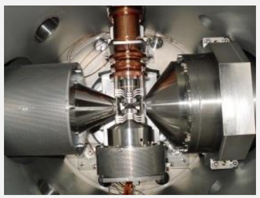
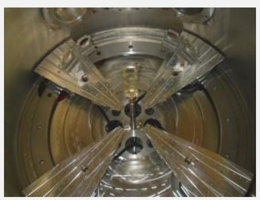
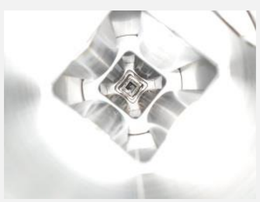
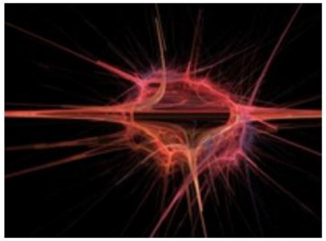


XXth Colloque GANIL 2017

15-20 Oct 2017 Amboise (France)

Laboratoire de physique corpusculaire

Weak interaction studies at GANIL/SPIRAL(2)

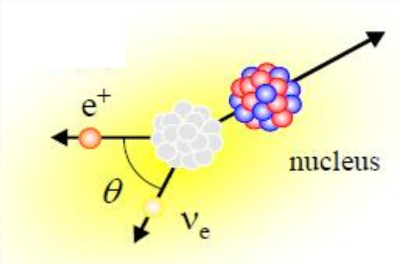
E. Liénard

LPC Caen, University of Caen Normandy

CNRS IN2P3 Les deux infinis · Normandie Université · UNICAEN Université Caen Normandie · ENSICAEN

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})

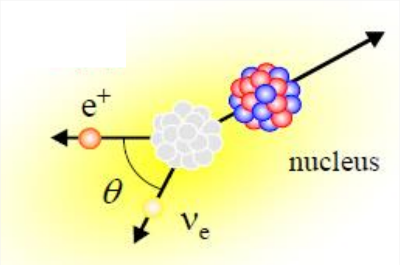
Nuclear β decay: a laboratory to test the Standard Model

- Correlations accessible to experiments

1. Between particles momenta

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

P, T conserving



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

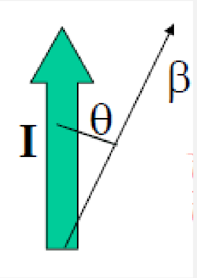
in V - A frame determination of ρ

2. Between momentum & spin

$$A\frac{\vec{J}.\vec{p}_e}{JE_e}$$

T conserving

sign change under P



F	GT	Mirror
No sense	A ≠ 0 $\Rightarrow$ P violation	$A\,(\rho)$

Test of MPV

in V - A frame determination of ρ

Nuclear β decay: a laboratory to test the Standard Model

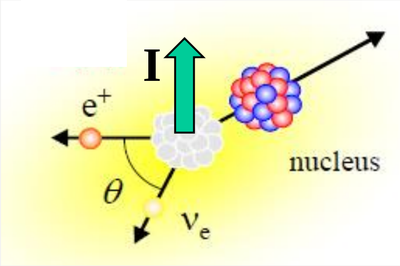
- Correlations accessible to experiments

3. Between momenta & spin

$$D\,\frac{\vec{J}.(\vec{p}_e\times\vec{q}\,)}{J(E_eE_\nu)}$$

P conserving

sign change under T



F	GT	Mirror
No sense	No sense	D ≠ 0 ⇒ T violation

Search for new sources of CP violation

- Precise measurements of "ft" values

(*M*, $T_{1/2}$, *BR*, ρ)

$$ft \propto \frac{1}{C_V^2|M_F|^2+C_A^2|M_{GT}|^2} \propto \frac{1}{C_V^2|M_F|^2(1+\rho^2)}$$

F	GT	Mirror
• C_V, CVC, V_{ud}, CKM • b_F	~~CAC~~ → M_{GT} ⇒ Phynu models	• C_V, CVC, V_{ud}, CKM • b_{GT} / b_F

Test of CVC & CKM unitarity

Fierz interference parameter

Nuclear β decay: a laboratory to test the Standard Model

- A special case: The Fierz term

$$b\,\frac{m_e c^2}{E_e}$$

always present, no correlation

P, T conserving

$$b \propto C_{exotic} \times C_{standard}$$ = 0 in SM ! $\Rightarrow$ *Test of V - A theory*

Observables sensitive to *b*:

1. β kinetic energy distribution

$$N(p_e) \propto W(p_e)(1 + b\frac{m_e c^2}{E_e})$$

requires "precise" detection of β particles

2. β–ν correlations

$$N(p_e,\theta) \propto W(p_e)\xi(1 + \tilde{a}\,\frac{v_e}{c}\cos(\theta))$$

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

$a \propto |C_{exotic}|^2$ and $b \propto C_{exotic}$ $\Rightarrow$ *b raises the sensitivity of correlation parameter !*

3. *Ft* values

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

sustained studies of pure F decays → excellent constraints on b_F

Exotic currents: the status

β–ν angular correlation: the best results

Relative precision

- GT: ^{6}He (Johnson *et al.* PRC 1963) → $\tilde{a}_{GT}$ = -0.3308 (30)
  corrected for radiative and recoil corrections (Glück NPA 1998)

  ^{8}Li (Sternberg *et al.* PRL 2015) → $\tilde{a}_{GT}$ = -0.3342 (39)

  ~ 1%

- F: ^{32}Ar (Adelberger *et al.* PRL 1999) → $\tilde{a}_{F}$ = 0.9989 (65)

  ^{38m}K (Gorelov *et al.* PRL 2005) → $\tilde{a}_{F}$ = 0.9981 (48)

  ~ 0.5%

Results used in a global analysis including all available data

Reviews:

REVIEWS OF MODERN PHYSICS, VOLUME 78, JULY–SEPTEMBER 2006

Tests of the standard electroweak model in nuclear beta decay

Nathal Severijns* and Marcus Beck†

Instituut voor Kern- en Stralingsfysica, Katholieke Universiteit Leuven, B-3001 Leuven, Belgium

