloud temperature	6.5%	6.8	off-line measurement
θx_{MCPPSD}	0.003 rad	0.1	present data
θy_{MCPPSD}	0.003 rad	0.1	present data
MCPPSD offset (x,y)	0.145 mm	0.3	present data
MCPPSD calibration	0.5 %	1.3	present data
d_{DSSSD}	0.2 mm	0.3	present data
E_{scint}		0.8	present data
E_{si}	10%	0.8	GEANT4
Background		0.9	present data
β Scattering	10%	1.9	GEANT4
Shake off	0 - 0.05	0.6	theoretical calculation
V_{RF}	2.5%	1.7	off-line measurement
total		7.5	

Systematic error dominated by the cloud size

First experiment with LPCTrap: the $^{6}He^{1+}$ case



- Pure Gamow-Teller decay → Exotic Tensor currents ($a_{\beta\nu} \neq -1/3$)?



- Analysis performed to extract P_shakeoff (complete simulation @ low statistics: ~ 4x10^5)

$P_{shake\text{-}off} = 0.02339(35)_{stat}(07)_{syst}$

- High precision: $\Delta P_{shake\text{-}off} = 3.6\ 10^{-4}$
- Excellent agreement: Theoretical value 0.02322

Couratin et al., PRL108 (2012)

- About a_{GT} :
  - $(\Delta a_{GT}/a_{GT})_{stat} \sim 0.45\ \%$
  - Difficulties to properly reproduce different experimental distributions → bad Chisquare!

Improvement of ion cloud modelling including gas cooling & space charge effects (GPU's, CUDA)
→ *CLOUDA (home-made code)*

Fabian et al., Hyp. Inter. 235 (2015)

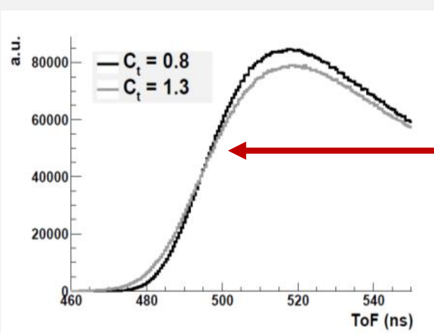
LPCTrap, $^{6}He^{1+}$: results & status

- Realistic cloud @ fixed T°

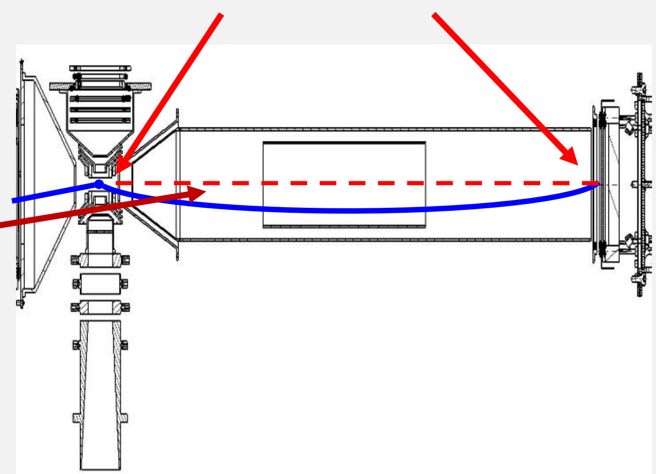
  decay (fixed *a*)
  - β tracked in GEANT4
  - recoil ion (2^+ or 3^+) followed by SIMION in realistic fields (trap & spectro)

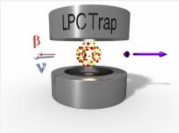
- In practice, experimental data are fitted with several simulations:
  - with different cloud T° (range including the "real" T°)
  - with different values of *a* (range including the final *a*)
  - with different ion charge states, 2^+ or 3^+

→ Free parameters: T, *a*, SO probability and d(source-RI detector)



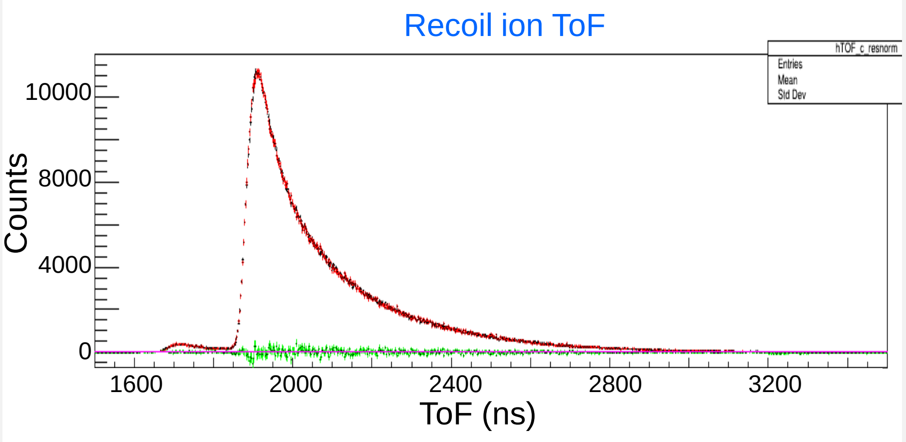
this shape also depends on this distance





LPCTrap, $^{6}He^{1+}$: results & status

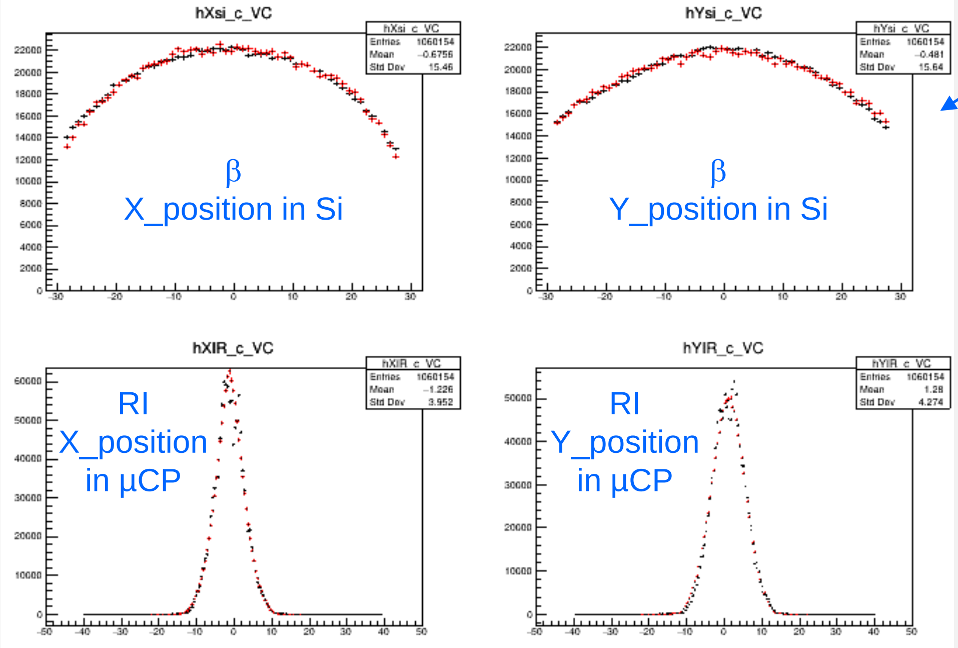
- Promising results!

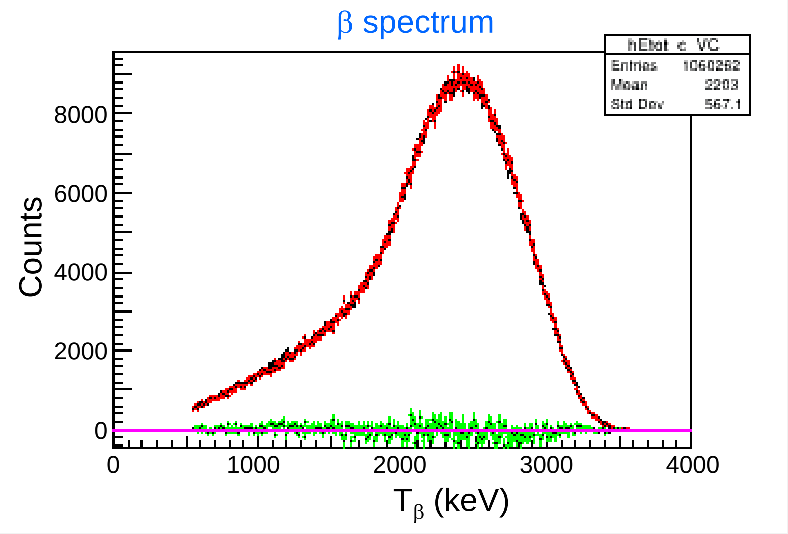


- Preliminary value: a = -0.3364 Xhi² = 1.004
  (low statistics in simulations so far)
- Statistics → $\sigma_{stat} \sim 0.0015$
- 1st study of syste. (T, BS, Calib) → $\sigma_{syst} \sim 0.004$

expected $\sigma_a / a < 1.5$ %

Recoil ToF is fitted and consistency is checked with other spectra





Exotic couplings: Overview of "a" measurements

adapted from González-Alonso et al PPNP104 (2019)

Table 6
Data from measurements in nuclear decays used in the fits. The columns list the parent nucleus in the transition, the type, the measured parameter, the experimental value with its 1σ uncertainty, the relative error, the value of $\langle m_e/E_e \rangle$

Parent	J_i	J_f	Type	Parameter	Value	Rel. error	Year / Setup
^{6}He	0	1	GT/β^-	a	$-0.3308(30)$[a]	0.91%	1963
^{32}Ar	0	0	F/β^+	$\tilde{a}$	0.9989(65)	0.65%	1999
^{38m}K	0	0	F/β^+	$\tilde{a}$	0.9981(48)	0.48%	2004
+ ^{8}Li	2	2	predom. GT/$\beta\alpha$	a	-0.3342(39)	1.17%	2015
^{6}He	0	1	GT/β^-- *recoil*	$\hat{a}$	Analysis under way	~ 2%	MOT (Seattle)
^{6}He	0	1	GT/β^-- *recoil*	$\hat{a}$	Analysis under way	~ 1.5%	Paul (Caen)

- ^{6}He is the best GT candidate *González-Alonso & Naviliat-Cuncic PRC94 (2016)*
- Almost nothing new since 1963 ….
- LPCTrap experiment still probably the present most sensitive!

  → relative error and/or sensitivity to "b"

$$\hat{a} = a + \alpha b$$

where α seems higher for the back-to-back configuration of LPCTrap…

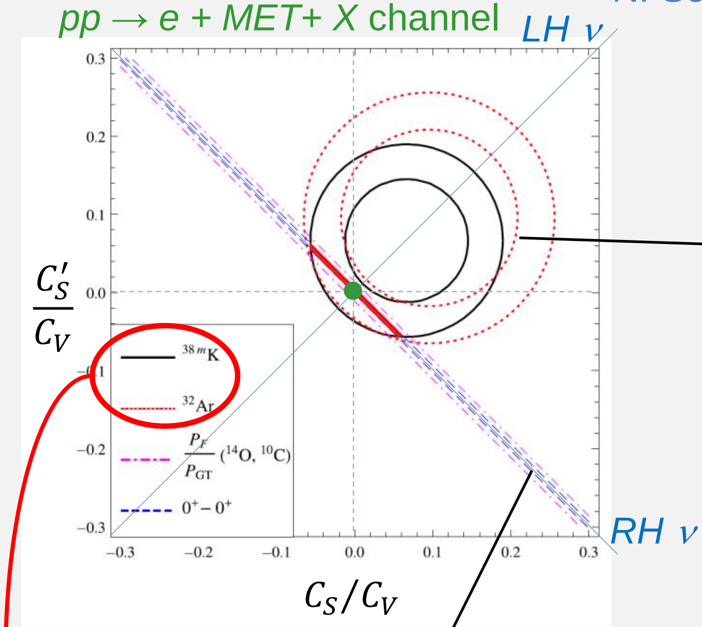
→ *Motivating to finish the analysis … but is it still relevant?*

Exotic currents beyond *V-A* theory: status

B.R. Holstein JPG41(2014)
N. Severijns & B. Blank, JPG44(2017)

