




HOHENRODA / GERMANY
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High precision measurements in mirror β decays at GANIL

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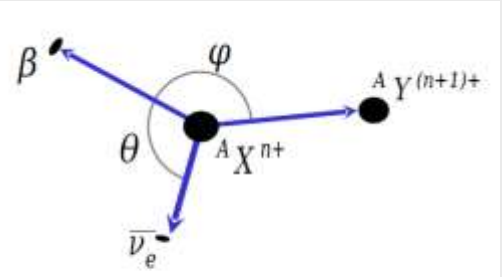
High precision measurements in nuclear β decays: why ?

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)



Meet the beast

high energy (E ~ M)

High precision measurements in nuclear β decays: how ?

@ low energy, "traces" are hidden in correlations:

$$\omega\left(\langle \vec{J} \rangle \mid E_e, \Omega_e, \Omega_\nu\right) dE_e\, d\Omega_e\, d\Omega_\nu$$

$$\propto \underbrace{F(\pm Z, E_e)}_{\text{Fermi function}} \quad \underbrace{p_e\, E_e\, (E_0 - E_e)^2\, dE_e\, d\Omega_e\, d\Omega_\nu}_{\text{phase space}}$$

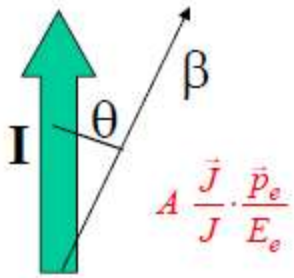
$$\times\ \xi \left\{ 1 + a\,\frac{\vec{p}_e \cdot \vec{q}}{E_e E_\nu} + b\,\frac{\gamma m_e}{E_e} + A\,\frac{\vec{J}}{J}\cdot\frac{\vec{p}_e}{E_e} + D\,\frac{\vec{J}\cdot(\vec{p}_e \times \vec{q})}{J(E_e E_\nu)} + \ldots \right\}$$

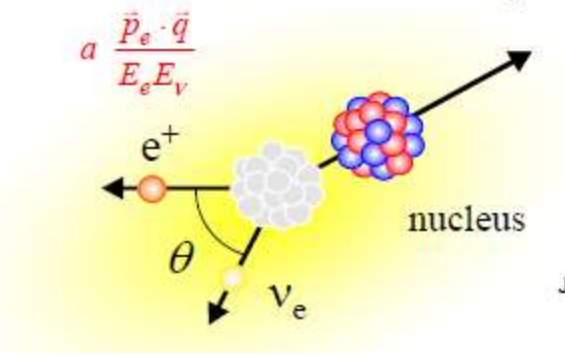
β-ν correlation

Fierz interference term (b ≡ 0 in standard model)

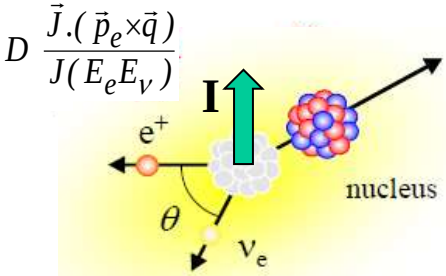
β-asymmetry

D-correlation





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

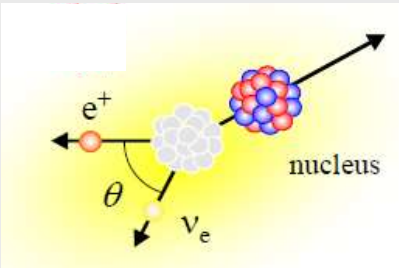


High precision measurements in nuclear β decays: examples

- *Unpolarized nuclei*
  - Recoil detection
  - β - recoil coincidences

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

LPCTrap@GANIL



a (C_S^2, C_V^2, C_T^2, C_A^2)

Pure GT: a_{GT} (C_T^2, C_A^2) = -1/3 (SM)

Pure F: a_F (C_S^2, C_V^2) = +1 (SM)

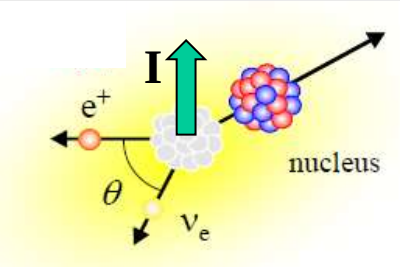
P, T conserving

Test of *V - A* theory

- *Polarized nuclei*
  - β - recoil coincidences
  - $\vec{J}$ known

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

Triple correlation



$D \propto$ Im ($C_S C_T^*$, $C_V C_A^*$)

D = 0 (SM)

Sensitive to T violation

Search for new sources of CP violation

High precision measurements *in mirror decays*: why mirrors ?

mixed decays with large F component

- *In V - A framework*

- $a\,\dfrac{\vec{p}_e.\vec{q}}{E_e E_\nu}$ $\qquad a_m = \dfrac{(1-\rho^2/3)}{(1+\rho^2)}$ $\qquad$ where $\rho = GT/F$ *is the mixing ratio*

⇨ *Test of CVC hypothesis, determination of V_{ud} (CKM matrix)*

- $D\,\dfrac{\vec{J}.(\vec{p}_e \times \vec{q})}{J(E_e E_\nu)}$ $\qquad D = \dfrac{-2\rho\, Im(\delta_{JJ'}(\frac{J}{J+1})^{1/2}\frac{C_A^*}{C_A})}{(1+\rho^2)}$ $\qquad$ *D* can be ≠ 0 <u>ONLY IF</u> $\rho \neq 0$, $\rho \neq \infty$

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

Precision measurements in mirror decays to determine V_{ud}

- *CVC hypothesis*

$$Ft(0^+ \rightarrow 0^+) = \frac{K}{2C_V^2(1+\Delta_R)} = constant$$

$\Rightarrow$ C_V = constant

- *Unitarity of the CKM matrix*

$\sqrt{2}\, C_V < G_F$ (μ decay) $\xrightarrow{\text{(quarks mixing)}}$

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

$\Rightarrow$ $V_{ud} = G_F / \sqrt{2}\, C_V$

unitarity condition:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 \quad ??$$

The measurement of V_{ud} in many transitions enables to test the CVC hypothesis and the unitarity of the CKM matrix

Precision measurements in mirror decays to determine V_{ud}

- *Data sources*

Hardy & Towner PRC91(2015)

Transition	$\lvert V_{ud}\rvert$
Super-allowed pure Fermi	0.97417 (21)
Neutron	0.9746 (13)
Pion	0.9728 (30)
Super-allowed mirror	0.9719(17)

Naviliat et al. PRL102 (2009)

- Best result from many measurements in 14 transitions
- Limited by theoretical corrections

- Result from existing data without specific measurements
- Great potential (many transitions)

Mirror transitions:

- New data in β decay, alternative to pure Fermi decays ($0^+ \rightarrow 0^+$)
- Many parameters to measure and to compute (corrections) in several decays

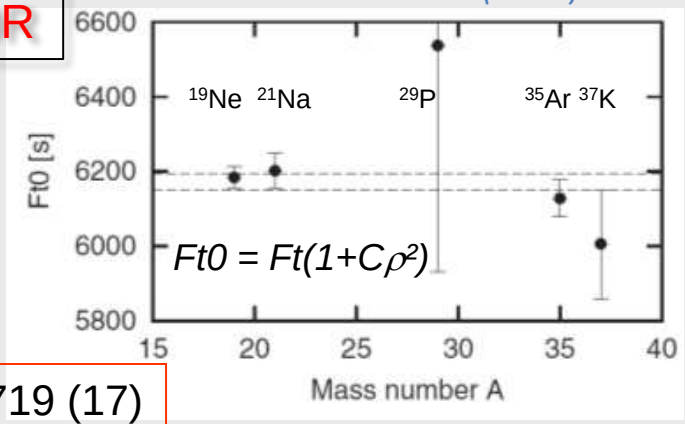
Final goals:

- Improve theoretical corrections
- Cross-check mirror vs pure Fermi
- Overall analysis → higher precision, best constraint