Oscar Naviliat-Cuncic‡

Université de Caen Basse-Normandie and Laboratoire de Physique Corpusculaire CNRS-ENSI, F-14050 Caen, France

(Published 29 September 2006)

IOP Publishing — Journal of Physics G: Nuclear and Particle Physics

J. Phys. G: Nucl. Part. Phys. **41** (2014) 114001 (29pp) — doi:10.1088/0954-3899/41/11/114001

Precision frontier in semileptonic weak interactions: theory

Barry R Holstein

Department of Physics-LGRT, University of Massachusetts Amherst, MA 01003, USA

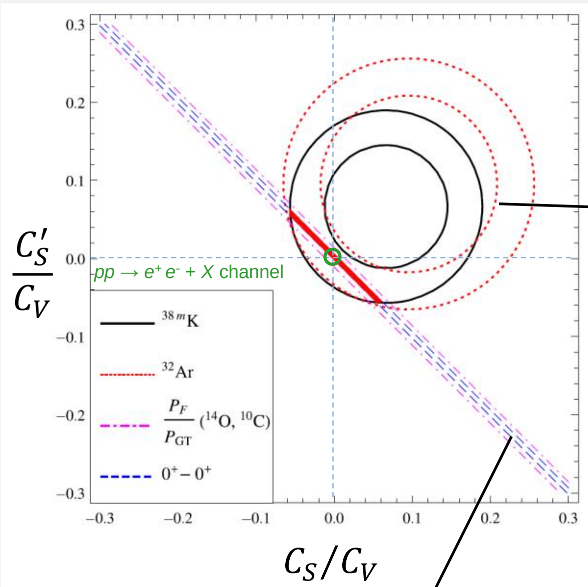
\+ Severijns *et al.* PhyScr 2013, Severijns JPG 2014, Wauters *et al.* PRC 2014 …

Exotic currents: the status

SCALAR

B.R. Holstein JPG41(2014)

TENSOR



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

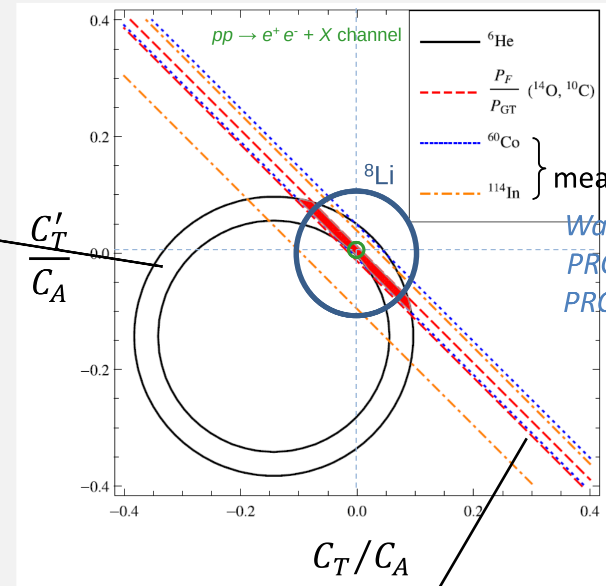
Circles because

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

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

$$\left|C^{(\prime)}_S / C^{(\prime)}_V\right| < 0.07$$

$$\left|C^{(\prime)}_T / C^{(\prime)}_A\right| < 0.09$$



A_β measurements

Wauters et al PRC80(2009) PRC 82(2010)

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

Hardy et al PRC79(2009)

$$P_F / P_{GT} \propto b_F - b_{GT}$$

Wichers et al PRC58(1987)

Carnoy et al PRC43(1991)

- Best constraints from "*b*", but "*a*" adds limits... ("*b*" unsensitive to right-handed ν !)
- In green: constraints from LHC (CMS data) *Naviliat et al ADP525(2013)* *Cirigliano et al PPNP71(2013)*

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

Exotic currents: status & projects

Many projects with precision level at 0.1% - 0.5 %

adapted from Severijns & Naviliat PST152(2013)

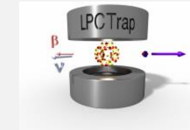
Parent	Technique	Team, laboratory	Remarks	
^{6}He	Spectrometer	ORNL	$a = -0.3308(30)$	1963
^{32}Ar	Foil; p recoil	UW-Seattle, ISOLDE	$\tilde{a} = 0.9989(52)(39)$	1999
^{38m}K	MOT	SFU, TRIUMF	$\tilde{a} = 0.9981(30)(34)$	2005
^{21}Na	MOT	Berkeley, BNL	$a = 0.5502(38)(46)$	2008
^{6}He	Paul trap	LPC-Caen, GANIL	$\tilde{a} = -0.3335(73)(75)$	2011
^{6}He	Paul trap	LPC-Caen, GANIL	Analysis under way	
^{8}Li	Paul trap; $\beta\alpha$	ANL	$\tilde{a} = -0.3342(26)(29)$	2015
^{35}Ar	Paul trap	LPC-Caen, GANIL	Analysis under way	
^{32}Ar	Foil; β-p coinc	CENBG, ISOLDE	In preparation	
^{19}Ne	Paul trap	LPC-Caen, GANIL	Analysis under way	
^{6}He	EIBT	Weizmann, SOREQ	In progress	
^{6}He	MOT	ANL, CENPA	In progress	
Ne	MOT	Weizmann, SOREQ	In progress	
~~^{21}Na~~	~~MOT~~	~~KVI-Groningen~~	~~In progress~~	
^{32}Ar	Penning trap	Texas A&M	In preparation	
^{8}He	Foil; $\beta\gamma$	NSCL	In preparation ?	