SCALAR

pp → e + MET+ X channel



a @ ~ 0.5%

$$Ft \propto \left(1+\langle m/E\rangle b_F\right)^{-1}$$

Hardy et al PRC79(2015)

$$\tilde{a} \approx a(1+\kappa b)$$

Circles because

$$a\,(C^2_{S,T}, C^2_{V,A})$$

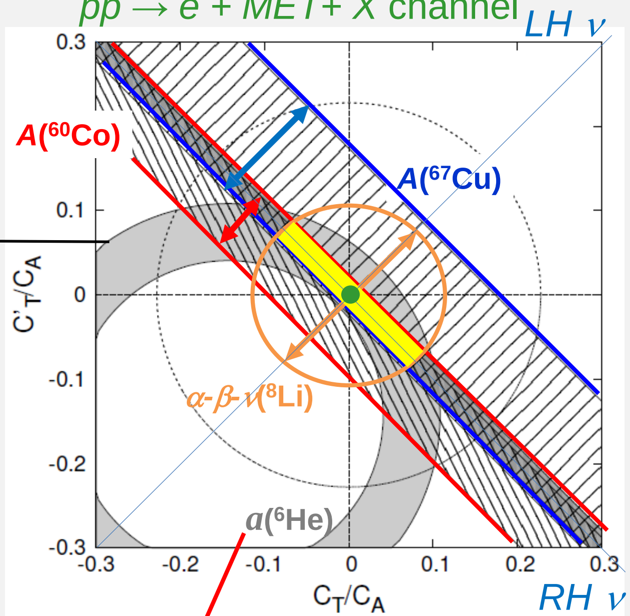
$$b\,(C_{S,T}, C_{V,A})$$

	LH	RH
$\lvert C_S/C_V \rvert <$	0.0038	0.068
$\lvert C_T/C_A \rvert <$	0.0064	0.078

González-Alonso et al PPNP104 (2019)

TENSOR

pp → e + MET+ X channel



a @ ~ 1%

- Best constraints from "*b*", but "*a*" adds limits... ("*b*" unsensitive to right-handed ν !)
- In green: constraints from LHC (CMS data) *Cirigliano et al PPNP71 (2013)* *González-Alonso et al PPNP104 (2019)*

Thanks to EFT!

⇒ ***Precision level at 10^{-3} needed to compete with LHC***

Exotic currents beyond *V-A* theory: status

adapted from González-Alonso et al PPNP104 (2019)

Table 3

Selected ongoing and planned experiments discussed in Section 3. See main text for details. The approximate relative precision goals are given together with their reference. If the SM value is zero, the absolute precision goal is then given. When precision goals are given as a percentage, relative uncertainties are meant. The symbol $\mathcal{O}$ refers to the estimated order of magnitude for a precision goal. The precisions given for a are obtained setting the Fierz term b to zero (see Section 4.2 and Ref. [95]).

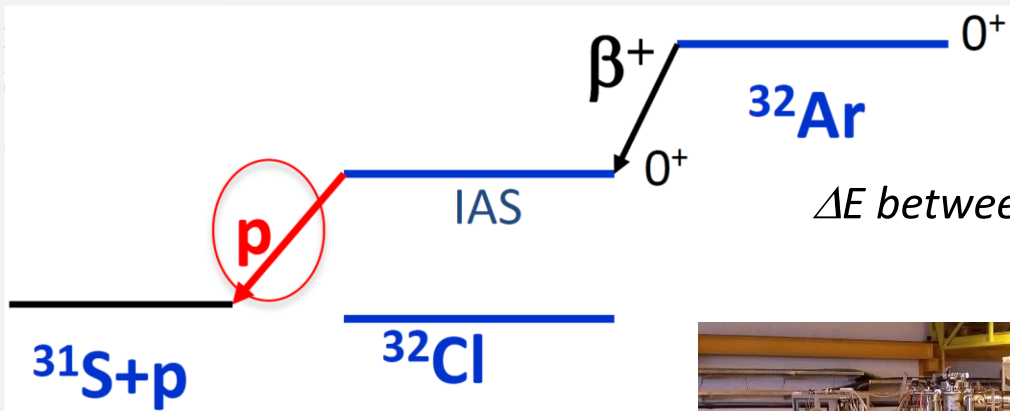
Coefficient	Precision goal	Experiment (Laboratory)	Comments
β-spectrum	$\mathcal{O}(0.01)$ [256]	Supercond. spectr. (Madison) [256]	Shape factor Eq. (51). Ongoing
β-spectrum	$\mathcal{O}(0.01)$ [253]	Si-det. spectr. (Saclay) [253,254]	Shape factor Eq. (51). Ongoing
b_{GT}	0.001	Calorimetry (NSCL) [115,260]	Analysis ongoing (^{6}He,^{20}F)
	$\mathcal{O}(0.001)$ [270]	miniBETA (Krakow–Leuven) [263–265,270]	Being commissioned
	$\mathcal{O}(0.001)$ [276]	UCNA-Nab-Leuven (LANL) [271,272,276]	Analysis ongoing (^{45}Ca)
a_F	0.1% [306]	TRINAT (TRIUMF) [306,310]	Planned (^{38}K)
	0.1% [343]	TAMUTRAP (TA&M) [343]	Superallowed β p emitters
	0.1% [79]	WISArD (ISOLDE) [79,177]	In preparation (^{32}Ar β p decay)
a	not stated	Ne-MOT (SARAF) [311,312]	In preparation (^{18}Ne,^{19}Ne,^{23}Ne)
a_{GT}	$\mathcal{O}(0.1)$% [315]	^{6}He-MOT (Seattle) [313,315]	Ongoing (^{6}He)
	not stated	EIBT (Weizmann Inst.) [316–318]	In preparation (^{6}He)
+ b_{GT}	0.001	b-STILED (LPCC/GANIL)	In preparation (^{6}He)

- Many projects with precision targeted @ ~ 0.1%
- LPCC involved in 2 projects → WISArD @ ISOLDE
  → b-STILED @ GANIL

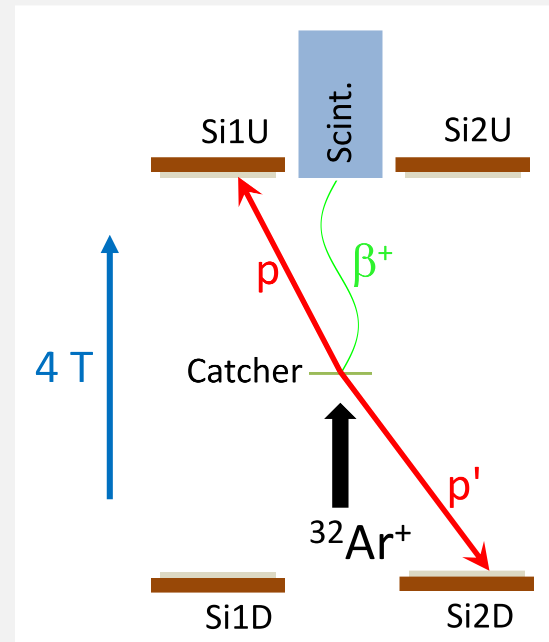
Exotic currents beyond *V-A* theory: the project WISArD

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

- Collaboration CENBG, LPCC, ISOLDE, IKS/Leuven, NPI/Cz Republic, …
- Funded by the French Research National Agency (ANR, 2018-2022)
- Measurement of a in ^{32}Ar decay through β– *delayed p* coincidences