Mirror transitions vs Pure Fermi (PF) transitions

MIRROR

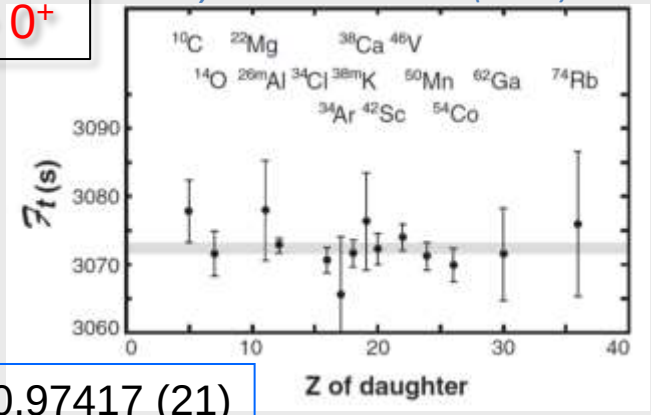
Naviliat et al. PRL102(2009)



V_{ud} = 0.9719 (17)

$0^+ \rightarrow 0^+$

Hardy & Towner PRC91(2015)



V_{ud} = 0.97417 (21)

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

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

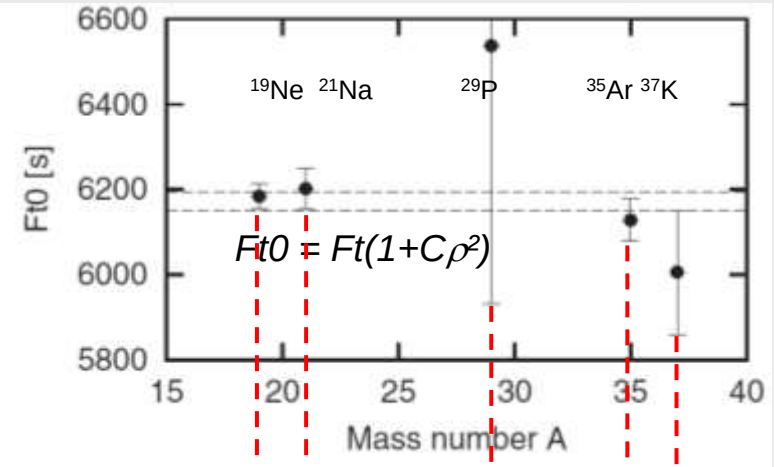
$$(Ft)^{mirror} = f_V t_{1/2}(1+\delta_R)(1+\delta_{NS}-\delta_C) = \frac{2K}{V_{ud}^2(1+\Delta_R)(1+\frac{f_A}{f_V}\rho^2)}$$

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

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

Mirror transitions: status

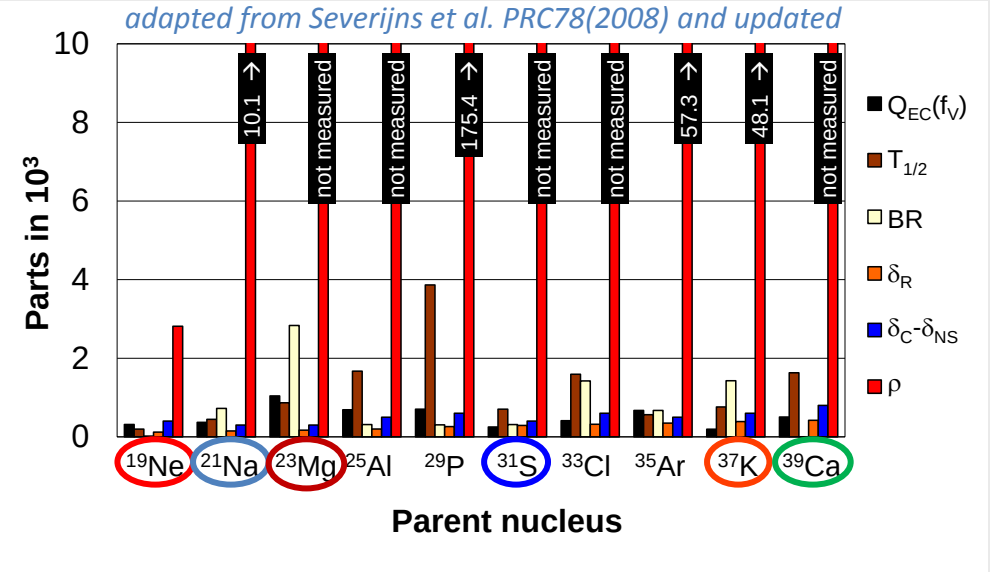
Naviliat et al. PRL102(2009)



ρ from *A* *a* *A* *A* *B*

(1975) (2008) (1990) (88-93) (2007)

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



^{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)*

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

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

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

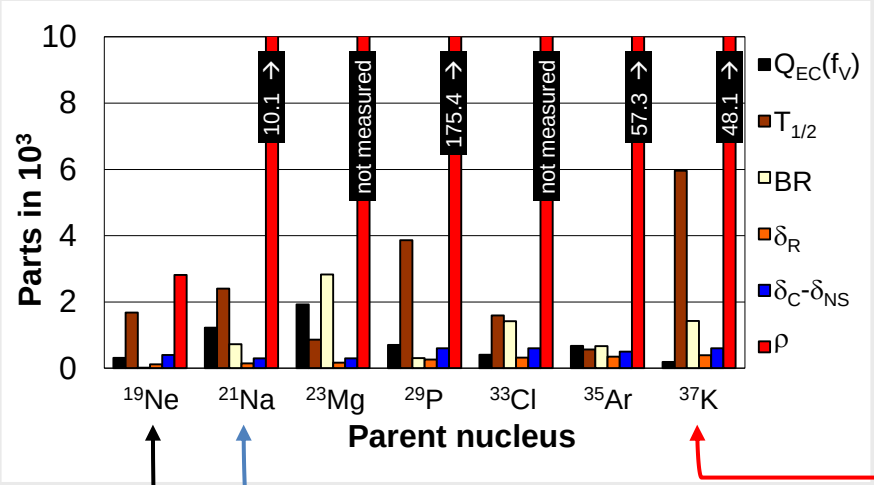
ρ = GT/F :

- the least or even not known quantity !
- precisely determined from correlation measurements

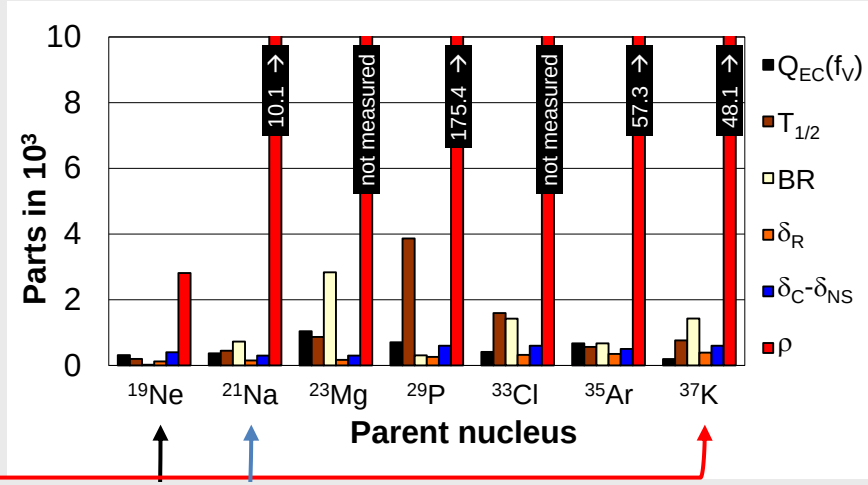
The scientific community is now involved in this field...

Update of data in 2015: *M*, $T_{1/2}$, *BR*

2009 *Naviliat et al. PRL102(2009)*



2015



$T_{1/2}(^{37}K)$: *Shidling et al. PRC90(2014)* → gain of a factor 7.8

$Q(^{21}Na)$: *Mukherjee et al. EPJA35(2008)* → gain of a factor 3.3

$T_{1/2}(^{21}Na)$: *Grinyer et al. PRC91(2015)* → gain of a factor 5.4

$T_{1/2}(^{19}Ne)$: *Broussard et al. PRL112(2014)* → gain of a factor 8.5

should change V_{ud} "mirror" value….