→ LPCTrap @ GANIL (^{6}He Paul trap, LPC-Caen, GANIL, Analysis under way)

→ WISArD @ ISOLDE (^{32}Ar Foil; β-p coinc, CENBG, ISOLDE, In preparation)

+ direct measurements of "b" with the same level of precision

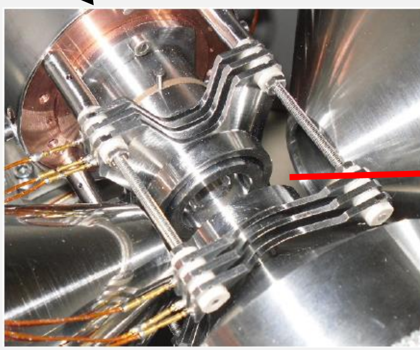
Exotic currents: LPCTrap@GANIL

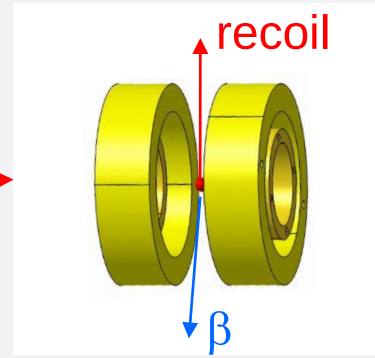


- *Decay source confined in a transparent Paul trap*

E. Liénard et al. HI236(2015)

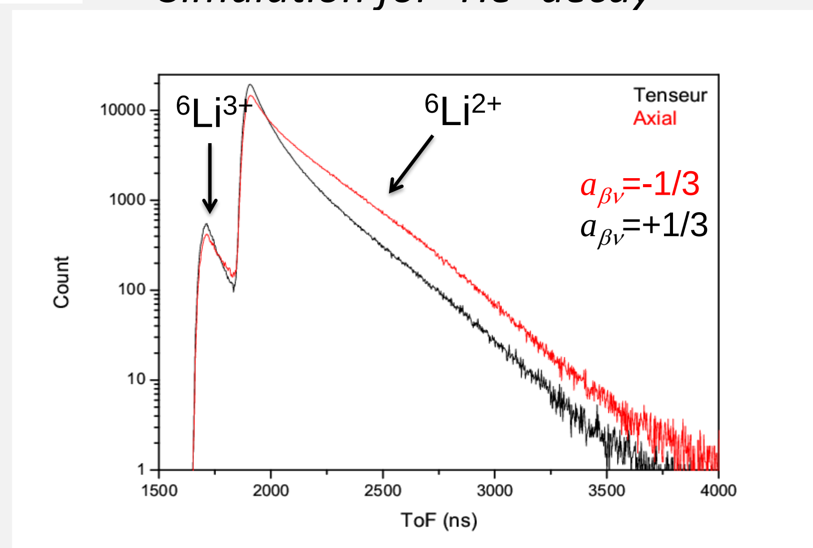
beam





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

Simulation for $^{6}He^{+}$ decay



- Any process modifying the kinematics must be identified and precisely controlled…!
- Here systematic effects dominated by ion cloud behaviour & β scattering

Reaching 0.1% precision level requires recurrent measurements campaigns without pressure…

→ Not possible @ GANIL ⇒ LPCTrap used in mirror decays studies (see later)

→ Allowed in smaller structures: ^{6}He-MOT @ CENPA / U. Washington (example)

Exotic currents: WISArD@ISOLDE

Weak-Interaction Studies with ^{32}Ar Decay

- *Decay source implanted in a thin foil*

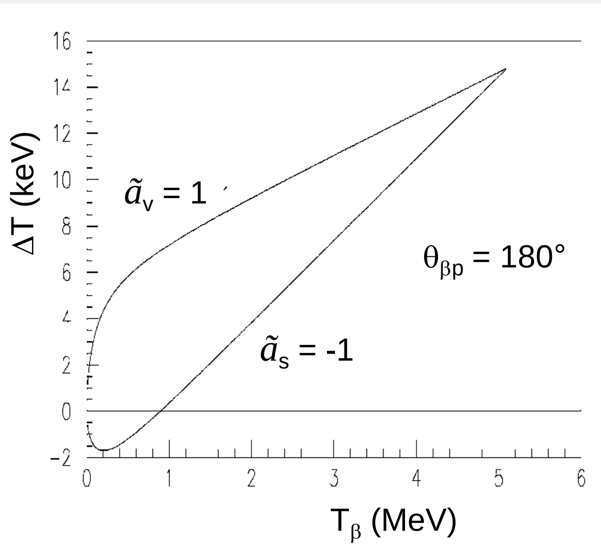
Severijns & Blank JPG44(2017)

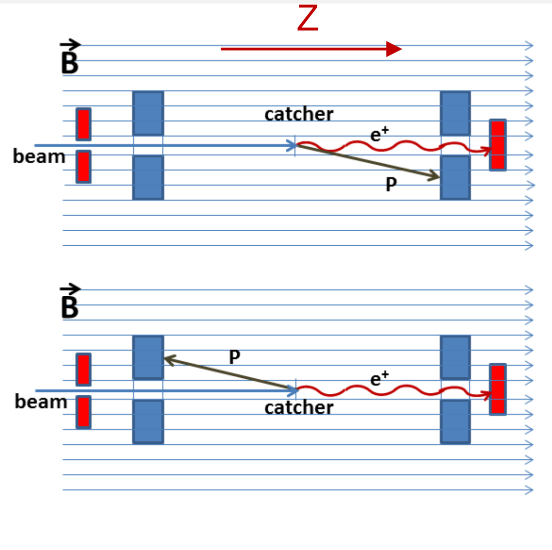
Detection of a delayed p emitted during recoil