ΔE between p_{up} & p_{down}

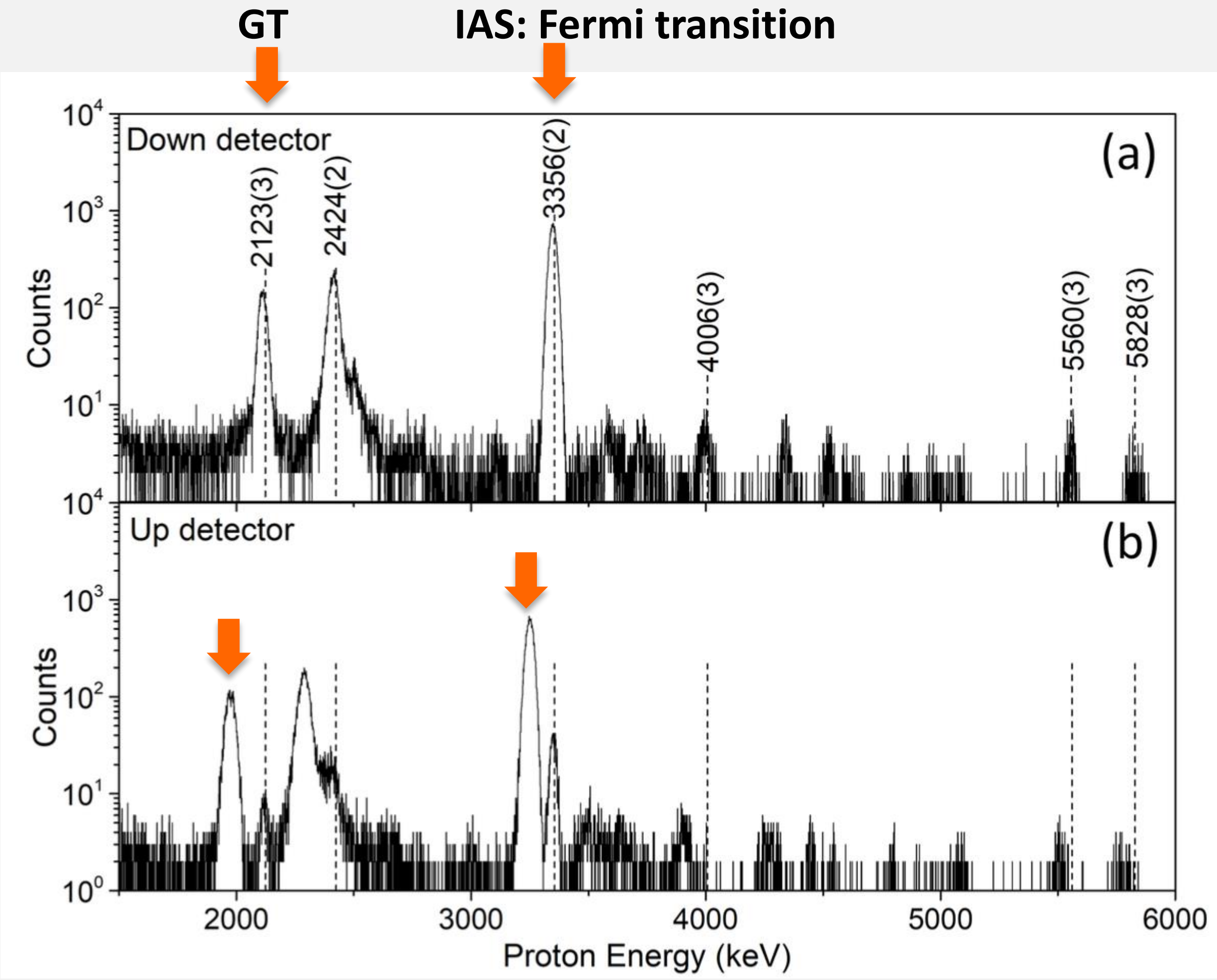


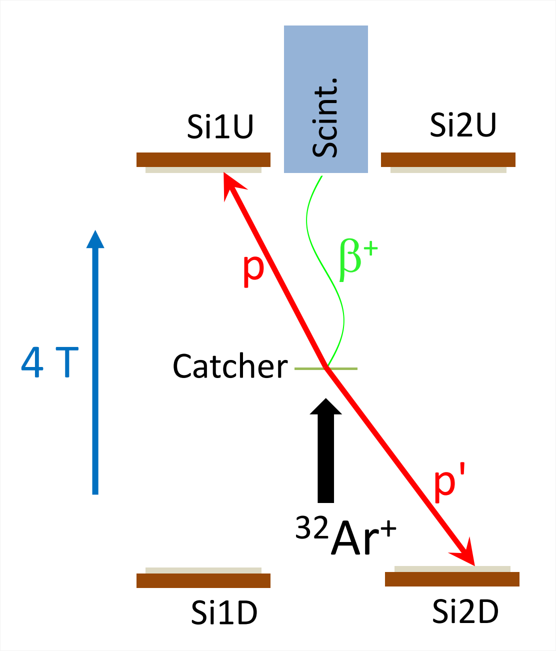
WISArD @ ISOLDE

Exotic currents beyond *V-A* theory: the project WISArD

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

- Measurement of a in ^{32}Ar decay through β – *delayed p* coincidences



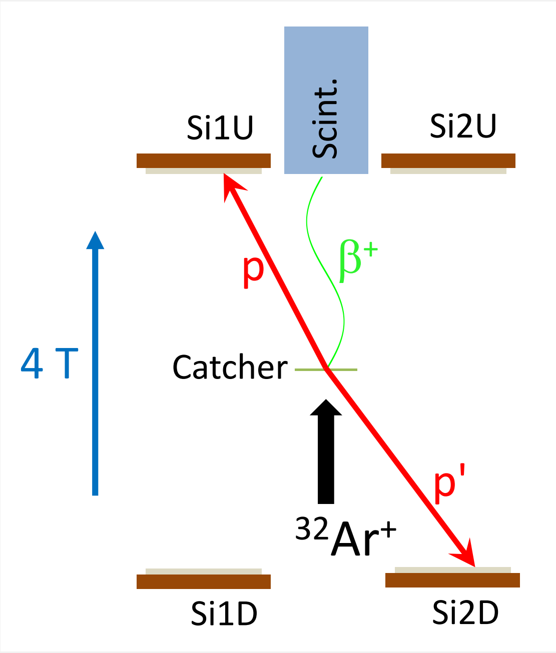


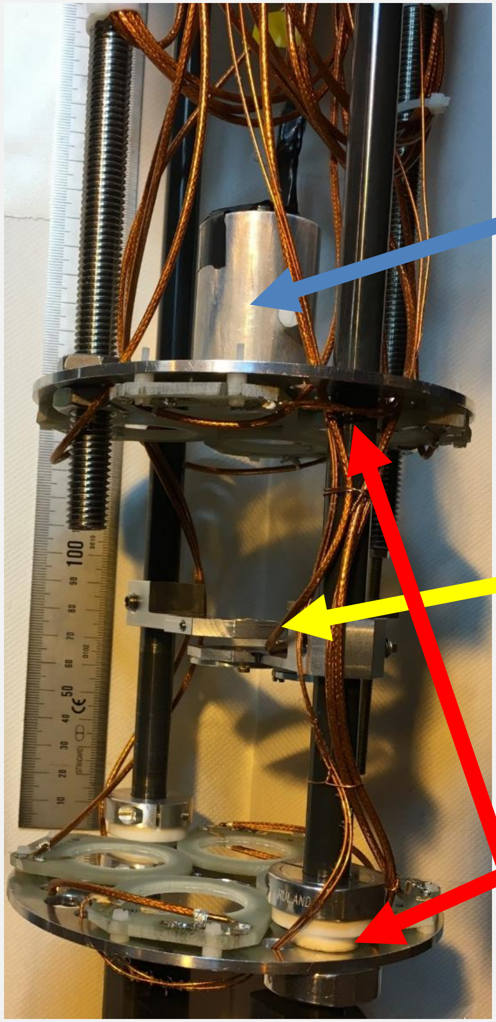
Exotic currents beyond *V-A* theory: the project WISArD

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

- Measurement of a in ^{32}Ar decay through β – *delayed p* coincidences

- Test experiment in Nov 2018
- Detectors from scratch





Beta Plastic scintillator + SiPM

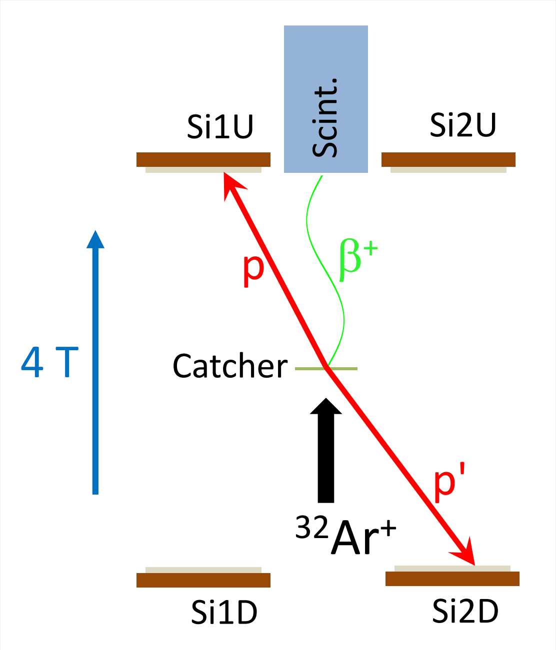
Catcher: 6.7µm Aluminized Mylar

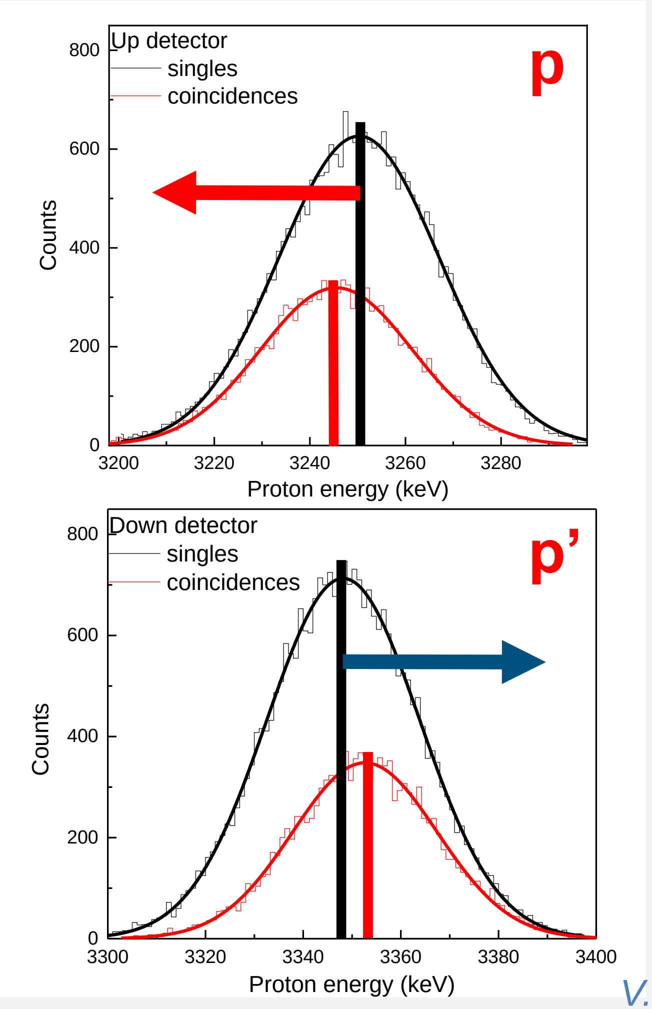
proton Si detectors planes
(FWHM ~ 35 keV @ 3.3 MeV)

Exotic currents beyond *V-A* theory: the project WISArD

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

- Measurement of a in ^{32}Ar decay through $\beta-$ *delayed p* coincidences





- Test experiment in Nov 2018
- Detectors from scratch
- Only 35 hours of data taking
- Unexpected results:

$$\tilde{a}_{\beta\nu}^{F} = 1.007\ (32)_{(stat)}\ (25)_{(syst)}$$

3rd best result in the world!

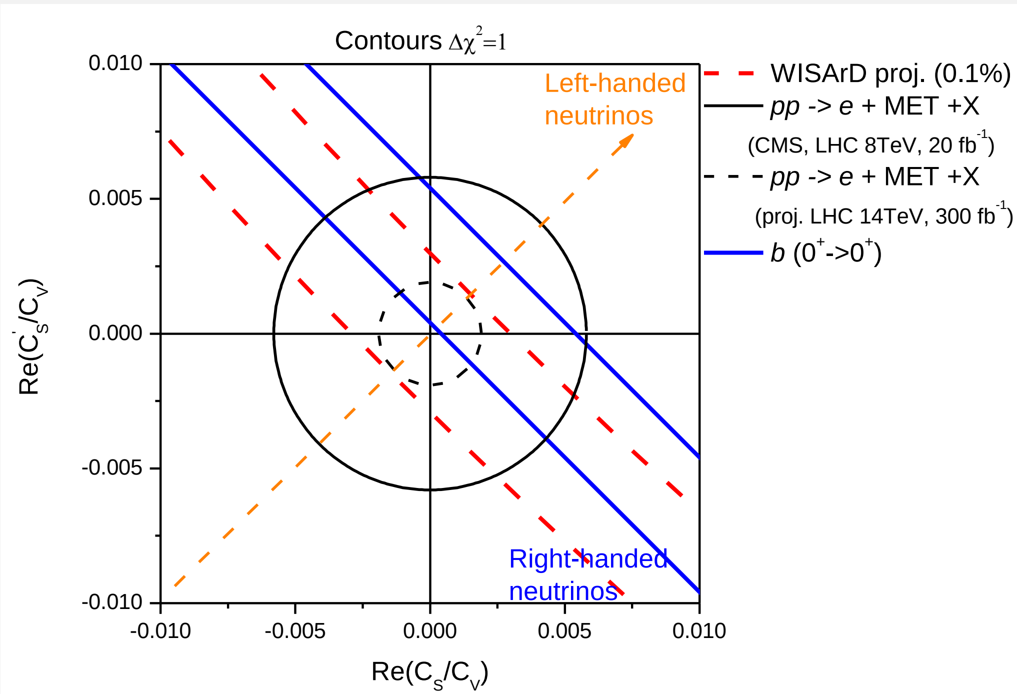
$$\tilde{a}_{\beta\nu}^{GT} = -0.222\ (86)_{(stat)}\ (16)_{(syst)}$$

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

Exotic currents beyond *V-A* theory: the project WISArD

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

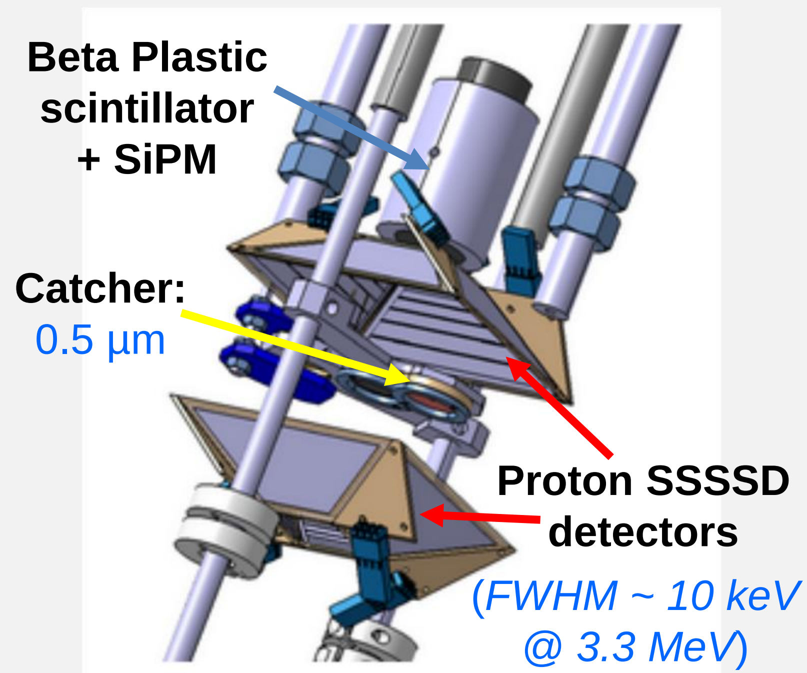
- Projected results: 0.1% seems accessible!



← *WISArD*

← *Future(!) LHC (14 TeV)*

González-Alonso et al PPNP104 (2019)



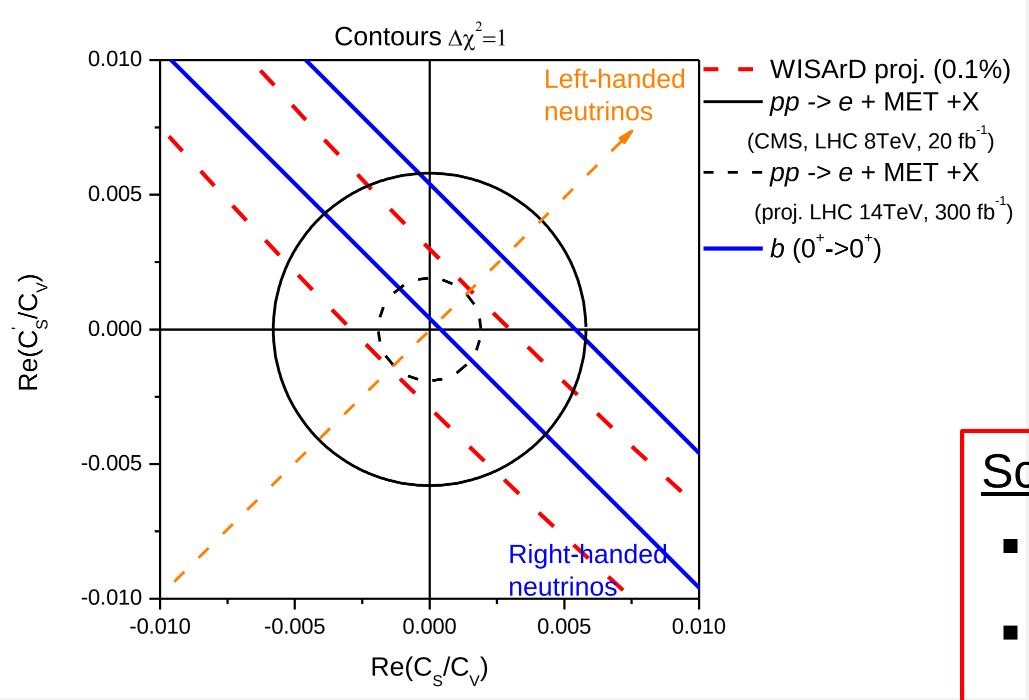
- $M_{newboson}$ > 5 TeV

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

Exotic currents beyond *V-A* theory: the project WISArD

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

- Projected results: 0.1% seems accessible!



