THE MORA PROJECT

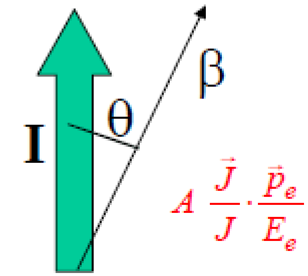
Matter's Origin from the RadioActivity of trapped and laser oriented ions

Pierre Delahaye for the MORA collaboration

β-decay as a laboratory for weak interaction

Review: Prog. Part. Nucl. Phys, M. Gonzalez Alonso, O. Naviliat Cuncic and N. Severijns, 2018

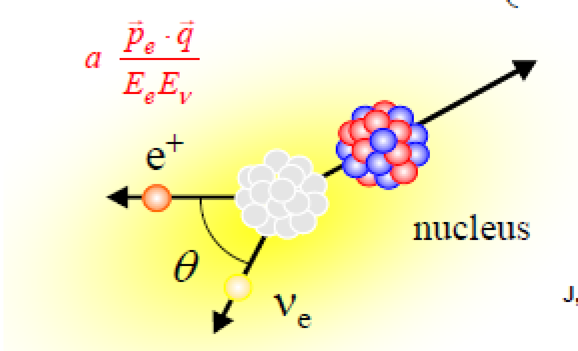
$$\omega\left(\langle \vec{J}\rangle \mid E_e, \Omega_e, \Omega_\nu\right) dE_e\, d\Omega_e\, d\Omega_\nu$$



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

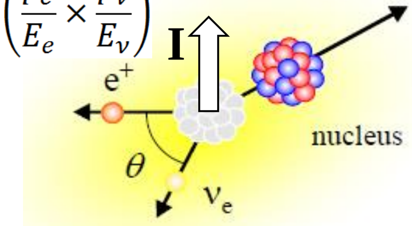
$$\times\ \xi\ \left\{1 + a\frac{\vec{p}_e\cdot\vec{q}}{E_e E_\nu} + b\frac{\gamma m_e}{E_e} + A\frac{\vec{J}}{J}\cdot\frac{\vec{p}_e}{E_e} + D\frac{\langle\vec{J}\rangle}{J}\cdot\left(\frac{\vec{p}_e}{E_e}\times\frac{\vec{p}_\nu}{E_\nu}\right) + \dots\right\}$$

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

$$D\frac{\langle\vec{J}\rangle}{J}\cdot\left(\frac{\vec{p}_e}{E_e}\times\frac{\vec{p}_\nu}{E_\nu}\right)$$

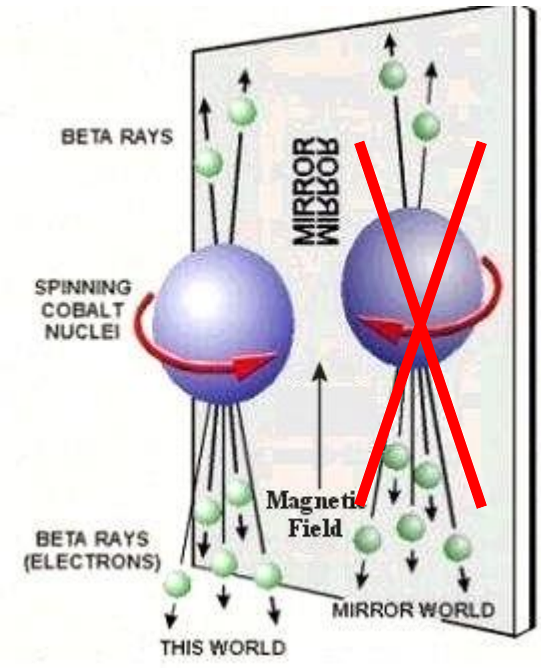


Correlations in nuclear β decay

Coupling constants of the β decay Hamiltonian: C_V, C_A and C_S, C_T

β-decay as a laboratory for weak interaction

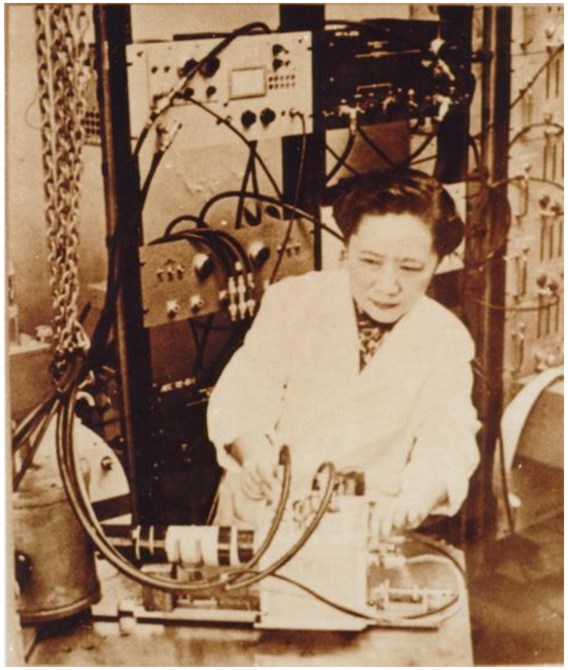
- Probing intrinsic symmetries



Parity violation in ^{60}Co decay

- *Polarized nuclei*

C. S. Wu et al., Phys Rev 105(1957)1413



$$A_\beta \frac{\langle \vec{J} \rangle}{J} \cdot \frac{\overrightarrow{p_e}}{E_e}$$