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

Update of data in 2015: *M*, $T_{1/2}$, *BR*

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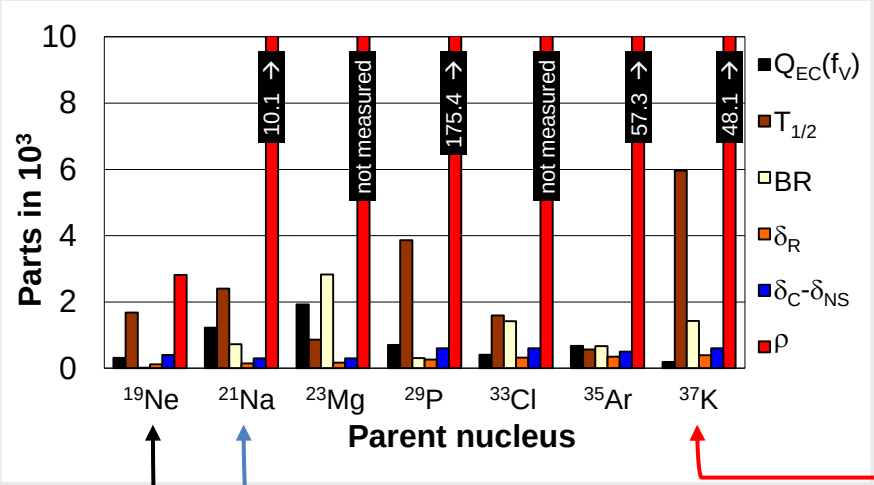
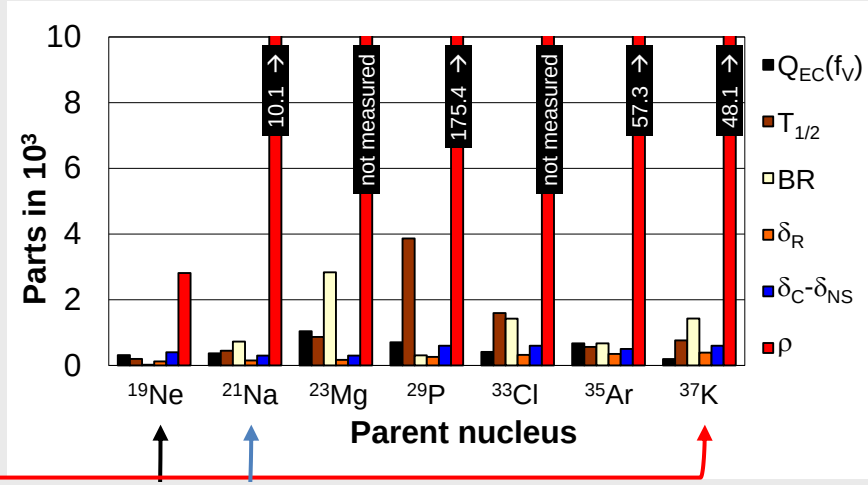


2015



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should change V_{ud} "mirror" value….

V_{ud} (2009) = 0.9719 (17) → V_{ud} (2015) = 0.9717 (17) !!

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

- ρ precisely determined from correlation measurements

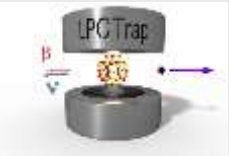
$$a_m = \frac{(1-\rho^2/3)}{(1+\rho^2)} \qquad A_m = \frac{\rho^2 - 2\rho\sqrt{J(J+1)}}{(1+\rho^2)(J+1)}$$

Severijns & Naviliat PST152(2013)

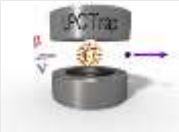
a or A @ 0.5% ?

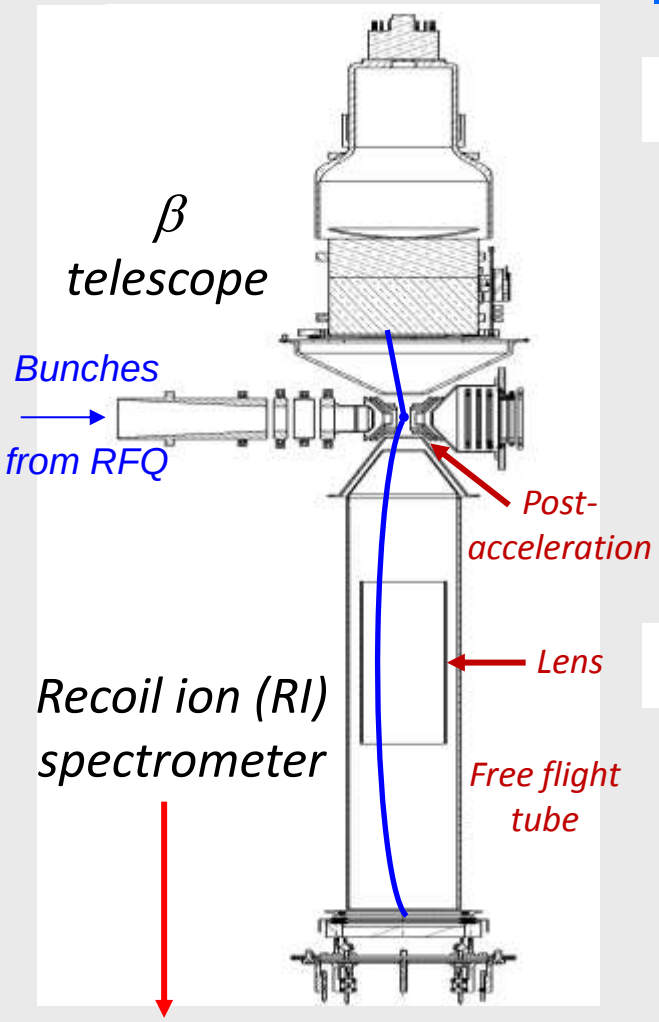
Parent nucleus	ΔV_{ud}	a $(\Delta V_{ud})^{\text{limit}}$	a Factor $\Delta\mathcal{F}t$	ΔV_{ud}	A $(\Delta V_{ud})^{\text{limit}}$	A Factor $\Delta\mathcal{F}t$
^{3}H	0.0011	0.0010	2.1	0.0011	0.0009	2.3
^{11}C	0.0025	0.0016	4.0	0.0207	0.0207	0.3
^{13}N	0.0017	0.0017	1.0	0.0123	0.0123	0.1
^{15}O	0.0020	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

A part of job could be achieved with LPCTrap….



The LPCTrap setup





- *Decay source confined in a transparent Paul trap*

Ban et al. ADP525 (2013)

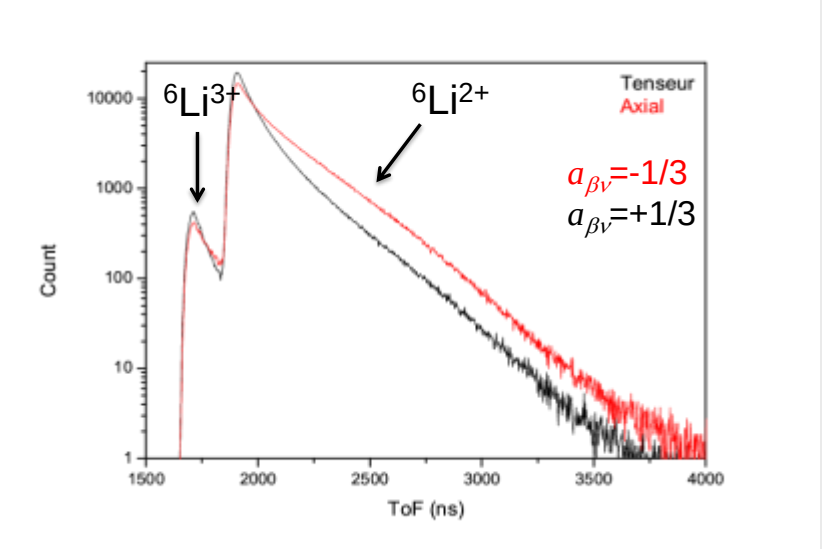
bunches

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

- *Parameters*
  - *β* energy
  - *β* position
  - recoil ion ToF
  - recoil ion position