← *WISArD*

← *Future(!) LHC (14 TeV)*

González-Alonso et al PPNP104 (2019)

- $M_{newboson}$ > 5 TeV

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

Schedule:

- 2018-2024: ISOLDE (^{32}Ar)
- 2020: experiment accepted by INTC
- 2025- …: DESIR
  - Higher intensity
  - Test of theoretical corrections
  - Other candidates (^{24}Si, ^{36}Ca, …)

Exotic currents beyond *V-A* theory: 2 promising projects

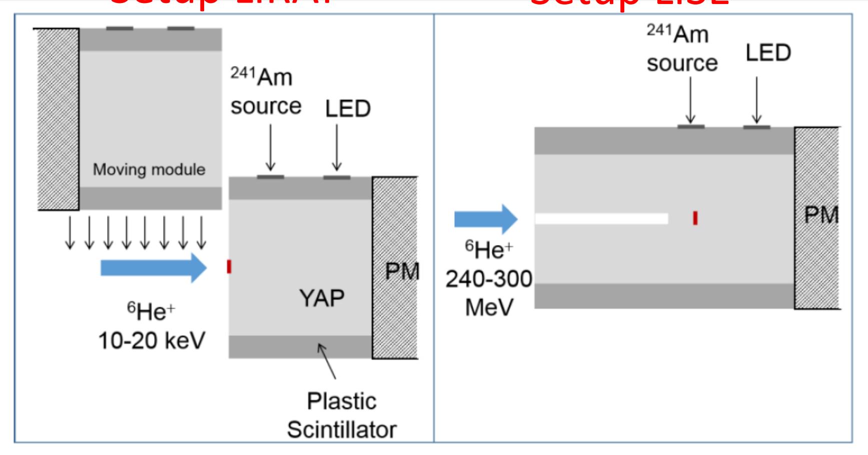
II. b-STILED (b: Search for Tensor Interactions in nucLear bEta Decay)

- Collaboration LPCC, GANIL, LnHB
- Funded by the French Research National Agency (ANR, 2021-2025)
- Determination of b_{GT} in ^{6}He decay with the β spectrum shape
  - β scattering $\rightarrow$ "Calorimetric" method

González-Alonso & Naviliat-Cuncic PRC94 (2016)

Low Energy — High Energy (in the sense of Nuclear Physics)

Setup LIRAT — Setup LISE



Implantation on the surface ($\rightarrow$ 2 detectors)

Implantation in depth R(beam) > R (β)

- HE setup already tested @ MSU

  X. Huyan et al., HI237 (2016)
  X. Huyan et al., NIMA879 (2018)

- GANIL can host the 2 setups

Schedule:
- 2020-2025: GANIL (^{6}He)
- 2021: 1st experiment in 3 weeks!

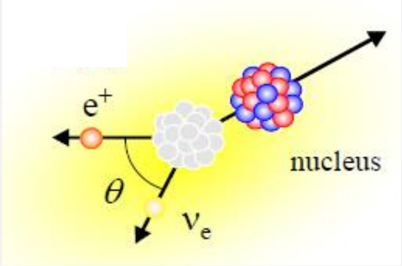
Correlation measurements: "End" of LPCTrap? Not yet…

Between particles momenta

$$a\frac{\vec{p}_e.\vec{p}_\nu}{E_e E_\nu}$$

P, T conserving

Vector	Parity	Time
p **J**	**-p** **J**	**-p** **-J**



F	GT	Mirror
-1 < a ≤ 1 Exotic Scalar currents	-1/3 ≤ a < 1/3 Exotic Tensor currents	a (ρ) where ρ = GT/F

Test of V - A theory

< 0.1% to stay competitive with HE physics

in V - A frame determination of ρ

~ 0.5 % is sufficient

González-Alonso et al PPNP104 (2019)

High precision experiments !

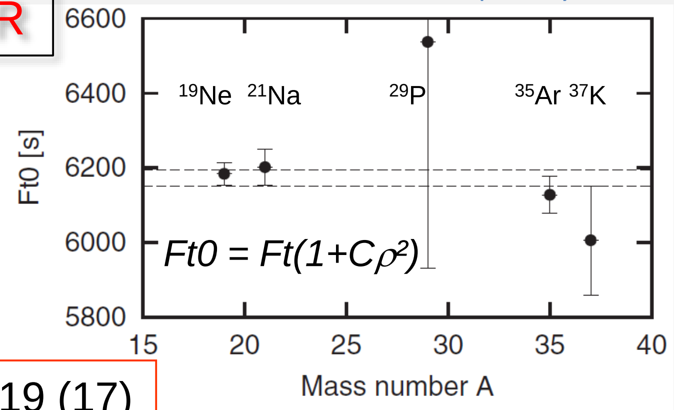
- $$\rho^2 = \frac{|M_{GT}|^2 \, C_A{}^2}{|M_F|^2 \, C_V{}^2} = \frac{1-a}{a+1/3}$$
- In mirror decays, Fermi component is large

→ alternative to $0^+ \rightarrow 0^+$ to test CVC hypothesis

Mirror transitions vs Pure Fermi (PF) transitions

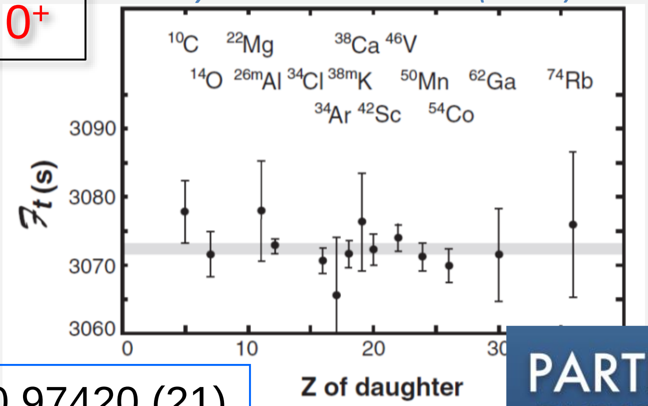
MIRROR

Naviliat et al. PRL102 (2009)



$0^+ \rightarrow 0^+$

Hardy & Towner PRC91 (2015)



PARTICLE PHYSICS BOOKLET

V_{ud} = 0.9719 (17)

V_{ud} = 0.97420 (21)

a factor of ~10 less precise

$$(Ft)^{PF} = f_V t_{1/2}(1+\delta_R)(1+\delta_{NS}-\delta_C) = \frac{K}{V_{ud}^2(1+\Delta_R)}$$

($T_{1/2}$, *BR*, *M*) measurements

$$(Ft)^{mirror} = f_V t_{1/2}(1+\delta_R)(1+\delta_{NS}-\delta_C) = \frac{2K}{V_{ud}^2(1+\Delta_R)(1+\frac{f_A}{f_V}\rho^2)}$$

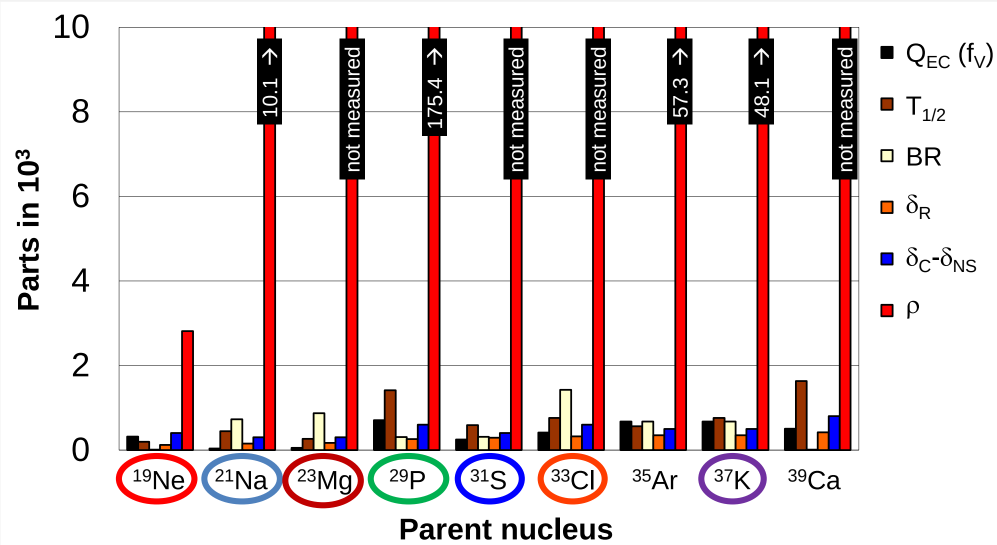
($T_{1/2}$, *BR*, *M*, ρ) measurements

δ_R , δ_{NS} , Δ_R: radiative corrections
δ_C: isospin symmetry breaking
} < 1%

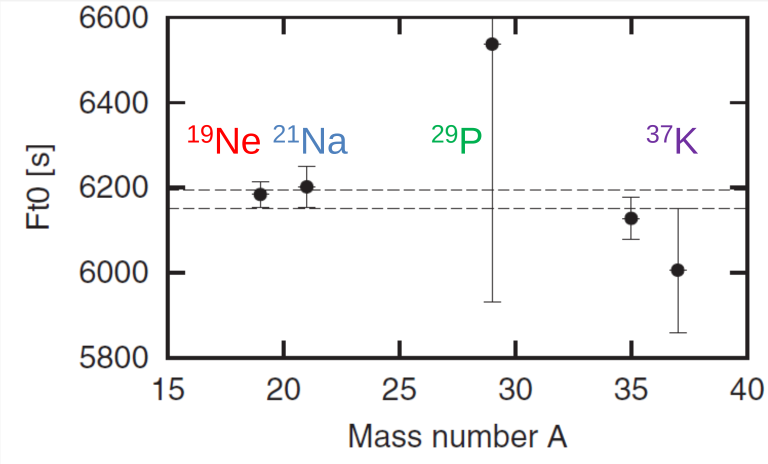
⇒ *ρ is the limiting parameter !*

Mirror transitions: Status

adapted from Severijns et al. PRC78 (2008) and updated



Naviliat et al. PRL102 (2009)



^{19}Ne T$_{1/2}$: *Broussard et al. PRL112 (2014)*
BR: Rebeiro et al. PRC99 (2019)

^{21}Na M: *Karthein et al. PRC101 (2020)*
T$_{1/2}$: *Grinyer et al. PRC91 (2015)*

^{23}Mg M: *Karthein et al. PRC101 (2020)*
T$_{1/2}$, BR: *Magron et al. EPJA53 (2017)*

^{29}P T$_{1/2}$: *Long et al. PRC101 (2020)*

^{31}S M: *Kankainen et al. PRC82 (2010)*
T$_{1/2}$: *Bacquias et al. EPJA48 (2012)*

^{33}Cl T$_{1/2}$: *Grinyer et al. PRC92 (2015)*

^{37}K T$_{1/2}$: *Shidling et al. PRC90 (2014)*

The scientific community involved in this field... BUT

V_{ud} (2009) = 0.9719 (17)

in 2021 with new $T_{1/2}$, Br & M

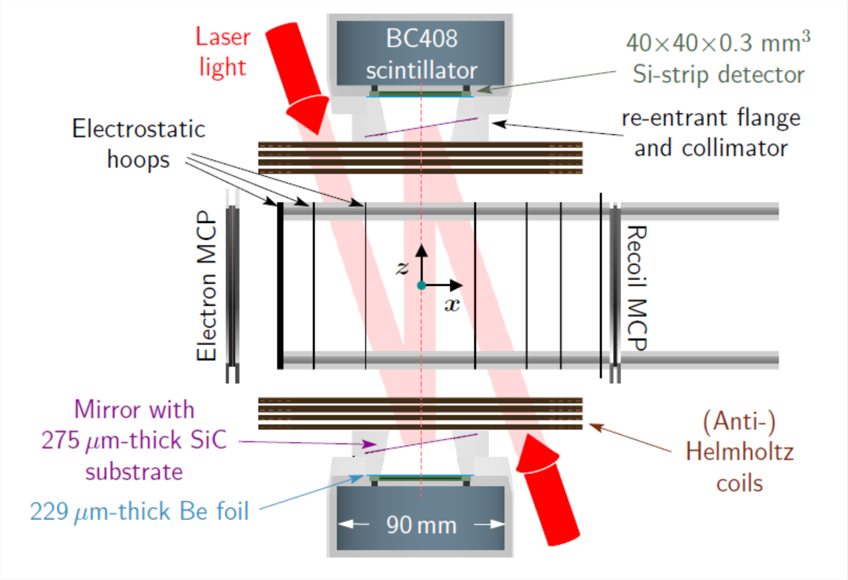
V_{ud} = 0.9719 (17) !