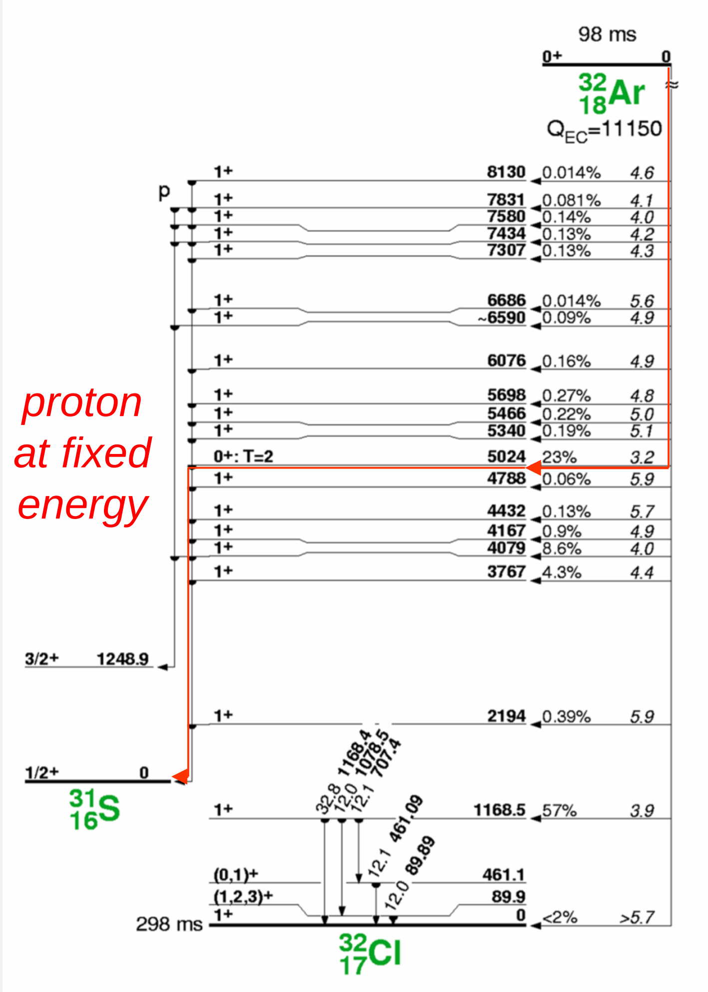
- p emitted during recoil → kinetic shift (~10keV) $\propto a$

$$\Delta T = \frac{(p_{shift}^2 - p^2)}{2m_p} = \frac{<r_z>}{2M_{ion}}\left(\frac{<r_z> m_p}{M_{ion}} + 2p\right)$$

where $<r_z>$ is a weighted mean of Z-component of recoil momentum $\propto a$







Exotic currents: WISArD@ISOLDE

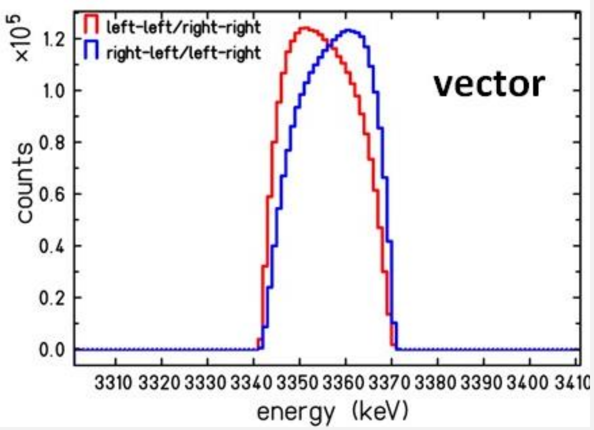
Weak-Interaction Studies with ^{32}Ar Decay

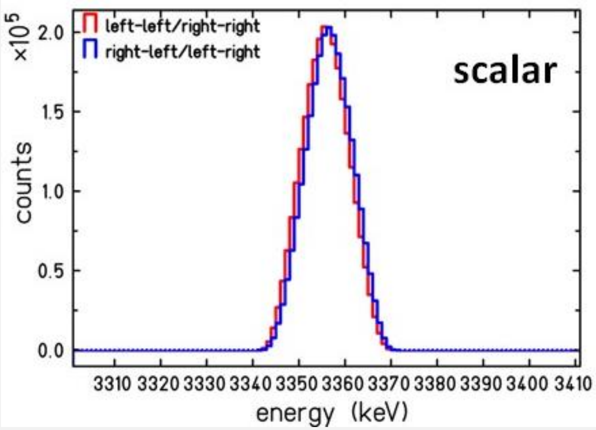
Severijns & Blank JPG44(2017)

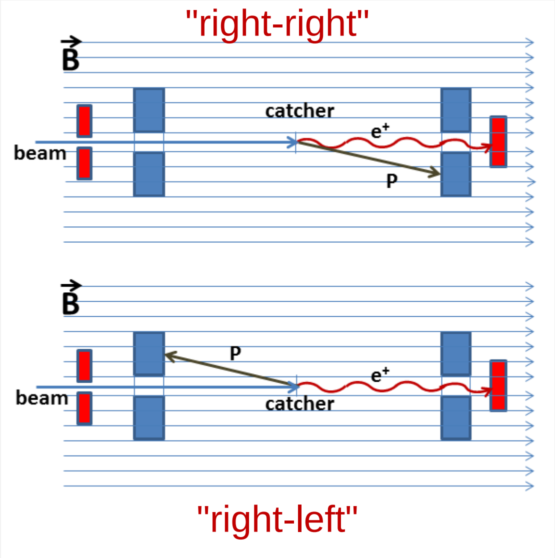
• *Decay source implanted in a catcher foil*

Detection of a delayed p emitted during recoil

- p emitted during recoil → kinetic shift (~10keV) $\propto a$
- β - p coincidences at 0° & 180° in the WITCH magnet
  → double kinetic shift







Simulation performed with 5 keV resolution on p kinetic energy (~ 3.3 MeV)

- globally, the vectorial current induces a kinetic shift contrary to the scalar current
- method avoids the recoil detection and is unsensitive to β scattering → 0.1% seems reachable

Interesting candidates: ^{32}Ar, ^{20}Mg, ^{22}Al, ^{24}Si, ^{36}Ca… → *@ GANIL: SPIRAL & S^3 using PIPERADE in DESIR*

Exotic currents: the Fierz interference term *b*

- *Direct measurement of b*

$$N(p_e) \propto W(p_e)\,(1 + b\,\frac{m_e c^2}{E_e})$$

Requirement: *a clean measurement of the β spectrum especially at low energy !!*

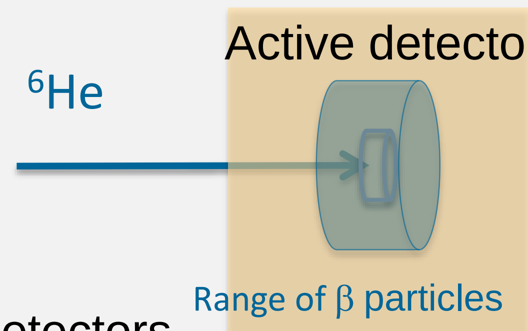
Examples:

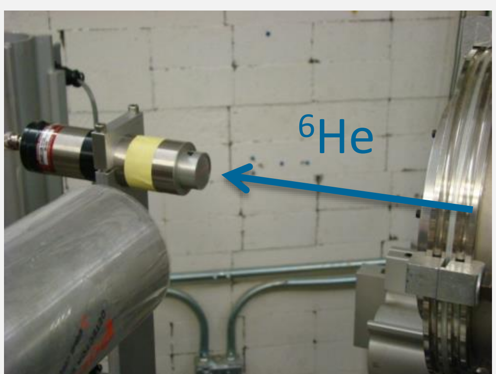
- ^{6}He @ Seattle using MOT (*Garcia, Mueller,...& LPC Caen*)
- ^{6}He @ MSU (*Naviliat et al*)
- ^{45}Ca, ^{60}Co, ^{67}Cu @ Krakow-Leuven (*Severijns et al*) using miniBETA spectrometer

"High" energy

Principle: pure ^{6}He beam implanted in Crystals

@ 40-50 MeV/A such as range > range (β)





© O. Naviliat-Cuncic

- Test with CsI(Na) and NaI(Tl) detectors
- Careful analysis of beam induced background in the detectors
- Precision goal: 10^{-3}

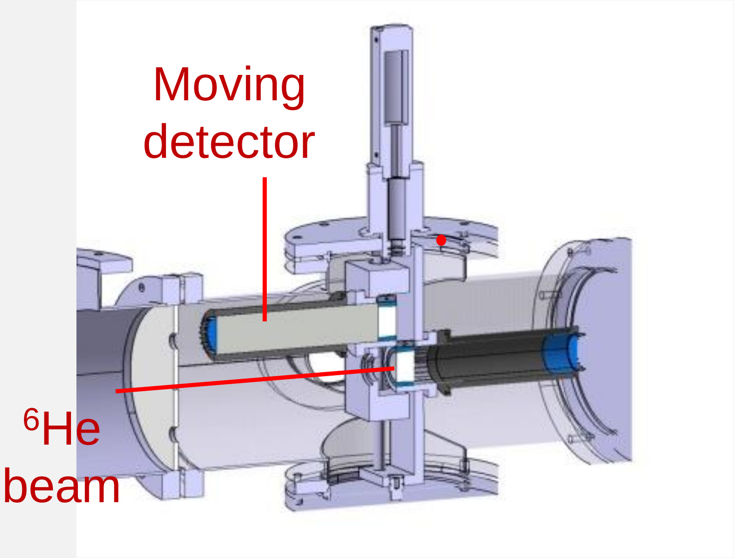
Exotic currents: the Fierz interference term *b*

• *Direct measurement of b*

$$N(p_e) \propto W(p_e)\,(1 + b\,\frac{m_e c^2}{E_e})$$

- *At "low" energy* ^{6}He @ GANIL (*Fléchard et al*)

Source : SPIRAL @ LIRAT or DESIR



- Implantation in solid scintillator
- ~ 4π detection with high control of linearity (~ 0.1%)
- Response function measured with e^- accelerator in Cherbourg (CERAP, ~ 0.2 MeV ≤ T_e ≤ 3.5 MeV precision 0.1%, available in 2018)
- Control of back-scattering & external BG with vetos
- Precision goal: 10^{-3}

Violation of fundamental symmetries: the Time Reversal

- *T violation = CP violation*

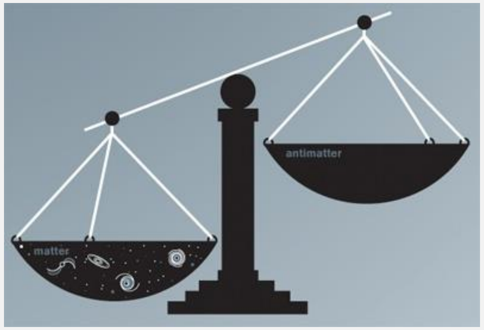


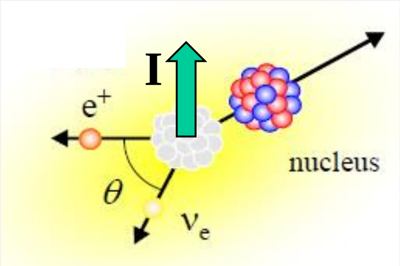
Illustration: Sandbox Studio

- Observed in meson decays but not enough to account for the large matter – antimatter asymmetry
- T-odd correlations in beta decay (*D* and *R*) and n-EDM enable to search for new sources of CP violation
- Current best results in nuclear decays:

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

n decay → *D* = (−0.94 ± 1.89 ± 0.97) 10^{-4} *Mumm et al. PRL107 (2011), Chupp et al. PRC86 (2012)*

- *CP violation: D measurement*



$$D\,\frac{\vec{J}.(\vec{p}_e\times\vec{q}\,)}{J(E_eE_\nu)}$$

- β - recoil coincidences
- $\vec{J}$ known

→ *LPCTrap ?*

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

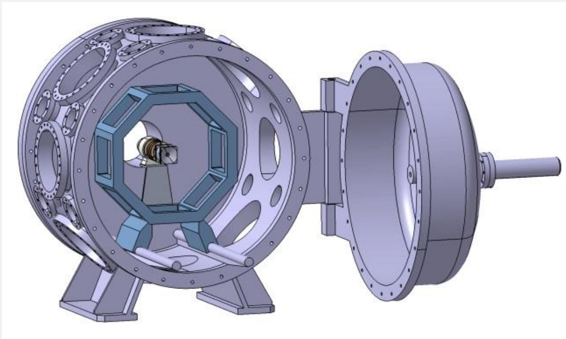
- *D* ≠ 0 → $\rho \neq 0$
  → Mirror decay !