P odd

$A_\beta\,(C_A^2, C_V C_A)$

β-decay as a laboratory for weak interaction

Review in Prog. Part. Nucl. Phys, M. Gonzalez Alonso, O. Naviliat Cuncic and N. Severijns, 2018

- EFT analysis gives direct comparison between high energy searches and beta decay
- Example: Sensitivity to NP: **Scalar** and **Tensor** current limits from LHC and beta decays

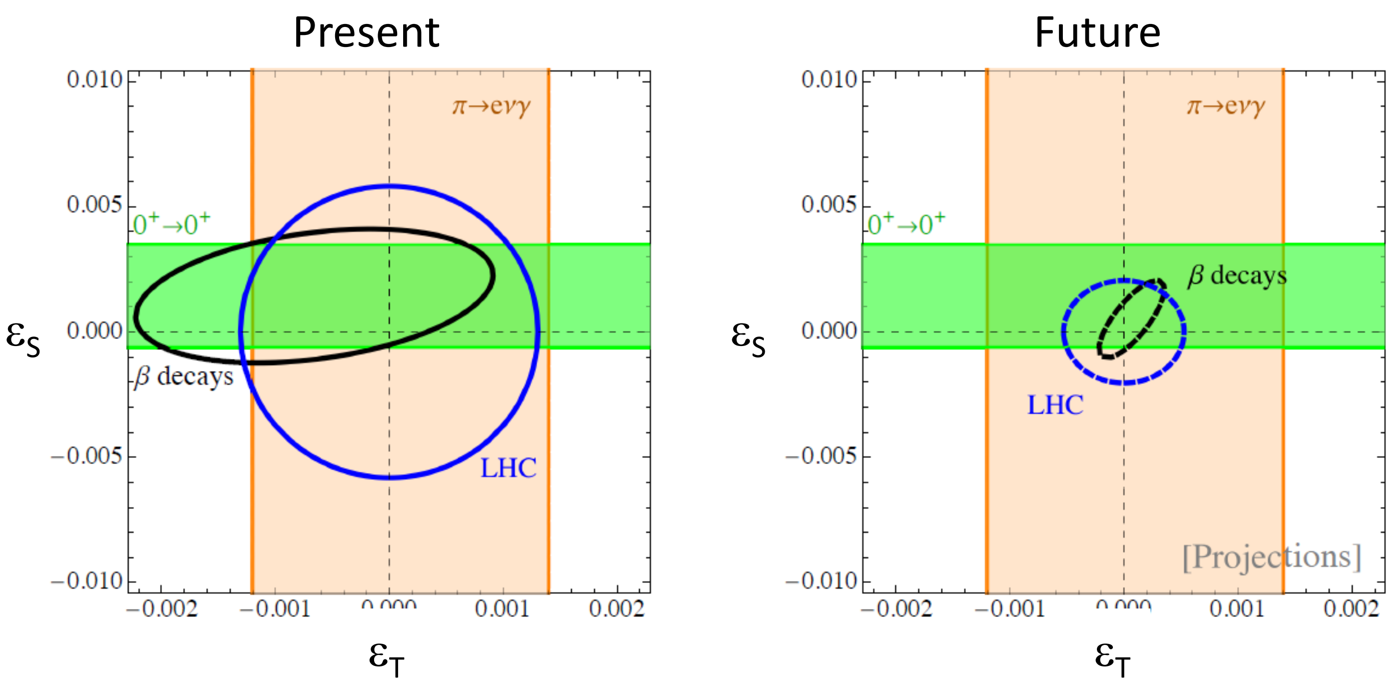


Figure 14: (Left) 90% CL constraints on $\epsilon_{S,T}$ at $\mu = 2$ GeV from β-decay data, *cf.* Eq. (87), with $\Delta\chi^2 = 4.61$, (black ellipse), from the analysis of $pp \to e + \text{MET} + X$ at the 8-TeV LHC (20 fb^{-1}) [12] (blue ellipse), and from radiative pion decay, *cf.* Eq. (118) [23] (orange band). The green band shows the 90% CL bound ($\Delta\chi^2 = 2.71$) using only superallowed Fermi decays. (Right) Same figure but using projected β-decay data, *cf.* Eq. (100) (black) and projected LHC bounds from $pp \to e + \text{MET} + X$ searches with 14 TeV and 300 fb^{-1} [23] (blue).