For V_{ud} determination, ρ improvements are necessary ...

Mirror transitions: Status

Recent results: Measurement of A_β in ^{37}K (TRIUMF) & in ^{19}Ne (Princeton)

Fenker et al. PRL 120 (2018)   Combs et al. arXiv:2009.13700v2



- Source confined in MoT of TRINAT
- Detection of β in Z direction with nucleus polarization in ±Z
- Degree of P measured by laser probe & detection of photo-ions
  → $P_{\sigma-} = 99.13(8)\%$ $P_{\sigma+} = 99.12(9)\ \%$

⇨ $A_\beta = -0.5707(18)$ 0.3% relative precision

⇨ $V_{ud} = 0.9719\ (17)$ → $V_{ud} = 0.9725\ (14)$!

one single shot → clear improvement on V_{ud} & ^{37}K is not the most sensitive case …

Mirror transitions: Status

- ρ precisely determined from correlation measurements

$$a_m = \frac{(1-\rho^2/3)}{(1+\rho^2)} \qquad A_m = \frac{\rho^2 - 2\rho\sqrt{J(J+1)}}{(1+\rho^2)(J+1)}$$

Severijns & Naviliat-Cuncic PST152(2013)

a or *A* @ 0.5% ?

better sensitivity with a measurements

^{19}Ne, ^{21}Na, ^{23}Mg, ^{31}S, ^{35}Ar, ^{37}K

LPCTrap@GANIL ?

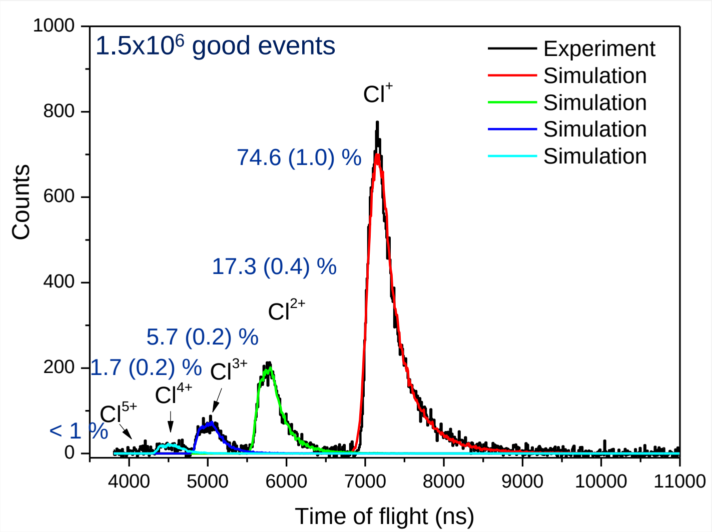
	a			*A*		
Parent nucleus	ΔV_{ud}	$(\Delta V_{ud})^{limit}$	Factor $\Delta\mathcal{F}t$	ΔV_{ud}	$(\Delta V_{ud})^{limit}$	Factor $\Delta\mathcal{F}t$
^{3}H	0.0011	0.0010	2.1	0.0011	0.0009	2.3
^{11}C	0.0025	0.0016	4.0	0.0207	0.0207	0.3
^{13}N	0.0017	0.0017	1.0	0.0123	0.0123	0.1
^{15}O	0.0020	0.0016	2.4	0.0023	0.0020	1.9
^{17}F	0.0019	0.0013	3.1	0.0341	0.0341	0.1
^{19}Ne	0.0011	0.0010	1.5	0.0011	0.0011	1.5
^{21}Na	0.0022	0.0017	2.7	0.0036	0.0034	1.3
^{23}Mg	0.0025	0.0018	3.1	0.0034	0.0030	1.9
^{25}Al	0.0019	0.0018	1.7	0.0056	0.0056	0.5
^{27}Si	0.0029	0.0018	4.1	0.0068	0.0066	1.1
^{29}P	0.0026	0.0018	3.4	0.0024	0.0014	4.3
^{31}S	0.0038	0.0018	5.9	0.0068	0.0061	1.8
^{33}Cl	0.0021	0.0018	2.0	0.0013	0.0006	6.0
^{35}Ar	0.0019	0.0018	1.1	0.0007	0.0004	4.8
^{37}K	0.0034	0.0017	5.8	0.0050	0.0041	2.3
^{39}Ca	0.0024	0.0016	3.5	0.0032	0.0027	2.2
^{41}Sc	0.0029	0.0022	2.7	0.0299	0.0299	0.2
^{43}Ti	0.0076	0.0018	13.2	0.0167	0.0151	1.6
^{45}V	0.0112	0.0020	17.7	0.0115	0.0032	11.2

not the most sensitive

$(\Delta V_{ud})^{limit}$ → only $\Delta\rho$ contributes in uncertainty

"Mirror" studies with LPCTrap: $^{35}Ar^{1+}$ & $^{19}Ne^{1+}$ cases

$$^{35}_{18}Ar^{1+} \rightarrow ^{35}_{17}Cl^{0\rightarrow 5+} + \beta^{+} + \bar{\nu}_e$$



Shakeoff *Couratin et al. PRA88 (2013)*

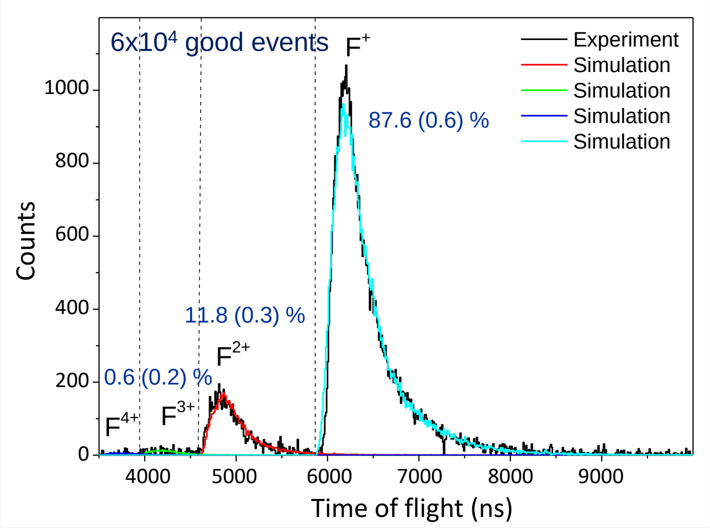
- Excellent agreement when including Auger emission

About a_m

- $(\Delta a_m / a_m)_{stat} \sim 0.15\ \%$
- Analysis of data: after ^{6}He…

⇨ High precision potential result…

$$^{19}_{10}Ne^{1+} \rightarrow ^{19}_{9}F^{0\rightarrow 4+} + \beta^{+} + \bar{\nu}_e$$



Shake-off *Fabian et al. PRA97 (2018)*

- Overestimation of neutrals & highest charge states

  needs of e – e correlations for systems with low Z?

About a_m

- $(\Delta a_m / a_m)_{stat} \sim 11\ \%\ \ (a_m \sim 0\ \ldots)$
- Analysis of data: after ^{6}He…

⇨ Best precision for a_m but no effect on ΔV_{ud}

"Mirror" studies with LPCTrap: $^{35}Ar^{1+}$ & $^{19}Ne^{1+}$ cases

Final results between 2 extrema: "ideal" & "conservative"

"ideal" → $\sigma_{syst} = \sigma_{stat}$

"conservative" → $\sigma_{syst} = 0.005$

Nucleus	Date	*a*	σ_{stat}	σ_{tot} (ideal)	σ_{tot} (conservative)
^{6}He	2006	-0.3335	0.0073	/	/
	2010	-1/3 (SM)	0.0015	0.0021	0.0052
^{35}Ar	2011	/	/	/	/
	2012	0.9004 (SM)	0.0013	0.0019	0.0052
^{19}Ne	2013	0.0438 (SM)	0.0046	0.0065	0.0068

^{35}Ar

- Expected results σ_a/a : *~ 0.21 %* *~ 0.58 %*
- Factor gained on σ_ρ/ρ : *~ 5.4* *~ 2.2*

$\sigma(V_{ud}) / V_{ud} = 1.7\times10^{-3}$ → 9×10^{-4} 1.4×10^{-3}

(in 2021 with only new $T_{1/2}$, Br & M)

Even in the worst case, the effect would be noticeable!

Mirror transitions: 2 recent reasons to continue

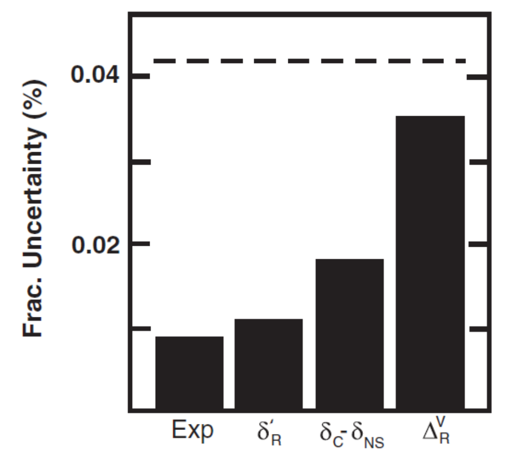
1. New theoretical corrections calculations reopen controversy!

$$(Ft)^{PF} = f_V t_{1/2}(1+\delta_R)(1+\delta_{NS}-\delta_C) = \frac{K}{V_{ud}^2(1+\Delta_R)}$$

Specific theoretical corrections (δ_R, δ_{NS}, δ_C)

Common radiative correction (Δ_R)

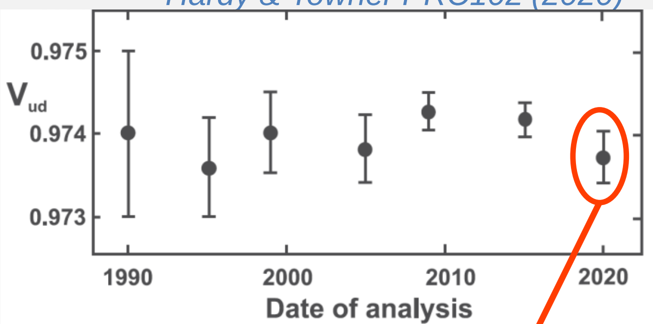
Hardy & Towner PRC91 (2015)



	"Old"	"Recent"	"Very recent"
Δ_R	0.02361 (38) Marciano et al PRL 2006	0.02467 (22) Seng et al PRL 2018	
Ft	3072.07 (63) s Hardy et al PRC 2015		3070.50 (117) (new δ_{NS}) Seng et al PRD 2019
V_{ud}	0.97420 (21)	0.97370 (14)	0.97395 (21)
CKM Unitarity	0.9994 (5)	0.9984 (4) *4 σ away!*	0.9989 (5) *2.2 σ away!*

New survey

Hardy & Towner PRC102 (2020)



possibly more, but the incompatibility of the $K_{\ell 3}$ and $K_{\ell 2}$ results for $|V_{us}|$ make a definitive conclusion elusive. Certainly, the $|V_{ud}|$ value reported here has had the effect of increasing tension in the unitarity test. Overall, the new data have opened