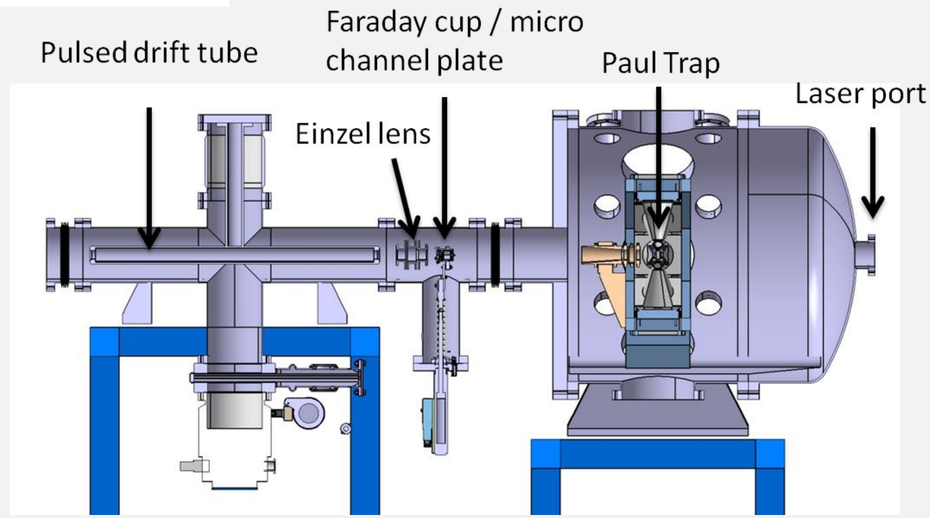
New SPIRAL beams

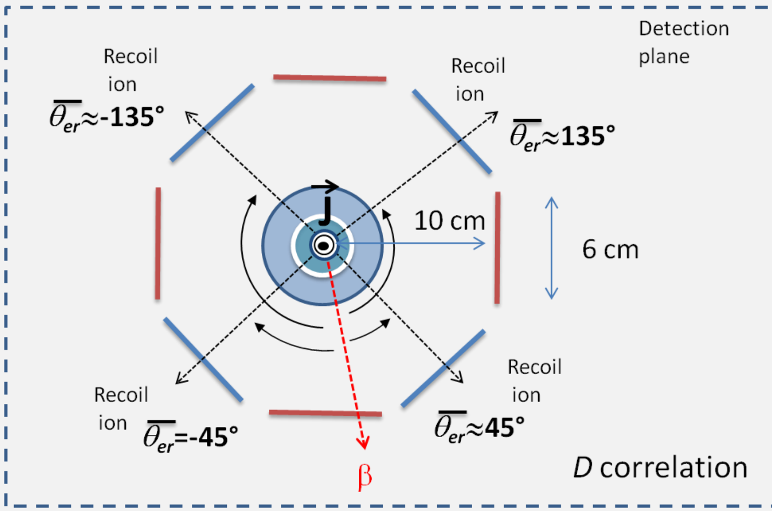
Test of CP violation: *D* measurement

- *Cloud polarization method: optical pumping*

  → New chamber, lasers & detectors







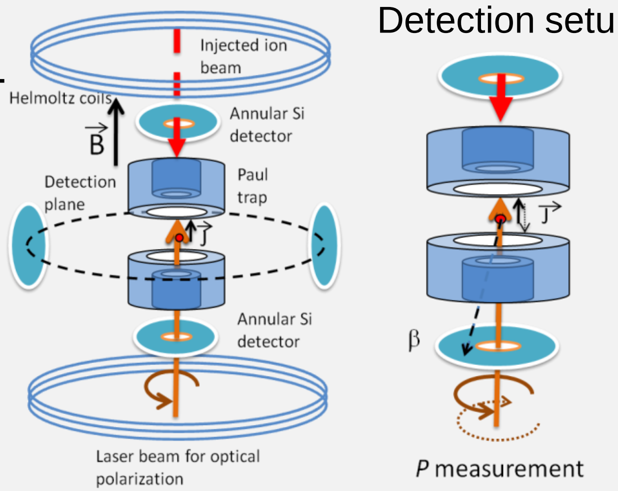
- Polarization achieved thanks to multiple interaction with laser @ adequate ν
  → *never done so far*
- Upgrade of the detector setup:
  → *arrangement of 8 detector modules*
- Interesting beams: ^{23}Mg, ^{39}Ca

"MORA" project (Matter's Origin from the RadioActivity of trapped and laser oriented ions)

MORA project

<u>Coordinator</u>: P. Delahaye

- ~ 630k€ funded by Normandy Region for 2 years (official response just received !!)
- GANIL – LPC Caen collaboration + contributions from JYFL, IKS Leuven, ISOLDE, IPNL, U Manchester
- T_0 : April 2018
- First step: ^{23}Mg cloud polarization measurement @ JYFL
  high degree expected (> 99% in 0.2ms)
  & measured through A_β



- Measurements of D
  - $D \propto \frac{N^+ - N^-}{N^+ + N^-}$ between 2 opposite polarization directions
  - First @ JYFL, improvement @ DESIR
  - Results expected in 1 week:

    JYFL: $\sigma_D \sim 5\times10^{-4}$

    DESIR: $\sigma_D \sim 5\times10^{-5}$ ⇨

- A factor 10 better than current result (^{19}Ne)
- Future candidate: ^{39}Ca

- Postdoc position for 2 years: trapping optimisation and first data taking at JYFL

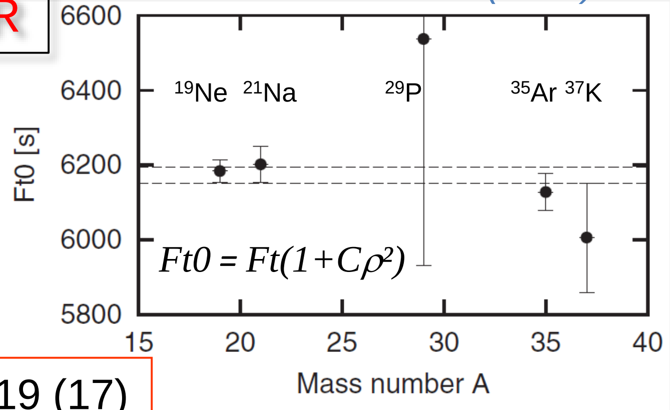
CVC, V_{ud} & CKM: *ft* values measurements