ε_S and ε_T : relative couplings of scalar and tensor currents vs V-A currents

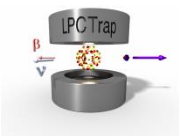
β-decay as a laboratory for weak interaction

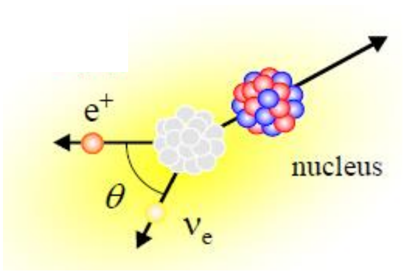
• *Unpolarized nuclei*

- Recoil detection
- β - recoil coincidences

$$a_{\beta\nu}\frac{\vec{p_e}}{E_e}\cdot\frac{\vec{p_\nu}}{E_\nu}$$

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 even

Search for exotic currents

• *Polarized nuclei*

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

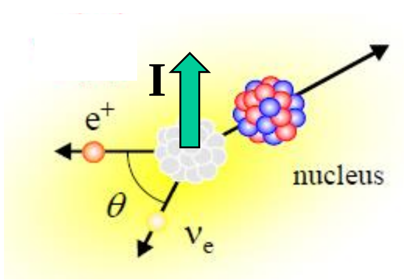
$$D\frac{\langle\vec{J}\rangle}{J}\cdot\left(\frac{\vec{p_e}}{E_e}\times\frac{\vec{p_\nu}}{E_\nu}\right)$$

Triple correlation

The MORA project!

THE MORA PROJECT

MATTER'S ORIGIN FROM RADIOACTIVITY



$D \propto \mathrm{Im}\,(C_V C_A^*)$

$D = 0$ (SM)

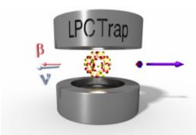
T odd

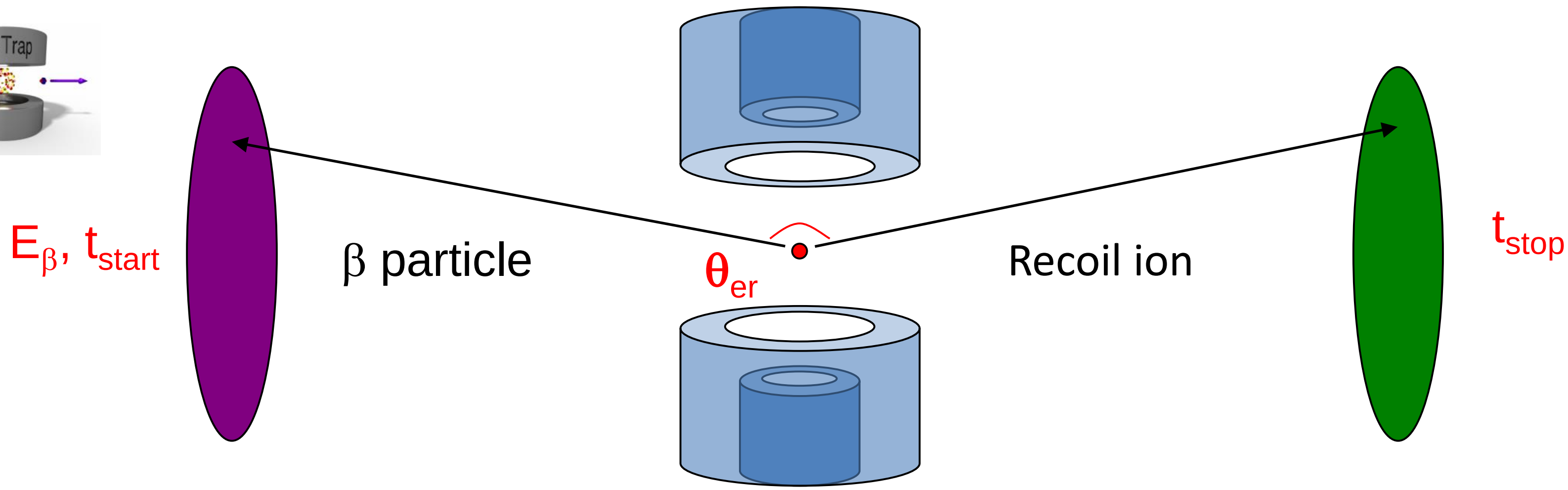
Search for new sources of CP violation

LPCTrap: a Paul trap based precision experiment

$$a_{\beta\nu}\frac{\overrightarrow{p_e}}{E_e}\cdot\frac{\overrightarrow{p_\nu}}{E_\nu}$$

- **Transparent Paul trap, UHV**
- **Ions confined in the middle of the device, nearly at rest**
- **In coincidence detection of the electron and the recoil ion**





Beta telescope
Silicone stripped detector
+ Scintillator

MCP
Delay lines anode

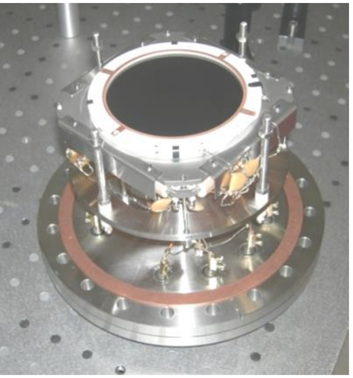
E. Liénard et al., Hyp. Int. 236 (2015) 1 and references therein.