$|V_{ud}| = 0.97373 \pm 0.00031.$

a factor ~ 1.5 less precise

Mirror transitions: 2 recent reasons to continue

2. New global approach → surprising effect of mirror decays!

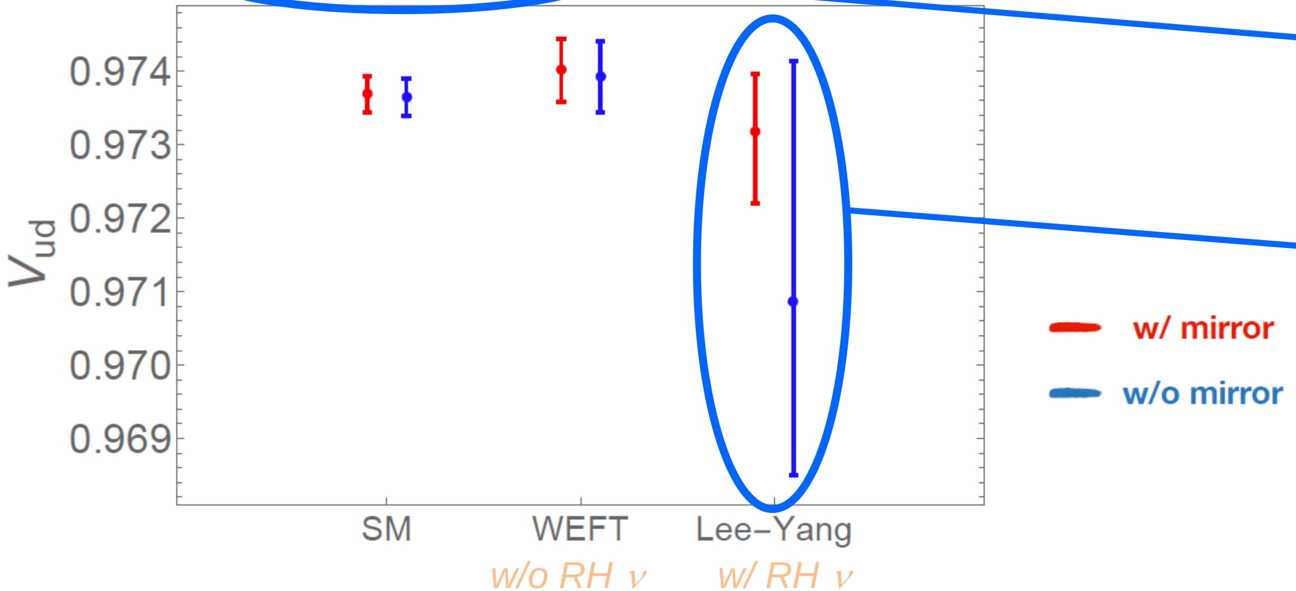
Falkowski et al. JHEP04 (2021)

Constraints on V_{ud} matrix element

Constraints on C_{V+} translate into constraints on the (polluted) CKM matrix element V_{ud}

$$C_V^+ = \frac{\tilde{V}_{ud}}{v^2} g_V \sqrt{1 + \Delta_R^V}, \qquad \tilde{V}_{ud} \equiv V_{ud}(1 + \epsilon_L + \epsilon_R)$$

Mirror data bring a factor of 3 improvement on the determination V_{ud} in the general scenario



When leaving all the SM constraints, Mirror decays bring a gain of a factor ~3 in V_{ud} determination!!

$$\text{(LY)}: \quad \tilde{V}_{ud} = 0.97317^{+(79)}_{-(97)}$$

compare with

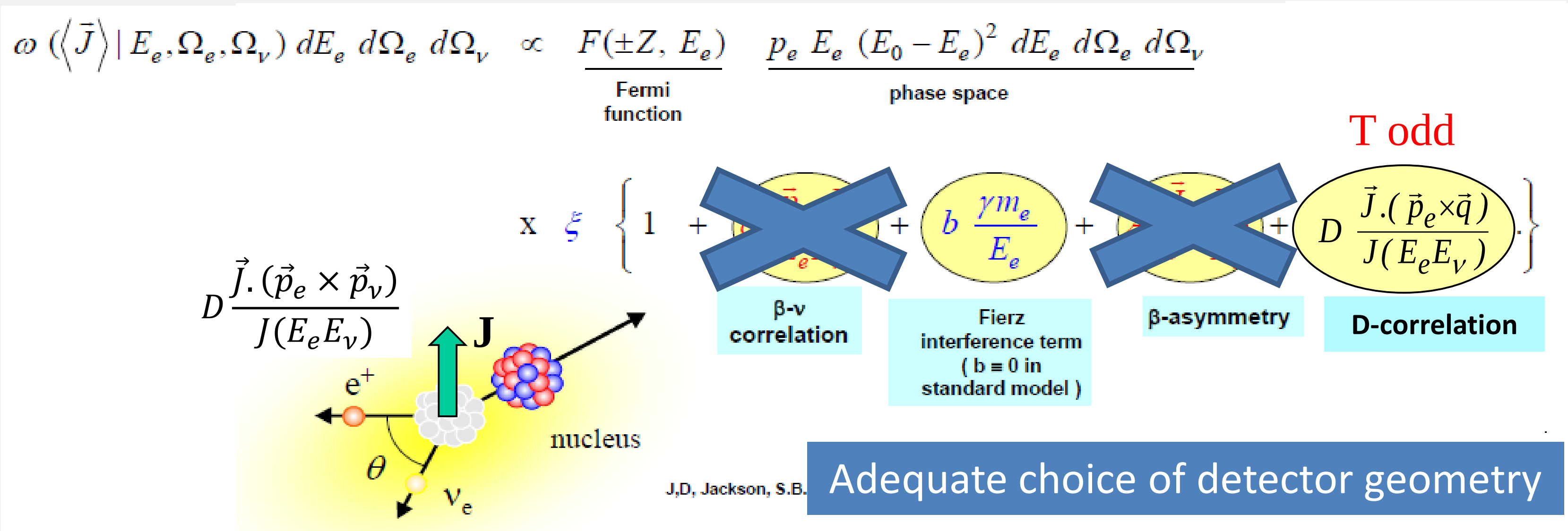
$$\text{(SM)}: \quad V_{ud} = 0.97369(25)$$
$$\text{(WEFT)}: \quad \tilde{V}_{ud} = 0.97401(43)$$

A. Falkowski, Workshop MORA, 09 October 2020

Correlation measurements: "End" of LPCTrap? Not yet…

I. Correlations between particles momenta: mirror decays for CVC & V_{ud}

II. Correlations between particles momenta and spin



- Sensitivity to *TRV* → sensitivity to *CP* violation (*CPT* theorem)
  new sources expected to explain matter/antimatter asymmetry

- Experimental method: $\beta\!-\!\nu$ correlation and decaying nucleus polarization

LPCTrap-like setup + lasers (optical pumping)

Search for CP violation in nuclear β decay: How?

II. Correlations between particles momenta and spin

$$D\frac{\vec{J}.(\vec{p}_e \times \vec{p}_\nu)}{J(E_e E_\nu)}$$

P conserving

sign changes under T

$$D = \frac{2\rho\ \frac{C_V}{C_A}\delta_{JJ'}\left(\frac{J}{J+1}\right)^{\frac{1}{2}}\ Im\left({}^{C_A}/_{C_V}\right)}{(1+\rho^2)}$$

D can be $\neq 0$ ONLY IF $\rho \neq 0$ & $\rho \neq \infty$

Measurement of D ≠ 0 (search for CP violation) has sense only in mirror decays !

$$D = F(X)\ Im\left({}^{C_A}/_{C_V}\right)$$

X	n	^{19}Ne	^{23}Mg	^{39}Ca
$F(X)$	0.3413 (8)	-0.4076 (6)	-0.5142 (10)	0.5584 (15)

Sensitivity to "New Physics" depends on ρ and J

$D = 0$ in SM *but …*

! e^- interacts with its environment: EM effects

Final State Interaction (D_{FSI})

X	n	^{19}Ne	^{23}Mg	^{39}Ca
$D_{FSI}(X)$	1.1×10^{-5}	1.6×10^{-4}	1.1×10^{-4}	-3×10^{-5}

At high precision, experiments could be sensitive to D_{FSI}

Search for CP violation in nuclear β decay: Why?

• Current situation

- CP violation observed in the K, B, D° meson decays is not enough to account for the large matter – antimatter asymmetry
- T-odd correlations in beta decay (*D* and *R*) and n-EDM searches are sensitive to larger CP violations by 5 to 10 orders of magnitude
- Current best results in nuclear decays:

^{19}Ne decay → $D = (1 \pm 6)\ 10^{-4}$ *Calaprice et al. Hyp. Int.22 (1985)*

n decay → $D = (-0.9 \pm 2.1)\ 10^{-4}$ *Mumm et al. PRL107 (2011)* *Chupp et al. PRC86 (2012)*

- n-EDM measurement seems to have a higher sensitivity….
  but → not for all possible extensions of SM (LQ models)
  → interpretation less direct

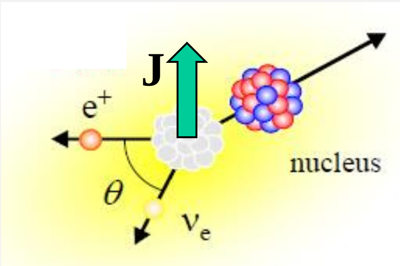
- Final precision of 2×10^{-5} on *D* *A. Falkowski, IJCLab, private communication*
  → probing a new particle > some TeV

⇨ *Enough room for high precision measurements of D in nuclear β decays*

Search for CP violation in nuclear β decay: the MORA project

$$D = \frac{2\rho \, \frac{C_V}{C_A} \delta_{JJ'} \left(\frac{J}{J+1}\right)^{\frac{1}{2}} \, Im\left({C_A}/{C_V}\right)}{(1+\rho^2)}$$

$$D \frac{\vec{J}.(\vec{p}_e \times \vec{p}_\nu)}{J(E_e E_\nu)}$$



D ≠ 0 in mirror decays ↓

Production of light exotic species in EU:
- ISOLDE
- IGISOL-4
- SPIRAL1
- …

Polarization of decaying nuclei ↓

Optical pumping (lasers) → very efficient method to polarize ions/atoms in traps

Fenker et al. PRL120 (2018)

Sensitivity to $\beta\nu$ correlation ↓

TRAP: ideal source for β–recoil measurements (TRINAT, BPT, LPCTrap, …)

Burkey et al. HI240 (2019)
Fabian et al. PRA97 (2018)

MORA: Matter's Origin from the RadioActivity of trapped and laser oriented ions *Delahaye et al. HI240 (2019)*

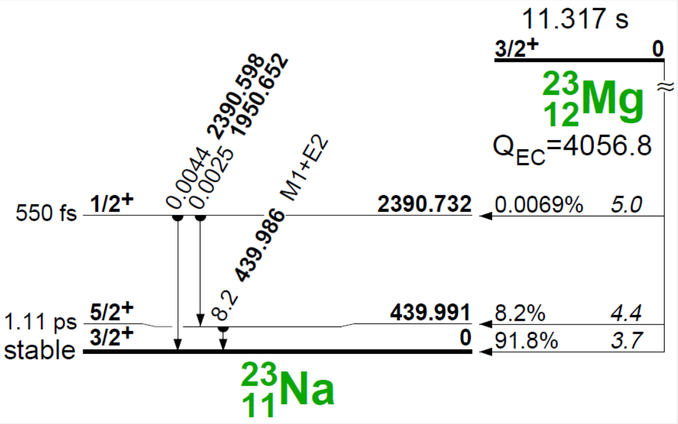
THE MORA PROJECT
MATTER'S ORIGIN FROM RADIOACTIVITY

Building of a new LPCTrap-like setup allowing ion cloud polarization using lasers, installed first @ JYFL (proof of principle, 1^{st} measurement)
later @ DESIR/GANIL (higher beam intensities)