Subject discussed in details in the next talk (Bertram Blank)

- *Nuclear mirror vs $0^+ \rightarrow 0^+$ decays*

MIRROR

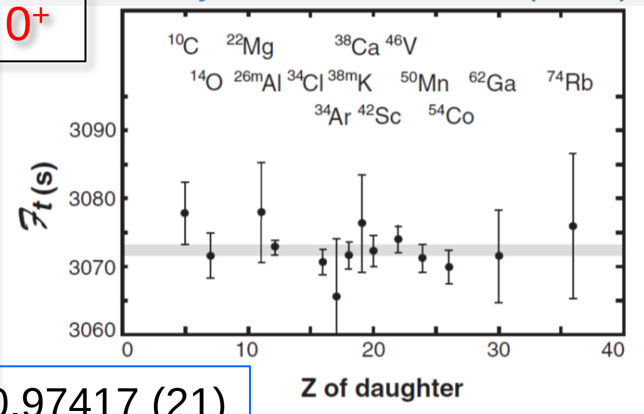
Naviliat et al. PRL102 (2009)



V_{ud} = 0.9719 (17)

$0^+ \rightarrow 0^+$

Hardy & Towner PRC91 (2015)



V_{ud} = 0.97417 (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

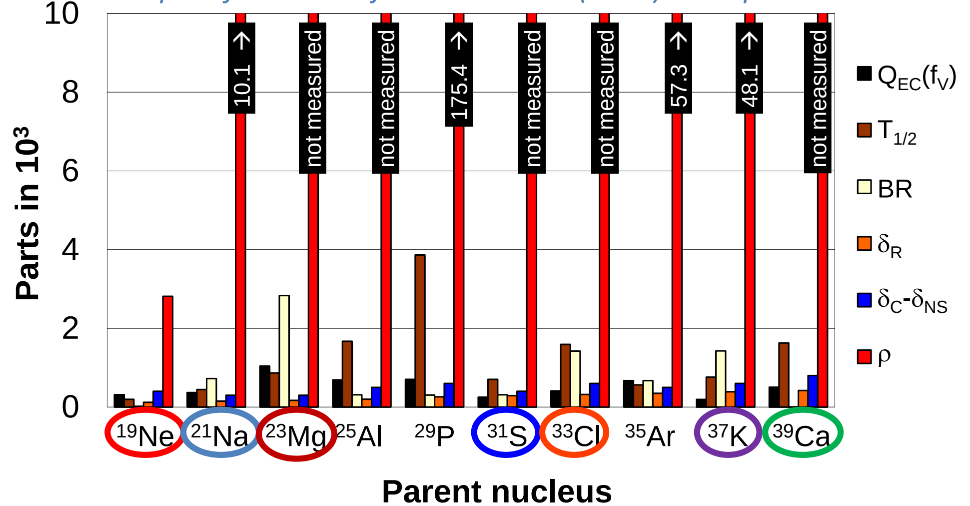
ρ is the limiting parameter !

CVC, V_{ud} & CKM: *ft* values measurements

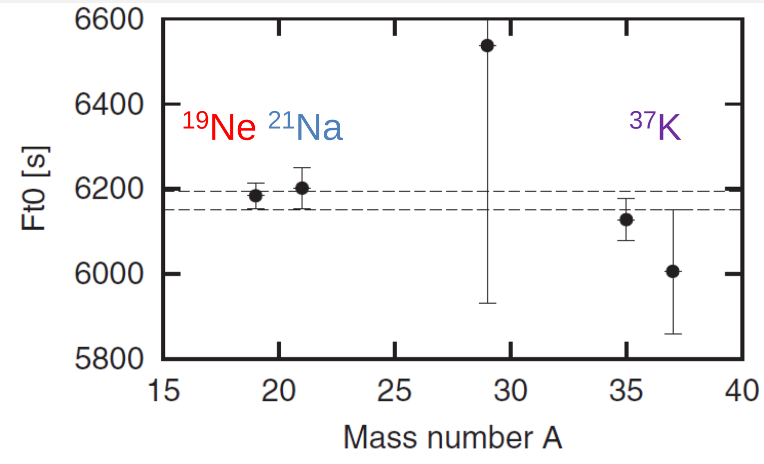
Subject discussed in details in the next talk (Bertram Blank)

- *Nuclear mirrors*

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



Naviliat et al. PRL102 (2009)



^{19}Ne $T_{1/2}$: *Broussard et al. PRL112 (2014)*

^{21}Na M: *Mukherjee et al. EPJA35 (2008)*
$T_{1/2}$: *Grinyer et al. PRC91 (2015)*

^{23}Mg M: *Saastamoinen et al. PRC80 (2009)*
$T_{1/2}$, BR: *Magron et al. EPJA53 (2017)*

^{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)*

^{39}Ca $T_{1/2}$: *Blank et al. EPJA44 (2010)*

The scientific community involved in this field... BUT

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

↓

V_{ud} (2017) = 0.9721 (17) !!

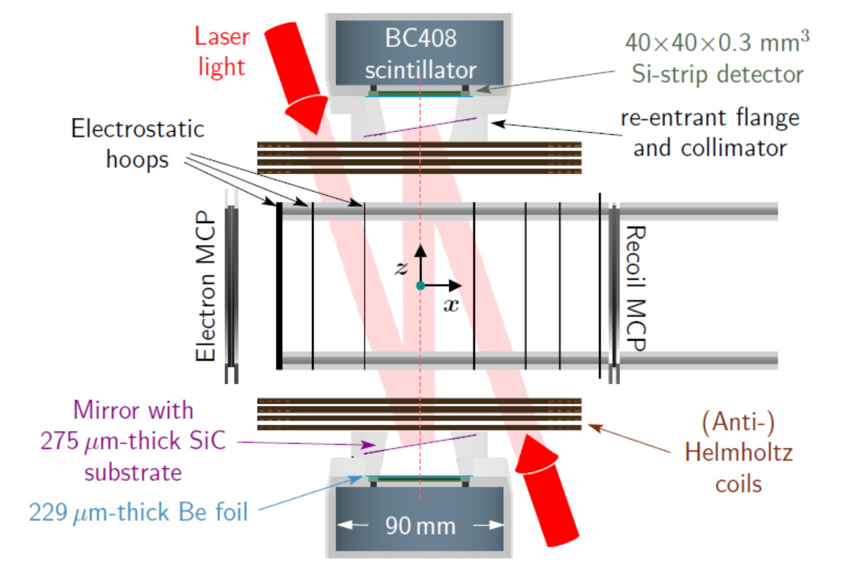
⇒ *For V_{ud} determination, ρ improvements are necessary ...*