  + timestamp in cycle & trap RF phase

Simulation for $^{6}He^{+}$ decay (GT)



- *BG suppression*
- *Control of systematic effects*

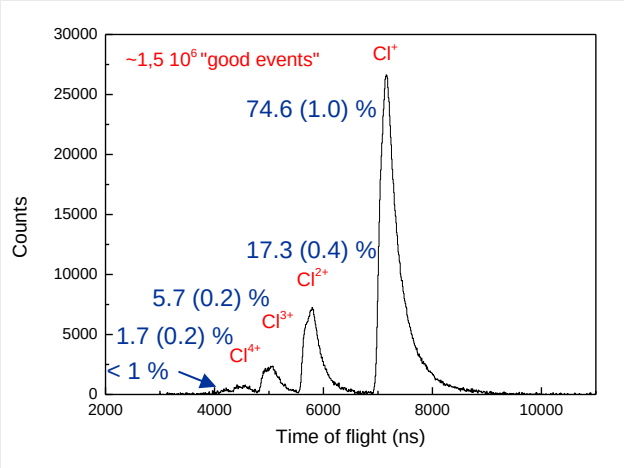
Update of "mirror" data in 2015: ρ ?

LPCTrap @ GANIL (LIRAT)

- Measurements of $a_{\beta\nu}$ and shakeoff probabilities in decay of $^{35}Ar^{1+}$ & $^{19}Ne^{1+}$

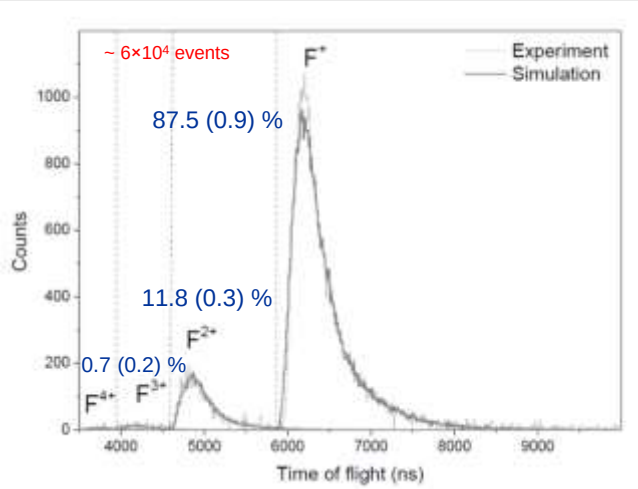
Ban et al. ADP525 (2013)

2011-2012: ^{35}Ar



Shakeoff: Couratin et al. PRA (2013)

2013: ^{19}Ne



Analysis of data in progress (development of new simulation tools…)

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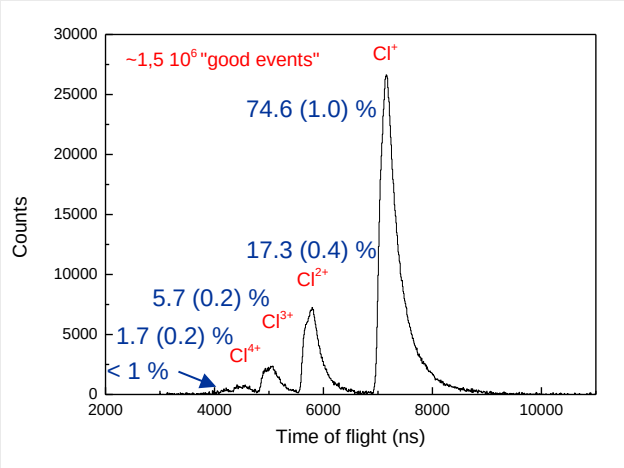

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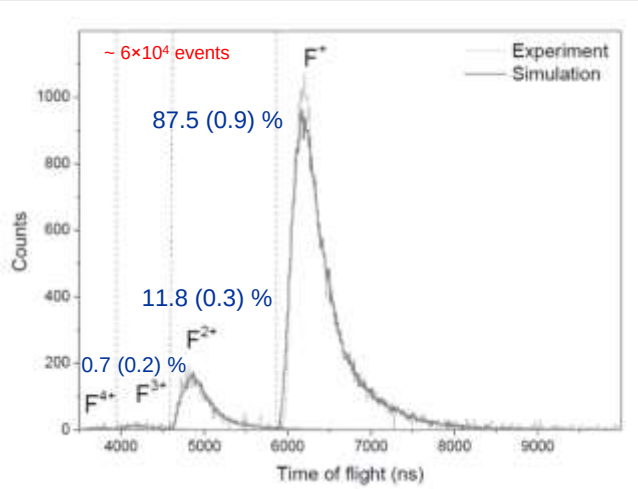


Analysis of data in progress (development of new simulation tools…)

- Expected results ($\Delta a / a$) : *~ 0.25 %* *~ 18 % (a ~ 0...)*
- Factor gained on $\Delta\rho / \rho$: *~ 4.5* *~ 1*

$\Delta V_{ud} / V_{ud}$ (2009) = 1.7×10^{-3} ⟶ $\Delta V_{ud} / V_{ud}$ (expected) = 9.7×10^{-4} !!

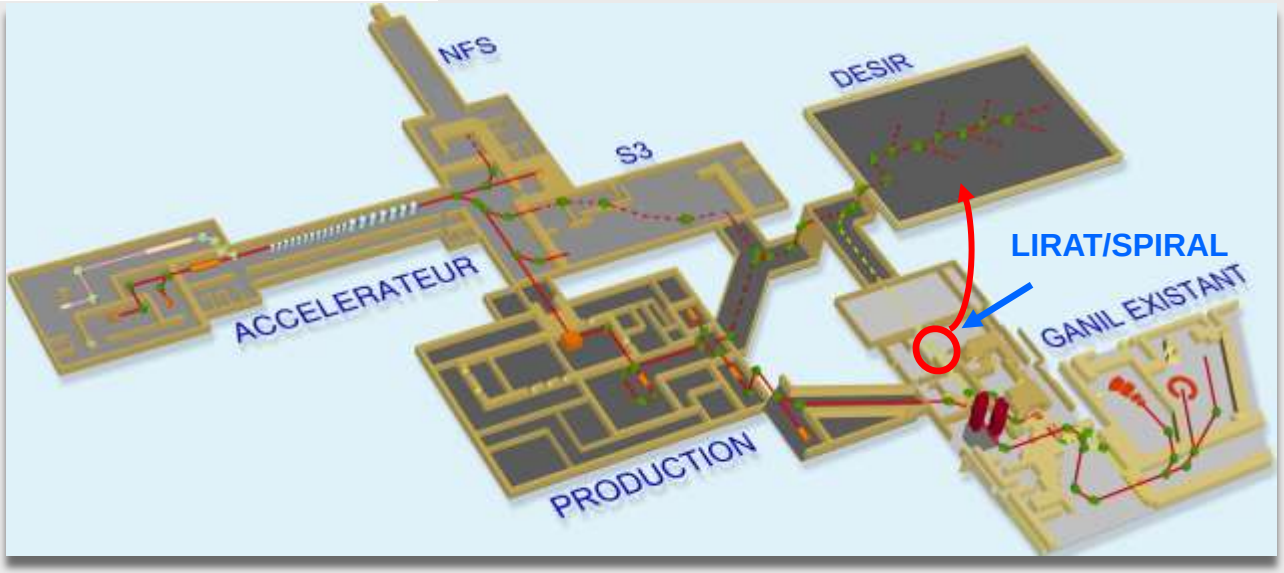
Future @ GANIL ?

- *Development of new beams @ SPIRAL*

Ion	$T_{1/2}$ (s)	Expected rate (pps)
^{21}Na	22.49	1.8E+08
^{23}Mg	11.32	4.3E+07
^{33}Cl	2.51	1.8E+07
^{37}K	1.22	1.1E+07

- Contact: Pierre Delahaye
- Available in 2017 ?