In coincidence measurement of:

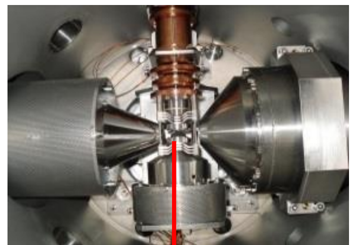
- the time of flight of the recoil ion t_R
- the beta particle energy E_β
- the angle between these two particles θ_{er}

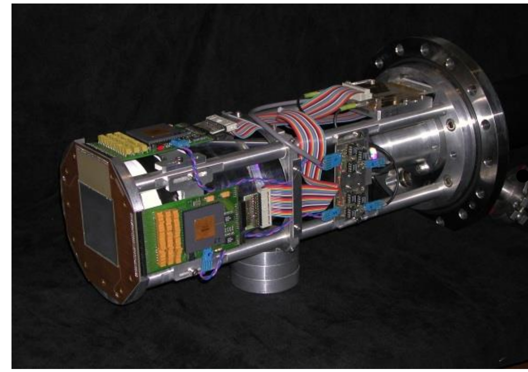
Trap and detection setup

G. Ban et al, ADP 525(2013)576 , E. Liénard et al., Hyp. Int. 236 (2015) 1 and references therein.

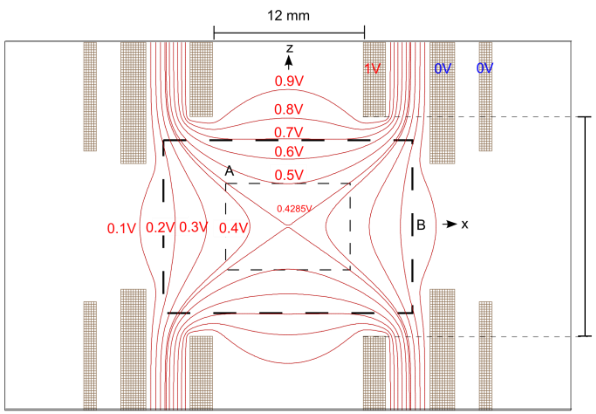


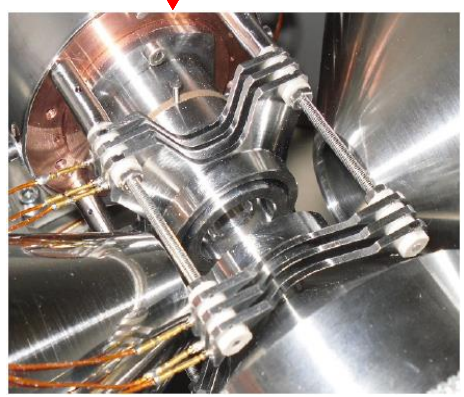
- MCP
  Active Ø80 mm
  σ_T ~ 200ps
- Delay lines
  σ_x, σ_y ~ 200μm
  E. Liénard et al. NIMA 551(2005)

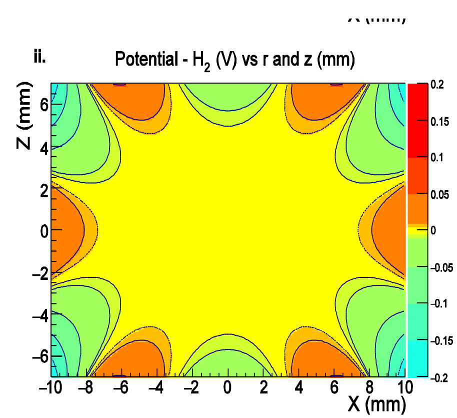




- DSS Si Detector
  60 x 60mm x 300μm
  1 mm resolution
- Plastic scintillator
  σ_E 10 % at 1 MeV
  σ_T ~ 200ps