$^{23}Mg^{1+}$: the first candidate for MORA

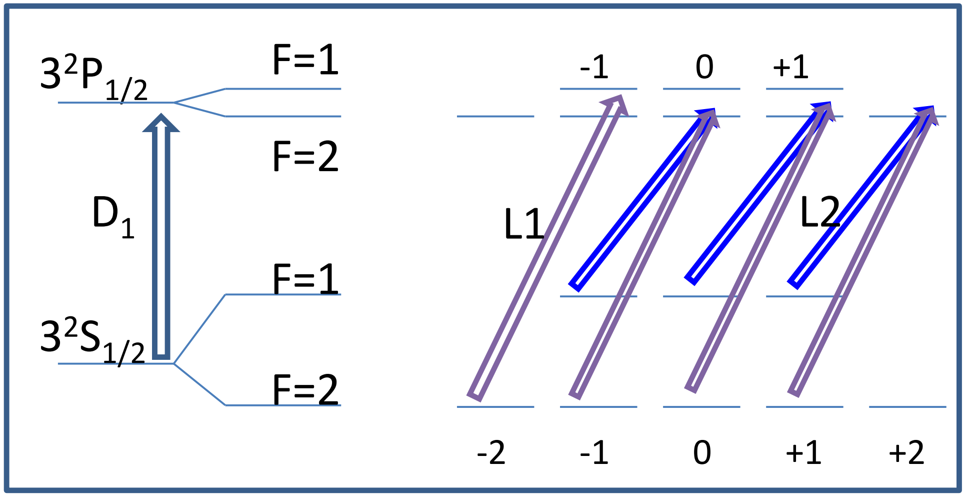
- The pros …

- Gain in sensitivity in NP of a factor 1.5 vs n decay
- Production rates
  - ✓ > 10^5 pps @ JYFL, measured in Oct 2018
  - ✓ > 10^8 pps expected at DESIR/GANIL



- Adapted lasers @ JYFL
  - ✓ Ti-Sa laser pulsed @ 10kHz
  - ✓ 20 µJ / pulse → ~ 99% polarization degree expected in 1 ms (velocity of trapped ions included in simulations) R. de Groote, X. Fléchard and W. Gins

$^{23}Mg^{1+}$ hyperfine structure F= I+J



Optical pumping

- Nuclear spin J interacts with atomic one I → F=I+J
- σ+ or σ- light (scan of hyperfine structure) forces ions in the m_F=±F state

Neyens et al. PRL94 (2005) Yordanov et al. PRL108 (2012)

L1+L2 lasers excited using a broadband pulsed Ti:Sa laser (tripled frequency → λ ~ 280nm)
σ+ polarization

$^{23}Mg^{1+}$: the first candidate for MORA

- … and cons

Solution

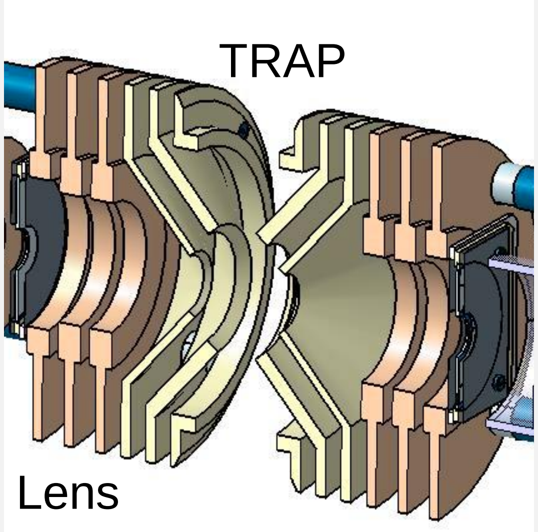
- Production rates & contamination
  > 10^5 pps @ JYFL, measured in Oct 2018
  with > 200 x more stable $^{23}Na^{1+}$

→ 1) Dedicated new sextupole downstream the gas cell
2) Use of MR-ToF-MS

- $T_{1/2}$ ~ 11 s
- LPCTrap: capacity ~ 10^5 ions/bunch
  ion lifetime ~ 0.5 s

Delahaye et al. EPJA55 (2019)

→ 1) Optimization of the new trap design:
- ✓ reduction of harmonics of order higher than 2
- ✓ increase of detection solid angle



We can expect: capacity > 10^6 ions/bunch
ion lifetime > 1 s

Benali et al., EPJA56 (2020)

$^{23}Mg^{1+}$: the first candidate for MORA

- … and cons

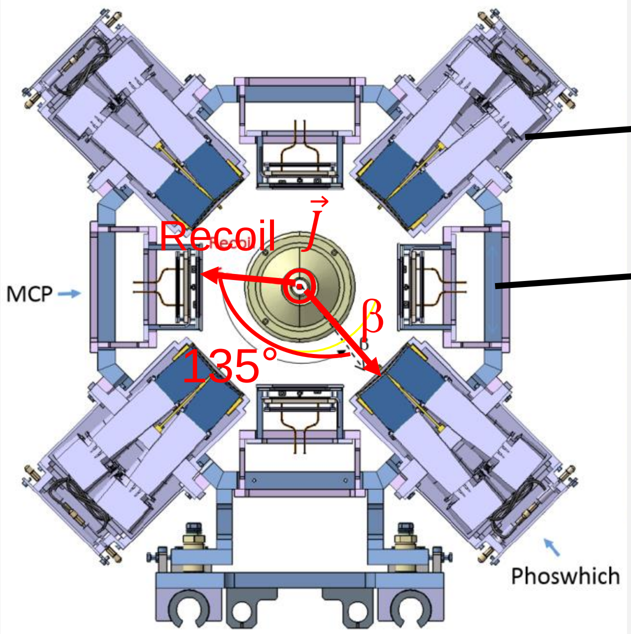
Solution

- Production rates & contamination
  $> 10^5$ pps @ JYFL, measured in Oct 2018
  with > 200 x more stable $^{23}Na^{1+}$

→ 1) Dedicated new sextupole downstream the gas cell
2) Use of MR-ToF-MS ?

- $T_{1/2} \sim 11$ s
- LPCTrap capacity: $\sim 10^5$ ions/bunch
  ion lifetime: ~ 0.5 s

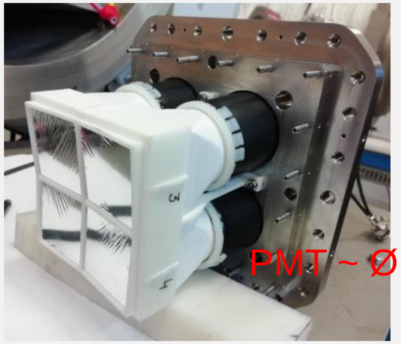
→ 2) Optimization of the number of detectors around the trap



emiT-like setup *Mumm et al. RSI75 (2004)*

4x4 "Phoswich" detectors for β particles

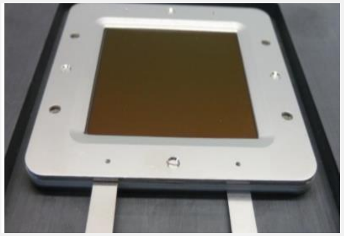
Plastic scintillators

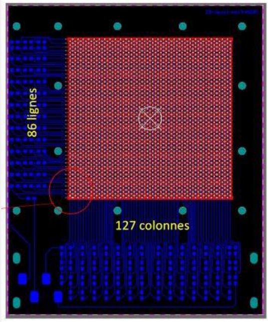


4 "RIDE" detectors for recoil ions

$$D \propto \frac{N^+ - N^-}{N^+ + N^-}$$

(for $\pm \vec{J}$ and ≠ detector pairs)





FLEX

µCP 50x50 + PSA

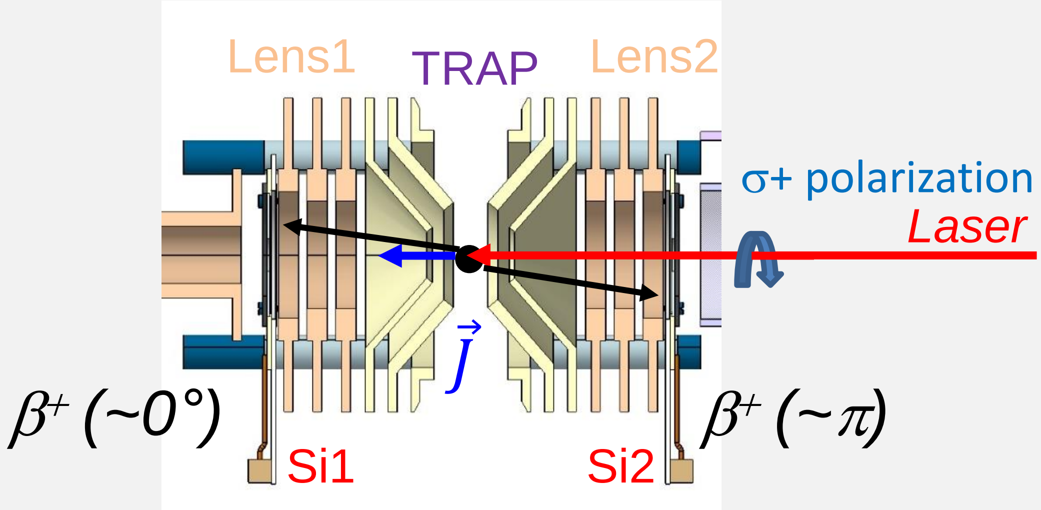
First measurement: the Polarization degree

Asymmetry in counting rates depends on the cloud polarization degree *P*

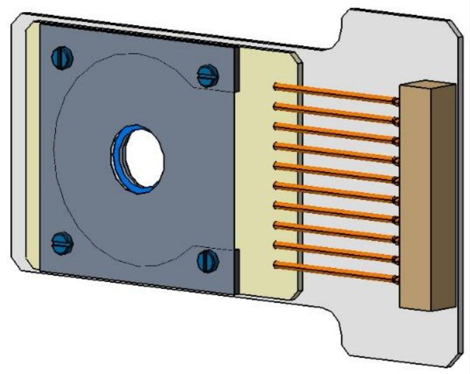
$$\frac{N^+ - N^-}{N^+ + N^-} \propto DP$$

P must be ① measured ② controlled during the experiment

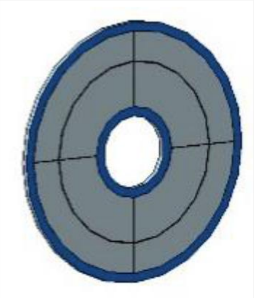
→ A_β measurement (*CS Wu -like experiment*)



Silicon detector



8 channels: 4 sectors, 2 rings



$$\frac{N^{\uparrow}_{\beta^+} - N^{\downarrow}_{\beta^+}}{N^{\uparrow}_{\beta^+} + N^{\downarrow}_{\beta^+}} \propto A_\beta \cdot P \qquad A_\beta \frac{\langle \vec{J} \rangle}{J} \cdot \frac{\overrightarrow{p_e}}{E_e}$$

First measurement: the Polarization degree

Asymmetry in counting rates depends on the cloud polarization degree *P*

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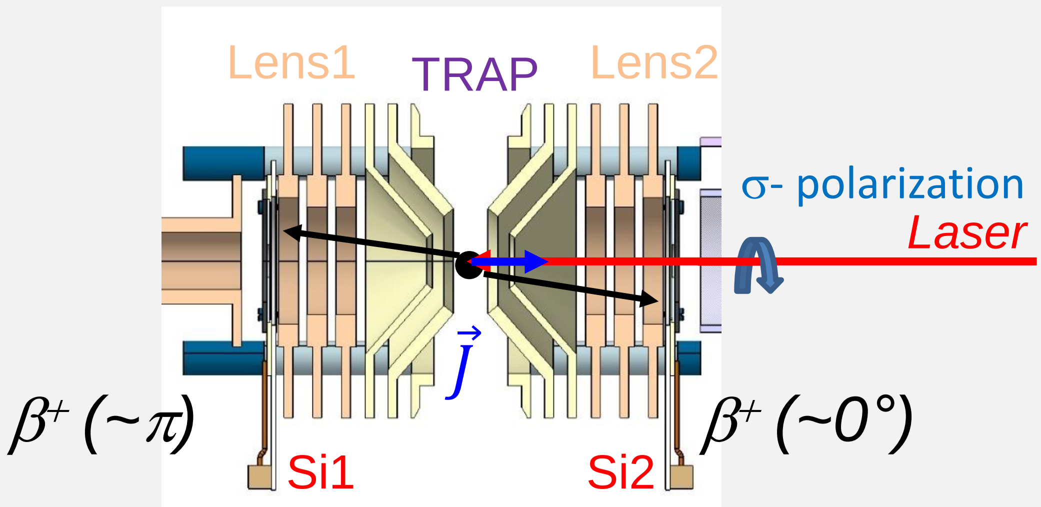
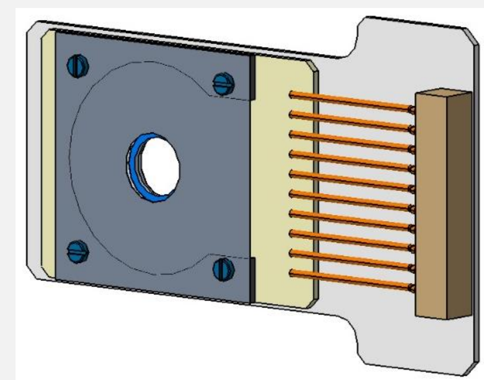