- *DESIR @ SPIRAL2 φ1+* (LoI 2011, 2014)



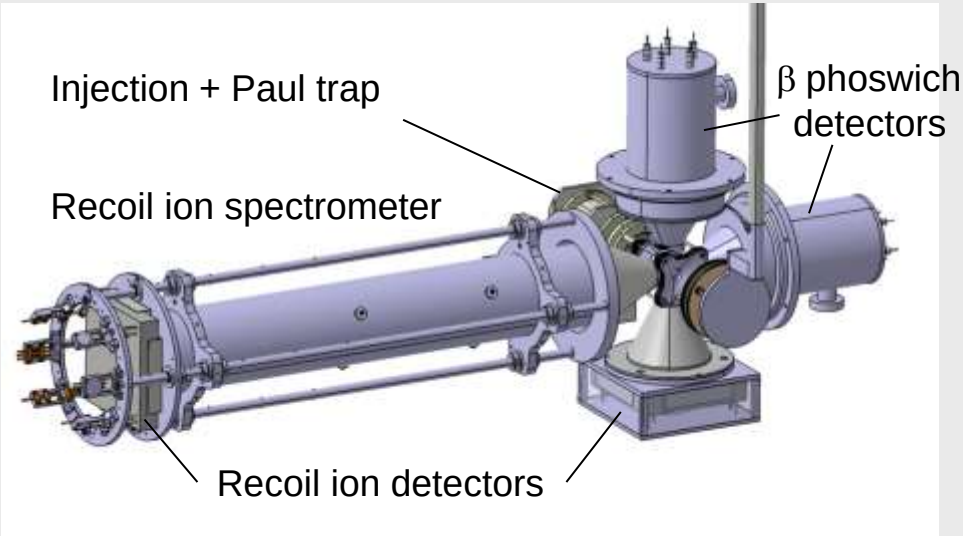
- In 2019 ?

What can we expect from *a* measurements ?

- Ion with rate > 1E+07 pps

Ion	$T_{1/2}$ (s)	Expected rate (pps)	Expected nb of coinc.	Estimated $a \pm \sigma_a$	New $\rho \pm \sigma_\rho$	Gain factor
^{21}Na	22.49	1.8E+08	1.7E+06	0.5587(18)	-0.7041(20)	3.6
^{23}Mg	11.32	4.3E+07	8.1E+05	0.6967(26)	0.5426(30)	new
^{33}Cl	2.51	1.8E+07	1.5E+06	0.8848(19)	0.3075(27)	new
^{37}K	1.22	1.1E+07	1.9E+06	0.6580(17)	0.5872(19)	14.2

- Estimation of coinc. (1 week):
  - Based on ^{35}Ar experiment
  - $T_{1/2}$ taken into account
  - LPCTrap → LPCTrap2
    - phoswich for β detection
    - detectors number X 2
    - FASTER DAQ system



➡ Gain in stat: factor of ~ 4

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- Error estimation on *a* :
  - Based on ^{6}He experiment
  - $\sigma_{stat} = \sigma_{syst}$

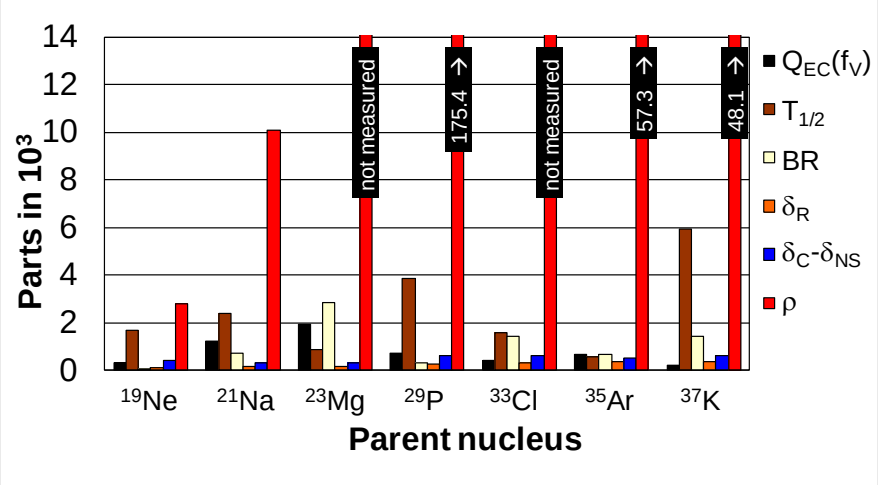
Fléchard et al. JPG38(2011)

$\rho^2 = (1-a)/(a+1/3)$
with a = "a_{SM}" *Severijns et al. PRC78(2008)*
+ combination with existing results

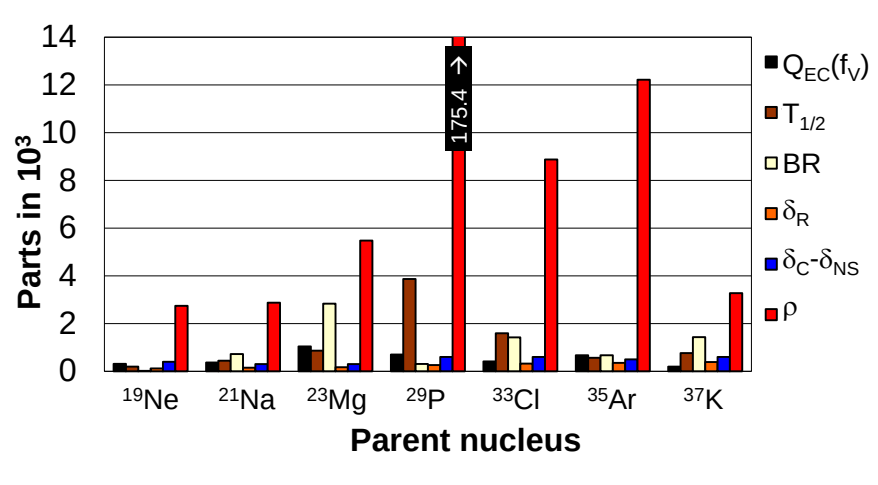
➡ Gain in stat: factor of ~ 4

What can we expect from *a* measurements ?

2009



LPCTrap2 @ GANIL

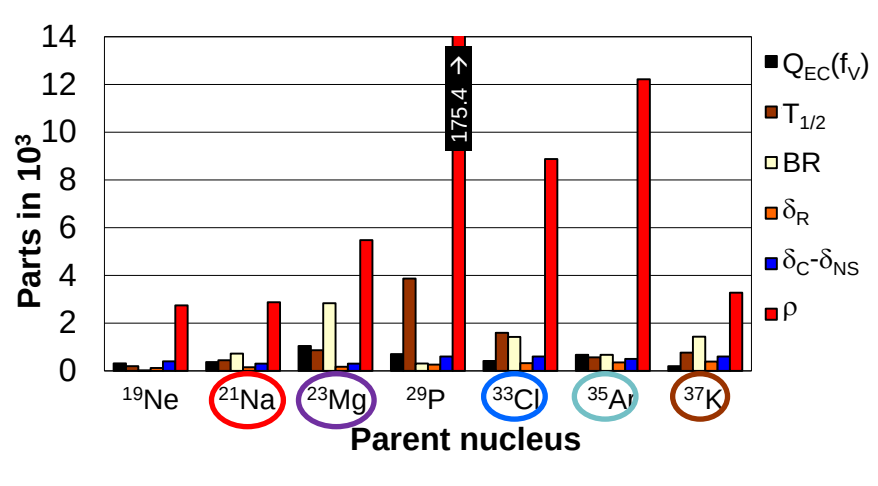


$\Delta V_{ud} / V_{ud} = 1.7\times10^{-3}$ ⇒ $\Delta V_{ud} / V_{ud} = 6\times10^{-4}$