- Trap
  Effective trapping radius 5mm

P. Delahaye et al, The open LPC Trap for precision measurements in beta decay, Eur. Phys. J. A (2019) 55: 101

Results of LPCTrap

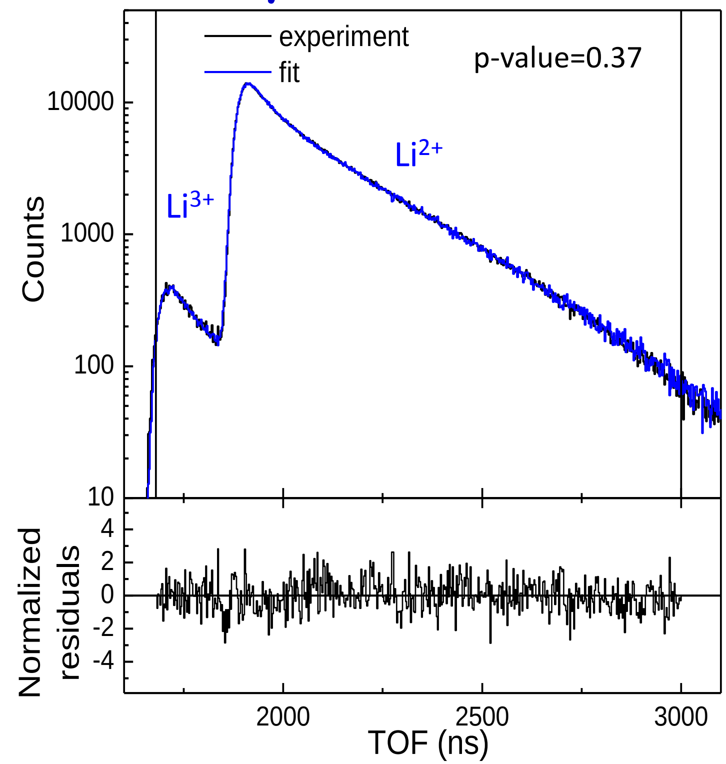
- $a_{\beta\nu}$ measurement for different nuclei
  - Analysis ongoing within « THESMOG »

RÉGION NORMANDIE

  - New constraints on $|C_T|/|C_A|$ from ^{6}He decay
  - Improvements on $\sigma(V_{ud})$ / V_{ud} from mirror decays of ^{35}Ar and ^{19}Ne

- Shake – off probabilities and precise tests of atomic physics models

^{6}He decay *Couratin et al., PRL108 (2012)*



Nucleus	Date	*a*	σ_{stat}	σ_{syst}	Published results
^{6}He	2006	-0.3335	0.0073	0.0075	σ_a /a ~ 3% Fléchard et al. JPG38 (2011)
	2010	-1/3 (SM)	0.0015	?	Shakeoff Couratin et al. PRL108 (2012)
^{35}Ar	2011	/	/	/	Shakeoff Couratin et al. PRA88 (2013)
	2012	0.9004 (SM)	0.0013	?	
^{19}Ne	2013	0.0438 (SM)	0.0046	?	Shakeoff Fabian et al. PRA97(2018)

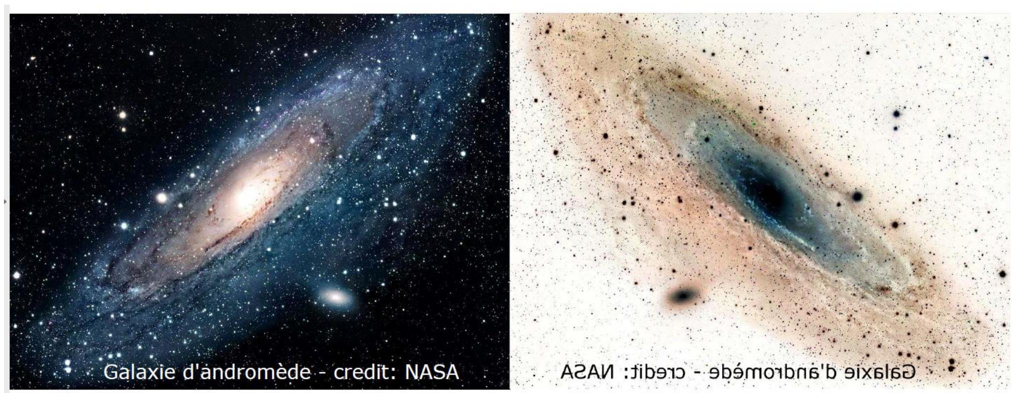
1

Precision measurement of the triple correlation *D*

$$D\,\frac{\langle\vec{J}\rangle}{J}\cdot\left(\frac{\overrightarrow{p_e}}{E_e}\times\frac{\overrightarrow{p_\nu}}{E_\nu}\right)$$

A non-zero *D* can arise from CP violation

- CP violation observed in the K and B - meson decays is not enough to account for the large matter – antimatter assymetry
- T-odd correlations in beta decay (*D* and *R*) and n-EDM searches are sensitives to larger CP violations by 5 to 10 orders of magnitude



See P. Herczeg, Prog. Part. Nucl. Phys. 46 (2001) 413.

Below 10^{-4}, Final State Interactions mimic a non zero correlation

***D* correlation measurement to the 10^{-5} level with some beam, laser and trapping R&D**

- Best measurement so far $D_n<2\ 10^{-4}$
- Complementary probe to search for New Physics with nEDM and LHC searches
- First approach /probe of D_{FSI}

Sensitivity to NP

- *D* correlation measurements in neutrons and nuclei
  - Best limits on T-violating phase $Im(C_V/C_A)$
    - neutron decay, D_n= (−0.94 ±1.89±0.97) 10^{-4} → $Im(C_V/C_A)$<(1.6±6.3)×10^{-4}

      emiT collaboration, PRL 107, 102301 (2011), Phys. Rev. C 86 (2012) 035505

      O. Naviliat-Cuncic and M. Gonzalez-Alonso, Ann. Phys. (Berlin) 525 (2013) 600.
    - ^{19}Ne decay, ***D*=0.0001 ±0.0006**, **limited by statistics**