Silicon detector



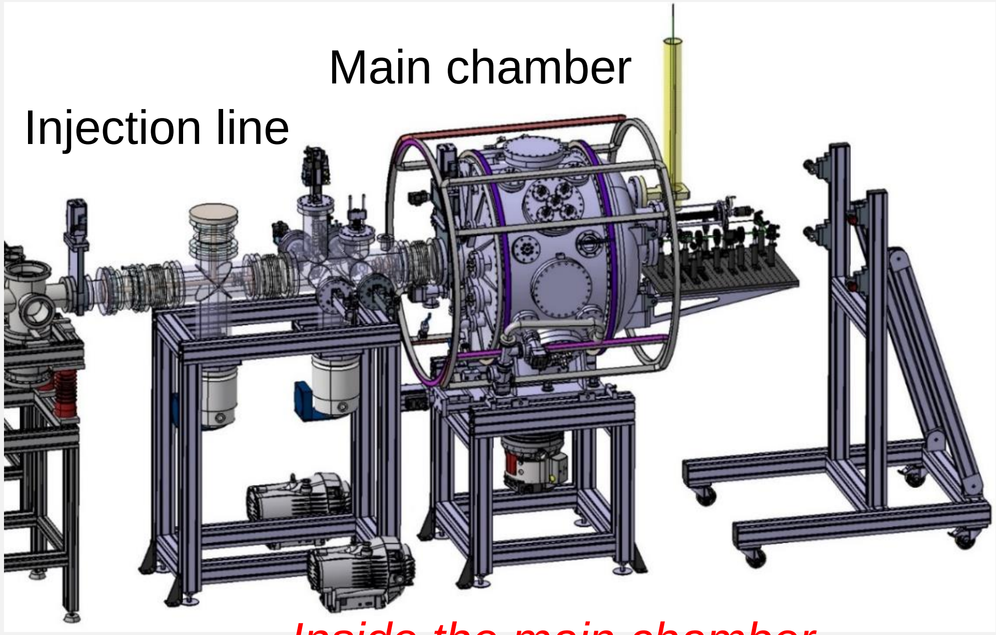
8 channels: 4 sectors, 2 rings

$$\frac{N^{\uparrow}_{\beta^+} - N^{\downarrow}_{\beta^+}}{N^{\uparrow}_{\beta^+} + N^{\downarrow}_{\beta^+}} \propto A_\beta \cdot P \qquad A_\beta \frac{\langle \vec{J} \rangle}{J} \cdot \frac{\vec{p_e}}{E_e}$$

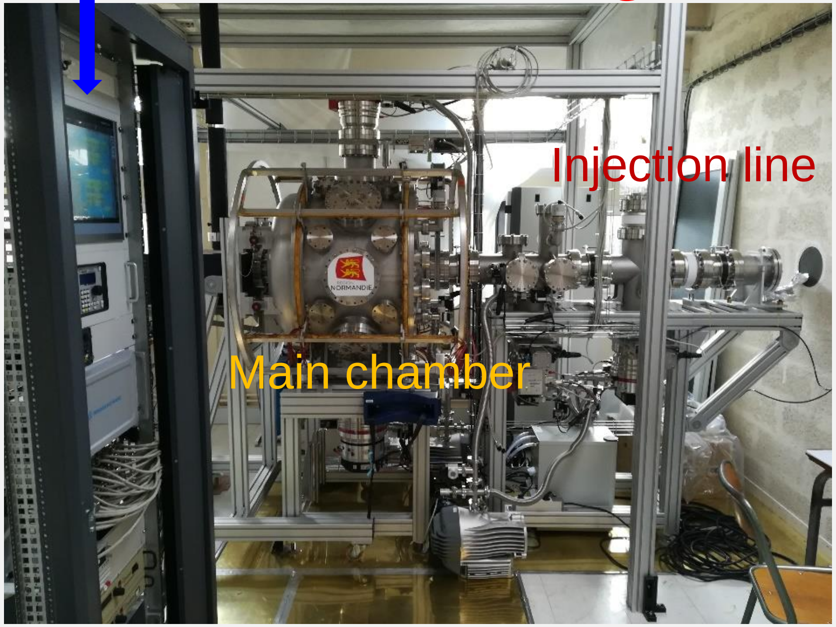
- $A_{SM} = -0.5584(17)$
  Severijns et al. PRC78 (2008)
- Precise knowledge not needed for *D* if *P* > 80%

MORA: status

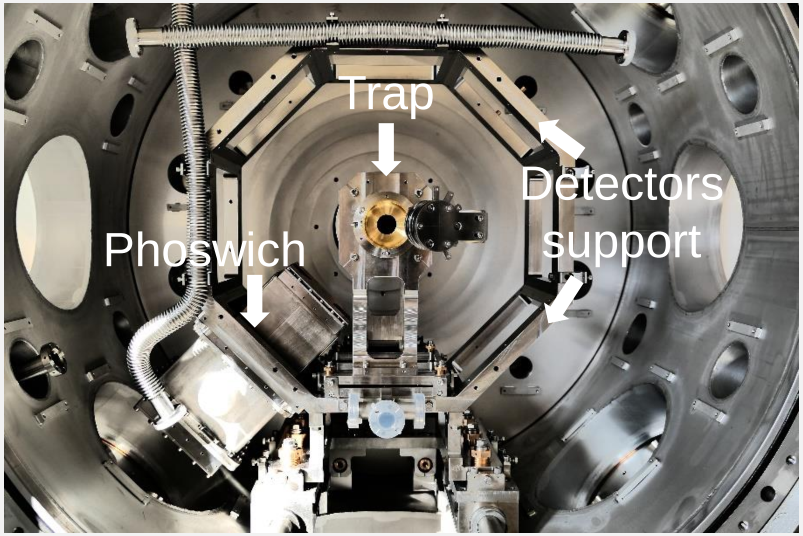
- Injection line & main chamber
  ✓ built & in commissioning
- Detection
  ✓ phoswich: tests & simulations
  ✓ RIDE – Si: tests & simulations
- Slow control
  ✓ operational



MORA @ LPCC



Inside the main chamber



MORA: status

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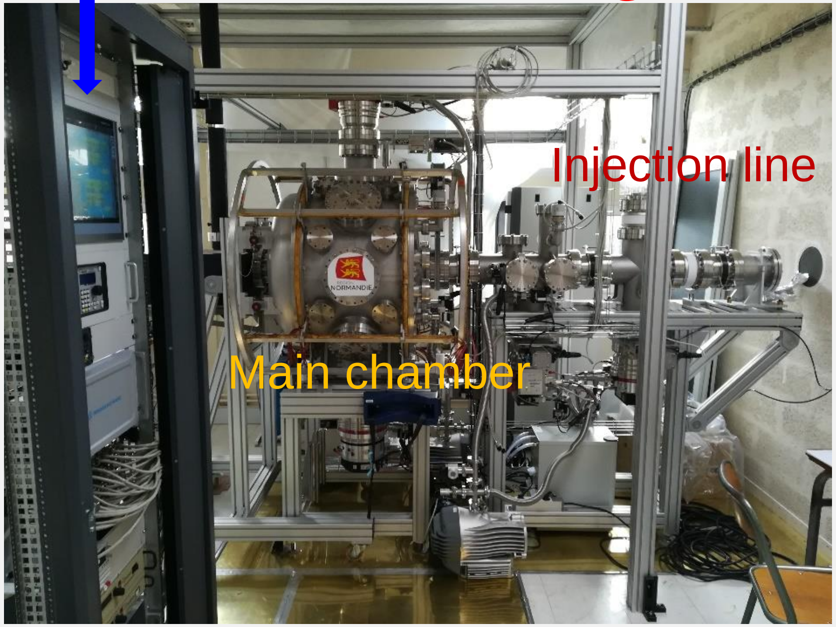
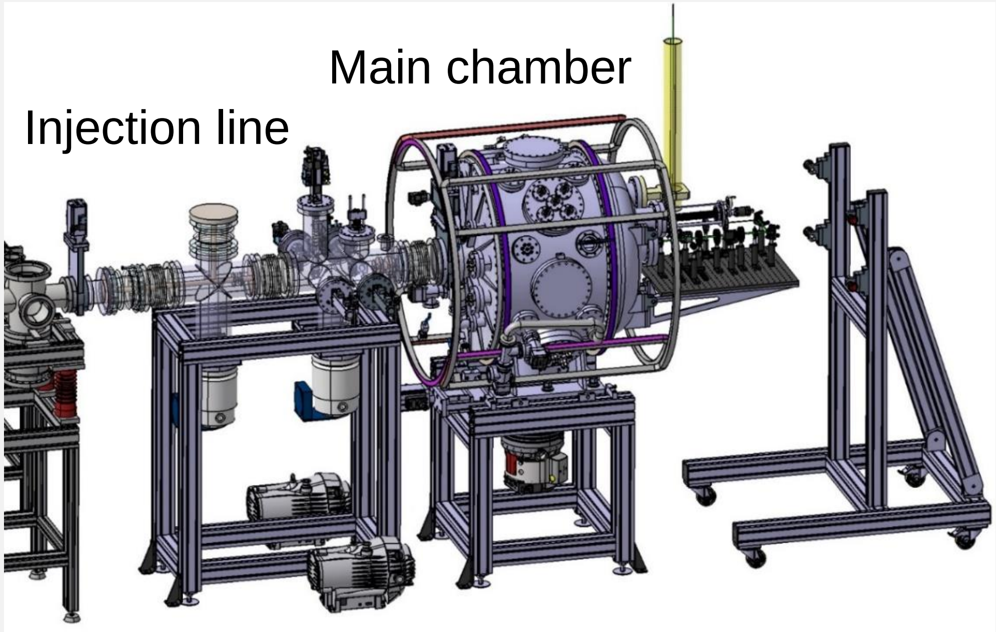
MORA @ LPCC





<u>Schedule</u>

- Setup fully tested @LPCC in summer 2021
- Installed @JYFL in fall 2021
- First measurements in 2021-2022:
  1. A_β for P determination
  2. D with limited stat

MORA: perspectives

THE MORA PROJECT
MATTER'S ORIGIN FROM RADIOACTIVITY

		Trapped ions/cycle	Data taking (days)	Num. of events (*P*)	σ_P (%)	Num. of coinc. (*D*)	Sensitivity on *D*	
from 2021	JYFL: *P*	2.0×10^4	8	1.7×10^5	1.9	1.5×10^6	1.0×10^{-3}	
	JYFL: *D*	2.0×10^4	32	6.7×10^5	0.94	6.1×10^6	5.2×10^{-4}	☑
from 2025	DESIR: *D*	1.0×10^6	24	2.5×10^7	0.15	2.3×10^8	8.5×10^{-5}	☑
	DESIR: *D*	5.0×10^6	24	1.3×10^8	0.07	1.2×10^9	3.8×10^{-5}	

with optimal trapping

☑ best precision in nuclear beta decay (i.e. compared to ^{19}Ne)

☑ best precision (i.e. compared to n) – constraint on D_{FSI} (~1.1×10^{-4})?
(DESIR/SPIRAL1: I(^{23}Mg) > 10^8 pps)

Next candidate: $^{39}Ca^{1+}$?
- → better sensitivity to NP (D_{FSI} ~ -3×10^{-5})
- → study required for production rate (LoI13_21)

MORA is funded by RÉGION NORMANDIE & ANR (AGENCE NATIONALE DE LA RECHERCHE)

SUMMARY

- High precision measurements in nuclear β decays
  - Sensitive tool to test the Standard Model, complementary to high energy physics
  - Information hidden in correlations

- Correlations between particles momenta
  - In pure transitions
    - Search for exotic currents (S or T): 0.1% precision is needed
    - WISArD (S, @ISOLDE) and b-STILED (T, @GANIL): promising projects
  - In mirror transitions
    - Determination of mixing ratio
    - LPCTrap or MORA (@GANIL/DESIR): clean environment *to be confirmed*

- Correlations between particles momenta and spin
  - In mirror transitions
    - Search for new sources of *CP* violation
    - MORA (@JYFL & @GANIL/DESIR): promising project …

Thank you for your attention

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