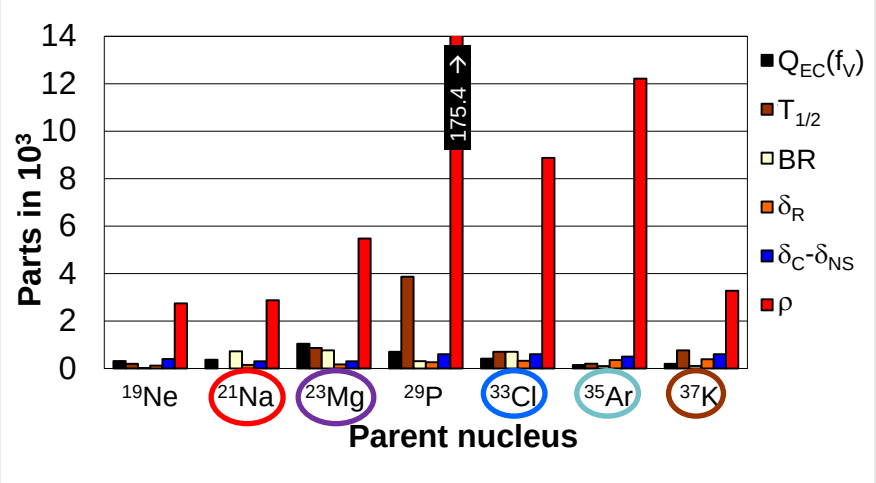
- Gain: factor of 2.8
- To be compared to $\Delta V_{ud} / V_{ud} = 2.2\times10^{-4}$ from pure Fermi

What can we expect from *a*, $T_{1/2}$, *BR* & *M* measurements ?

LPCTrap2 @ GANIL



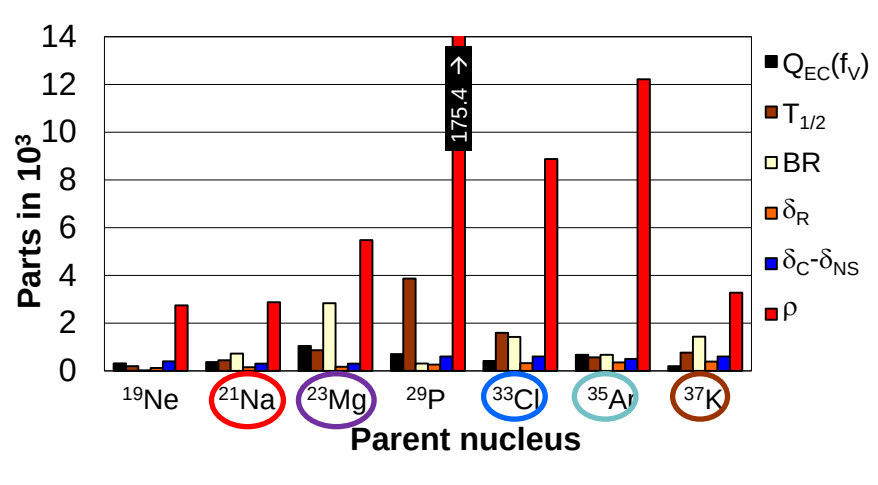
+ $T_{1/2}$, BR & M improvements



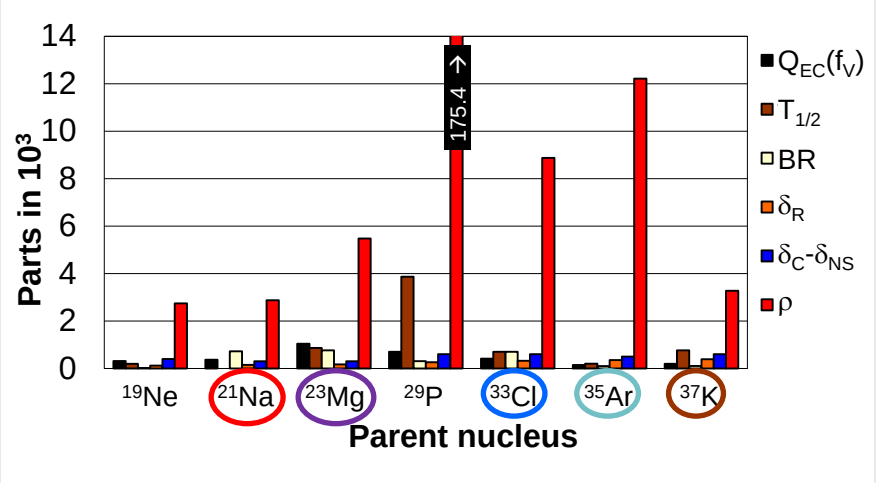
- ^{21}Na, expected gain: 2.5 ($T_{1/2}$) *Finlay et al. @ TRIUMF 2014*
- ^{23}Mg, expected gain: 3.7 (*BR*) *Blank et al. @ JYFLTRAP 2013*
- ^{33}Cl, expected gain: 2.2 ($T_{1/2}$), 2 (*BR*) *Kurtukian et al. @ SPIRAL1 ?*
- ^{35}Ar, expected gain: 2.8 ($T_{1/2}$), 6.6 (*BR*), 4.7 (*M*) *Finlay et al. @ TRIUMF 2015 ?*
- ^{37}K, expected gain: 14 (*BR*) *Kurtukian et al. @ ISOLDE 2014*

What can we expect from a, $T_{1/2}$, BR & M measurements ?

LPCTrap2 @ GANIL



+ $T_{1/2}$, BR & M improvements

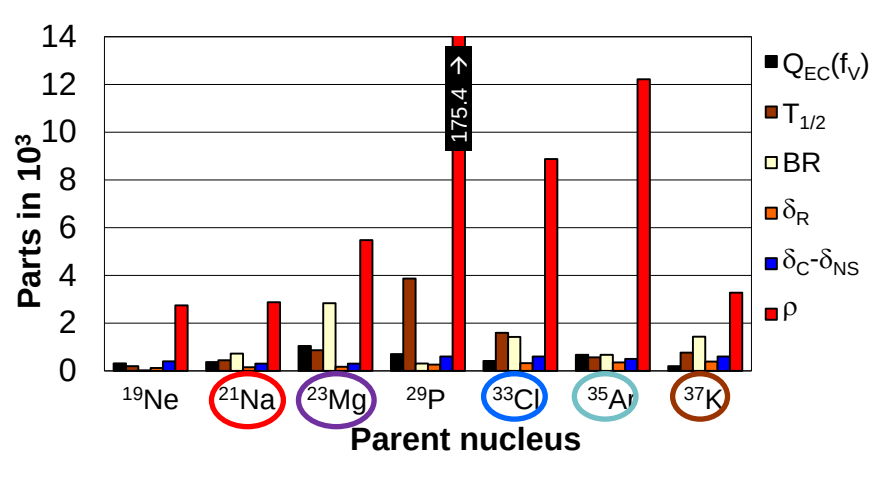


$\Delta V_{ud} / V_{ud} = 6\times10^{-4}$ ⇨ $\Delta V_{ud} / V_{ud} = 5\times10^{-4}$

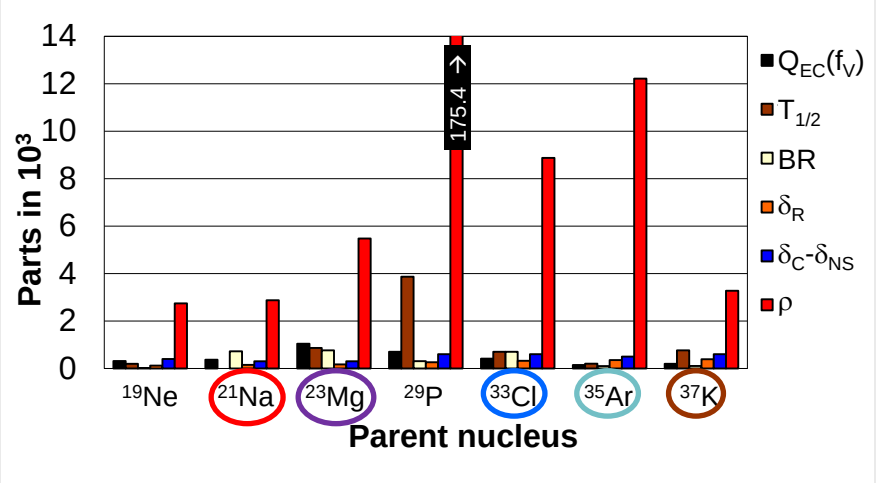
- Gain of a factor 1.2
- To be compared to $\Delta V_{ud} / V_{ud} = 2.2\times10^{-4}$ from pure Fermi
- Best cases: ^{35}Ar, ^{33}Cl and ^{37}K

What can we expect from a, $T_{1/2}$, BR & M measurements ?