      Calaprice et al, Hyp. Int. 22 (1985) 83
  - Sensitivities depends on the transition $D_X = F(X) \times Im(C_V/C_A)$

    J. D. Jackson S. B. Treiman and H. W. Wyld, Jr, Nucl. Phys. 4 (1957) 206.
  - Final State Interactions as well

    J. C. Brodine Phys Rev D1(1970)1

	n	^{19}Ne	^{23}Mg	^{39}Ca
F(X)	-0.55	0.66	0.82	-0.90
D_{FSI}	1.2×10^{-5}	1.5×10^{-4}	1.2×10^{-4}	-3×10^{-5}

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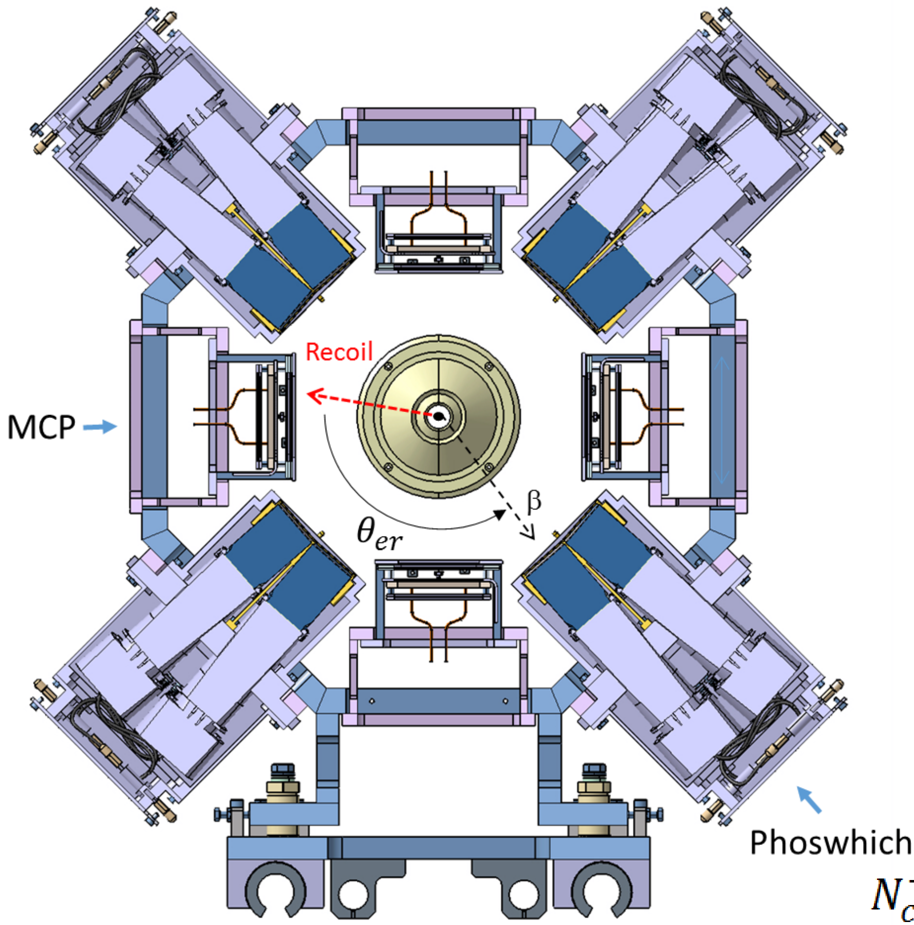
^{23}Mg and ^{39}Ca can be laser polarized as ions

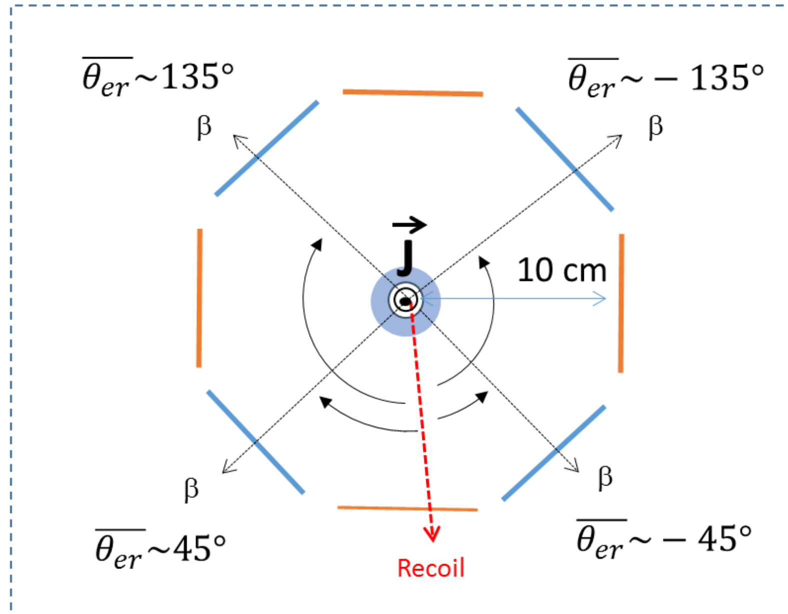
^{23}Mg best produced and laser polarized→ first candidate