CVC, V_{ud} & CKM: *ft* values measurements

Subject discussed in details in the next talk (Bertram Blank)

- *Nuclear mirrors*

Recent result: Measurement of A_β in ^{37}K (TRIUMF) Fenker et al. arXiv:1706.00414v1 2017



- 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} (2009) = 0.9719 (17) ⟶ V_{ud} (2017) = 0.9728 (14) !!

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

CVC, V_{ud} & CKM: *ft* values measurements

Subject discussed in details in the next talk (Bertram Blank)

• 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 PST152(2013)

a or *A* @ 0.5% ?

better sensitivity with a measurements

⇓

LPCTrap@GANIL !

^{21}Na →
^{23}Mg →
^{33}Cl →
^{37}K →

Parent nucleus	*a*			*A*		
	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

CVC, V_{ud} & CKM: *ft* values measurements

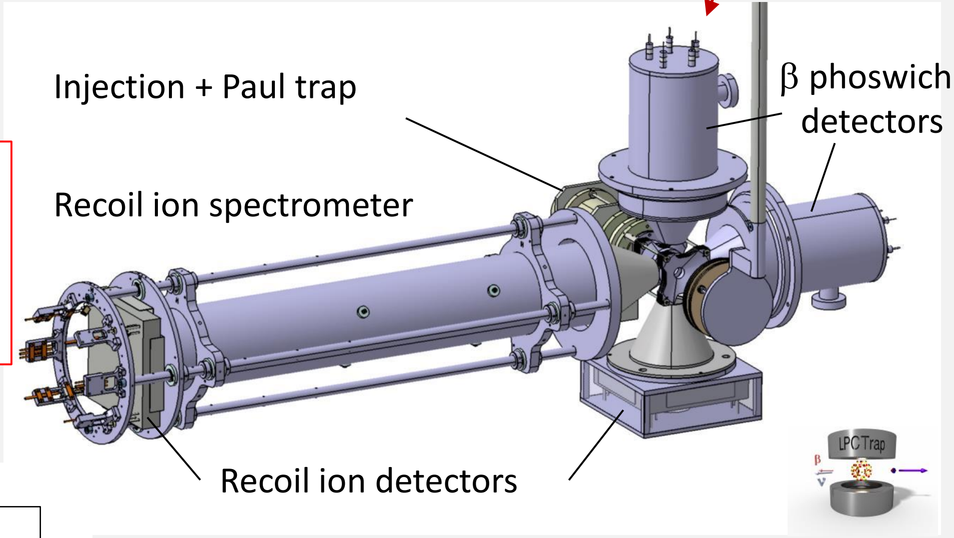
Subject discussed in details in the next talk (Bertram Blank)

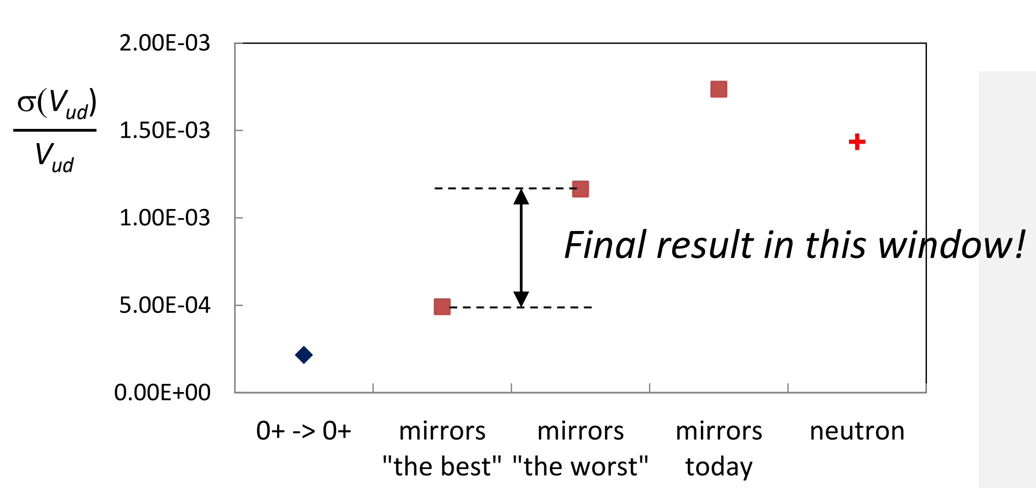
- *Nuclear mirrors*

Perspectives @ GANIL: Measurement of a in several mirror decays using LPCTrap2

Ion	$T_{1/2}$ (s)	Expected rate (pps)
^{21}Na	22.49	6.5E+08
^{23}Mg	11.32	2.1E+08
^{33}Cl	2.51	3.4E+07
^{37}K	1.22	7.4E+08

SPIRAL production > 10^7 pps





In any case, a significant improvement on V_{ud} is reachable

@ LIRAT and DESIR

CONCLUSION

- Nuclear beta decay = sensitive tool to study Weak Interaction
  - → Exotic currents existence
  - → Fundamental symmetries violation
  - → CVC hypothesis, CKM unitarity

thanks to precise measurements of distribution of events in correlations & ft values (M, $T_{1/2}$, BR, ρ) in pure and mirror transitions

- GANIL/SPIRAL(2) production platforms are useful
  - → SPIRAL 1: light nuclei with high intensities to measure correlations (*a*, *D*), *ft* in mirrors
  - → S3-LEB: light nuclei not accessible to SPIRAL1 & heavy nuclei for *ft* values (see BB's talk)

The best site to achieve such a program, with high quality beams, is DESIR !