LPCTrap2 @ GANIL



+ $T_{1/2}$, BR & M improvements



$\Delta V_{ud} / V_{ud} = 6\times10^{-4}$ ⇨ $\Delta V_{ud} / V_{ud} = 5\times10^{-4}$

- Gain of a factor 1.2
- To be compared to $\Delta V_{ud} / V_{ud} = 2.2\times10^{-4}$ from pure Fermi
- Best cases: ^{35}Ar, ^{33}Cl and ^{37}K

with only these 3 cases: $\Delta V_{ud} / V_{ud} = 5.6\times10^{-4}$
^{33}Cl, ^{37}K: good candidates for first experiments

Precision measurements in mirror decays to probe *CP* violation

• CP violation: status

- 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
- *D* correlation probes a region less accessible to n-EDM
- Current best results in nuclear decays:

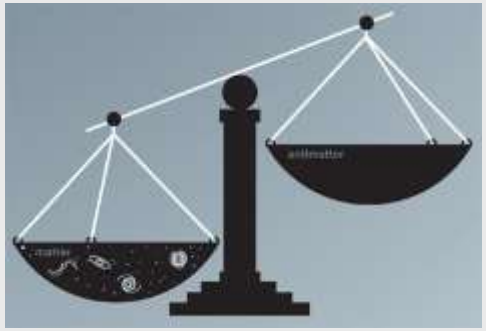
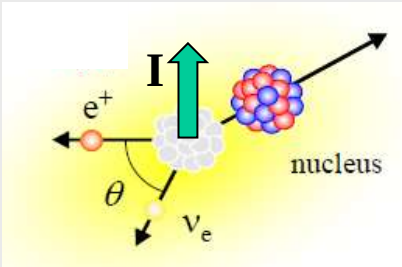


Illustration: Sandbox Studio

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

n decay → $D = (-0.94 \pm 1.89 \pm 0.97)\ 10^{-4}$ *Mumm et al. PRL 107 (2011), Chupp et al. PRC 86 (2012)*

• CP violation: *D* measurement



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

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

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

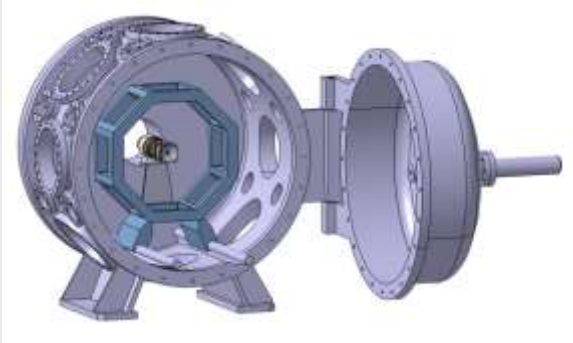
- $D \neq 0$ → $\rho \neq 0$
  → Mirror decay !

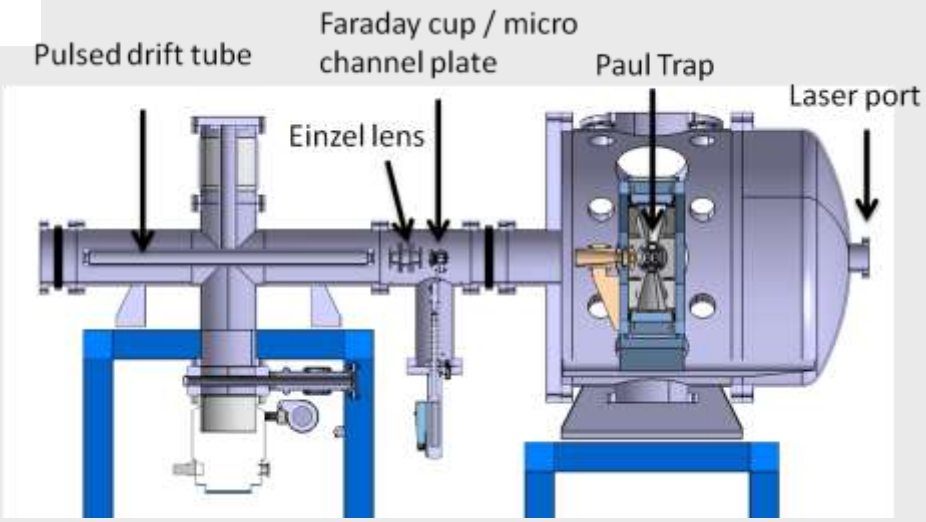
LPCTrap ?

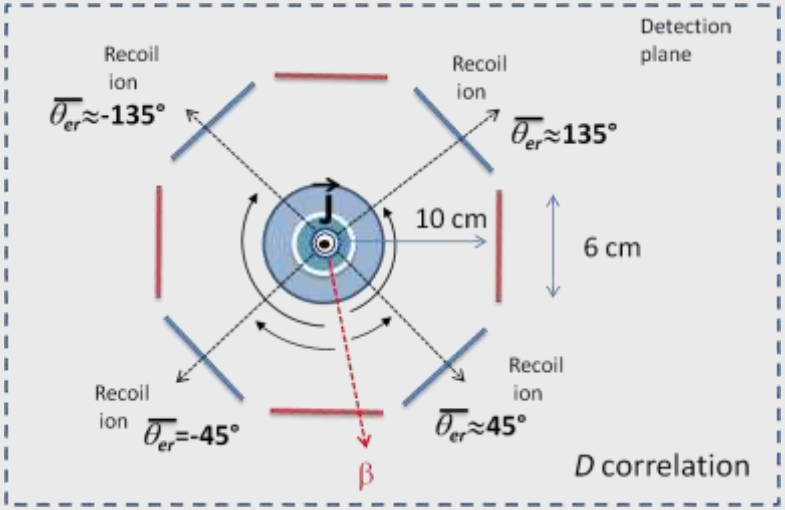
New SPIRAL beams…

Further development: cloud polarization from optical pumping

- New chamber, lasers & detectors







- Upgrade of the detector setup :
  → *arrangement of 8 detector modules*
- Lasers provided by COLLAPS (ISOLDE) or LUMIERE (DESIR)
- Interesting beams: ^{23}Mg, ^{39}Ca

"Winningmotions" project (Weak Interaction Novel INvestiGations Measuring the Orientation of Trapped IONS)

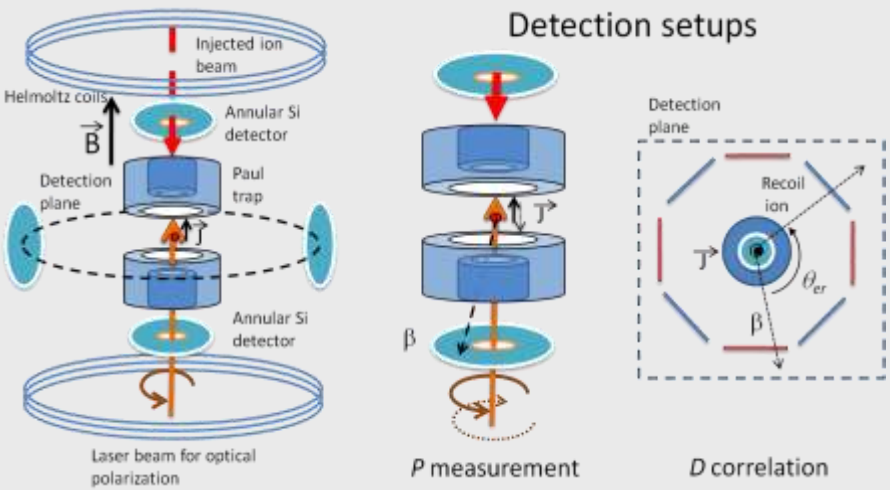
"Winningmotions" project

Coordinator: P. Delahaye
Labs involved: GANIL, IPNL, LPC Caen, IKS Leuven, ISOLDE, U Manchester, MPIK Heidelberg