D correlation measurement setup

P. Delahaye et al, The MORA project, Hyp. Int. (2019) 240:63



In trap optical polarization

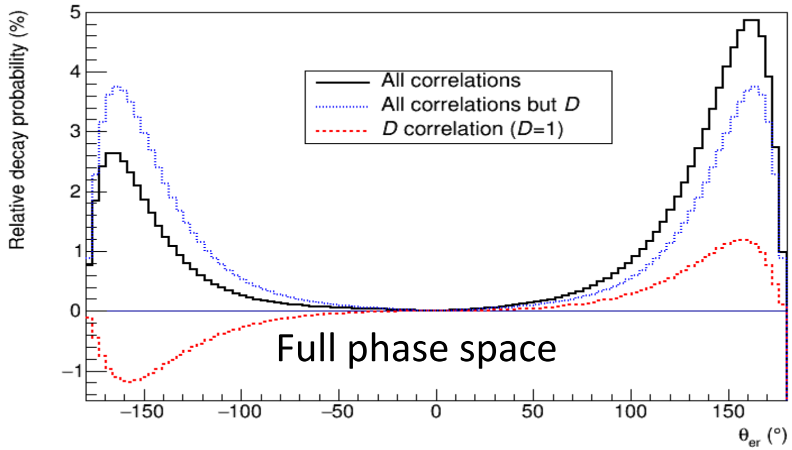


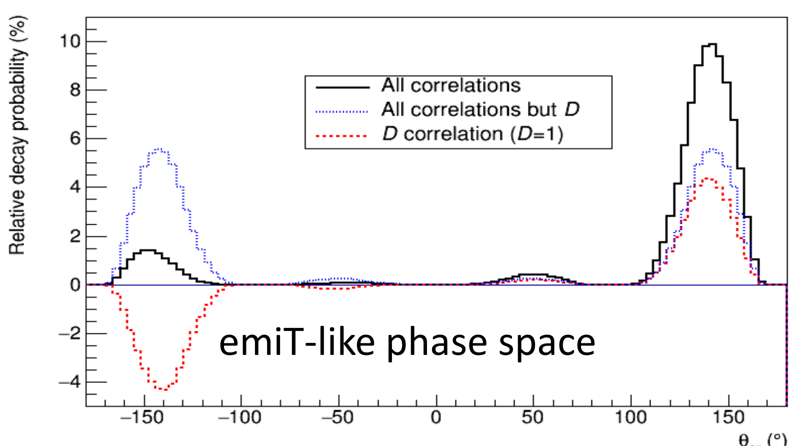
$$\frac{N_{coinc}^{+45°} + N_{coinc}^{+135°} - N_{coinc}^{-45°} - N_{coinc}^{-135°}}{N_{coinc}^{+45°} + N_{coinc}^{+135°} + N_{coinc}^{-45°} + N_{coinc}^{-135°}} = \delta \cdot D \cdot P$$

Where δ is depending on the phase space coverage

D correlation measurement setup

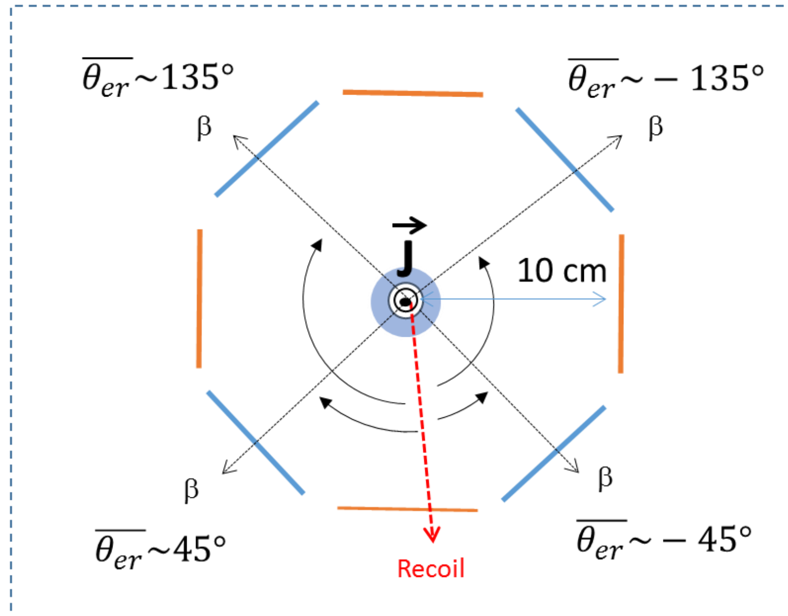
P. Delahaye et al, The MORA project, Hyp. Int. (2019) 240:63