- ^{23}Mg = "good" candidate
  - Ion cloud polarized by lasers (COLLAPS or LUMIERE)
  - High degree of polarization expected (~ 100%) and continuously measured through A_β (precisely known in many decays *Severijns et al. PRC78(2008)*)
  - Tests & 1st measurements @ ISOLDE, improved measurement @ DESIR
  - Results expected in 1 week:

    ISOLDE: $\sigma_D < 6\times10^{-4}$

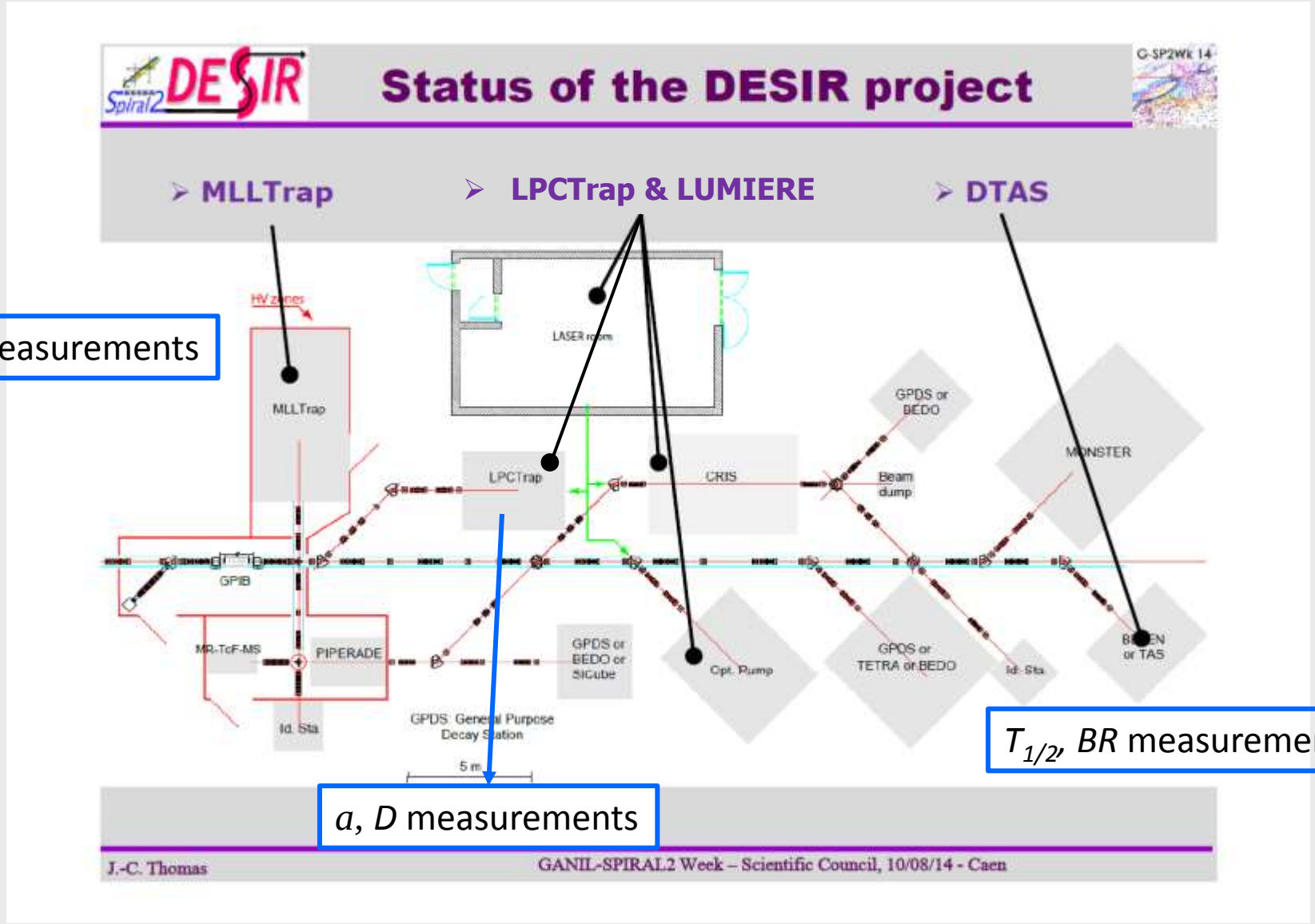
    DESIR: $\sigma_D < 2\times10^{-4}$



- A factor > 3 better than current result (^{19}Ne)
- At the level of the D_{FSI} value → first test for such calculation
- Final aim: $\sigma_D < 1\times10^{-4}$ / Future candidate: ^{39}Ca

Isotope	D_{FSI}
^{23}Mg	-1.3×10^{-4}
^{39}Ca	4.7×10^{-5}

DESIR layout (draft version)



Complete installation to measure $T_{1/2}$, BR, M, a and D

Conclusion

- High precision measurements in nuclear β decays
  - Sensitive tool to test the Standard Model, complementary to high energy physics
  - Information hidden in correlations
  - Development of traps for nuclear physics
    - clean radioactive sources
    - clean environment for correlations measurements

- Development of new beams @ GANIL → measurements in mirror decays
  - Short term plan: measurements of "a" at LIRAT & DESIR with LPCTrap2 using the new beams provided by SPIRAL (^{21}Na, ^{23}Mg, ^{33}Cl, ^{37}K)
    - required to improve ρ & V_{ud} deduced from mirror transitions
    - with M, T & BR improvements → "only" a factor 2.3 worse than "pure" Fermi
    - ^{33}Cl & ^{37}K : good candidates for first experiments
  - Longer term plan: measurement of the triple correlation D in ^{23}Mg decay
    - cloud polarization with laser in LPCTrap of second generation
    - first tests @ ISOLDE, final experiments @ DESIR
    - final aim: $\sigma_D < 1\times10^{-4}$ / search for new sources of CP violation

Thank you …

LPC Caen:

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Xavier Fabian
Xavier Fléchard
Etienne Liénard
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Gilles Quéméner

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Baptiste Fabre

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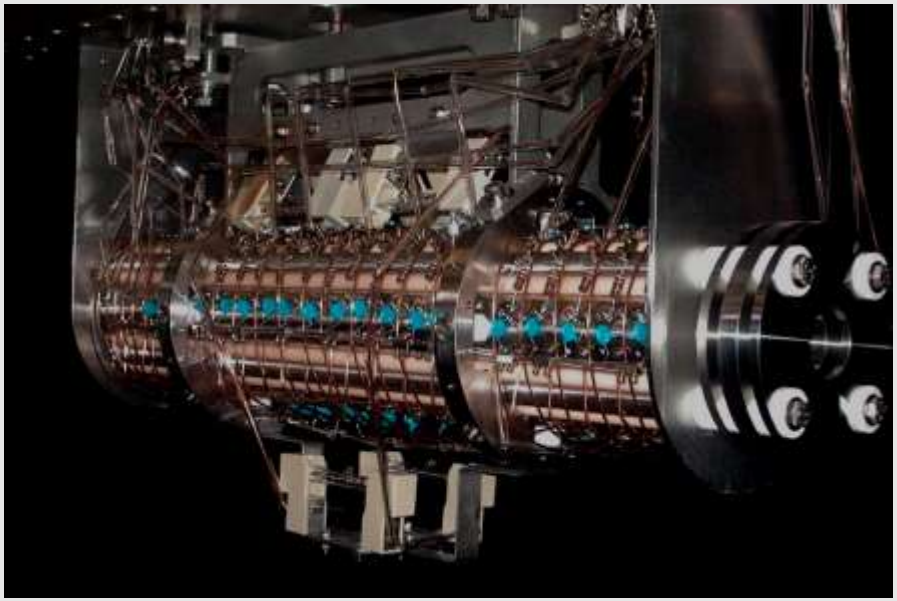
IKS KUL: Claire Couratin
Paul Finlay
Tomica Porobic
Nathal Severijns
Philippe Velten



and the LPC & GANIL technical staffs ….