δ=0.775(1) for ^{23}Mg, compared to δ~0.3 for the neutron

In trap optical polarization



$$\frac{N_{coinc}^{+45°} + N_{coinc}^{+135°} - N_{coinc}^{-45°} - N_{coinc}^{-135°}}{N_{coinc}^{+45°} + N_{coinc}^{+135°} + N_{coinc}^{-45°} + N_{coinc}^{-135°}} = \delta \cdot D \cdot P$$

Where δ is depending on the phase space coverage

D versus nEDM

- *D* correlation measurements
  - Best values
    - neutron decay, ***Dn*= (−0.94 ±1.89±0.97) 10^{-4}**, emiT collaboration, PRL 107, 102301 (2011), Phys. Rev. C 86 (2012) 035505
    - ^{19}Ne decay, ***D*=0.0001 ±0.0006** Calaprice et al, Hyp. Int. 22 (1985) 83, **limited by statistics**
- Current indirect bounds from nEDM as derived using an EFT approach
    - But the bounds from nEDM are still below those from *D,* at least for the leptoquark model
      - J. Ng and S. Tulin, Phys. Rev. D 85 (2012) 033001.
      - C.-Y. Seng et al., Phys.Lett. B 736 (2014) 147. → constraints relaxed by one order of magnitude
      - Summary in K.K. Vos et al, Rev. Modern Phys. 87 (2015) 1483
    - And *D* is a "cleaner" probe than nEDM, not a complex mixture of operators

    - *D* and nEDM are complementary approaches to search for CP violation
- New Physics probed with $\sigma_D < 5\times10^{-5}$
    - A full classification of models evading EDM constraints, such as leptoquarks, is still missing
    - A dedicated study using the EFT framework has just started

A. Falkowski, LPT Orsay

Why LQ models are so interesting

A non zero *D* is particularly sensitive to leptoquarks

- 3 Sakharov conditions for Baryogenesis (matter antimatter assymetry observed in the universe)
  - (i) a large C and CP violation
  - (ii) a violation of the baryonic number,
  - (iii) a process out of thermal equilibrium.
- 2 of the 3 conditions fulfilled, LQ appear in the first theories for Baryogenesis
  - A. Y. Ignatiev, N. V. Krasnikov, V. A. Kuzmin and A. N. Tavkhelidze, Phys. Lett. B 76(1978)436.
  - M. Yoshimura, Phys. Rev. Lett. 41(1978)281, M. Yoshimura Phys. Rev. Lett. 42(1979)746.
  - S. Weinberg Phys. Rev. Lett. 42(1979)850.
    - Decay out of equilibrium in GUT Theories
- Popular explanation for the flavor non conversation observed in B meson decay by the LHCb, BABAR and Belle collaborations

See eg Dumont et al, Phys Rev D 94 (2016)

- Projection on S1 scalar leptoquarks explaining the anomaly:
  - **Present: MS1 < 400–640 GeV (8 anf 13 TeV LHC searches)**
  - **Future: MS1 $\lesssim$ 600 - 800 GeV at the 14 TeV LHC with L = 300/3000 fb−1 of accumulated data**

Potentially discovery of a leptoquark up to 1.1TeV with over 5σ significance with a 14TeV LHC with L=3000fb^{-1}

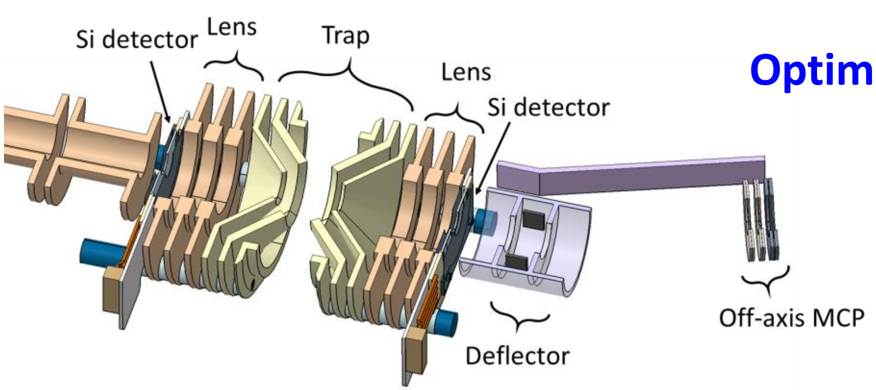
Competitive sensitivities from the *D* measurement

Experimental challenges

P. Delahaye et al, The MORA project, Hyp. Int. (2019) 240:63

- In trap polarization:
  - Novel method - not yet tested
  - Simulations with **10kHz pulsed lasers** → >99% polarization in ~1ms
- Trapping capacity and trapping half life
  - Presently $5 \cdot 10^5$ ions/bunch, aiming at $5 \cdot 10^6$/bunch
  - Presently 500ms, aiming at several s (^{23}Mg: $T_{1/2}$=11s)

Sensitivity $\sim \frac{1}{\sqrt{N}}$



Optimized trap geometry *M. Benali and G. Quemener*

Trapping radius

From: **4.5mm** (LPCTrap + environment)

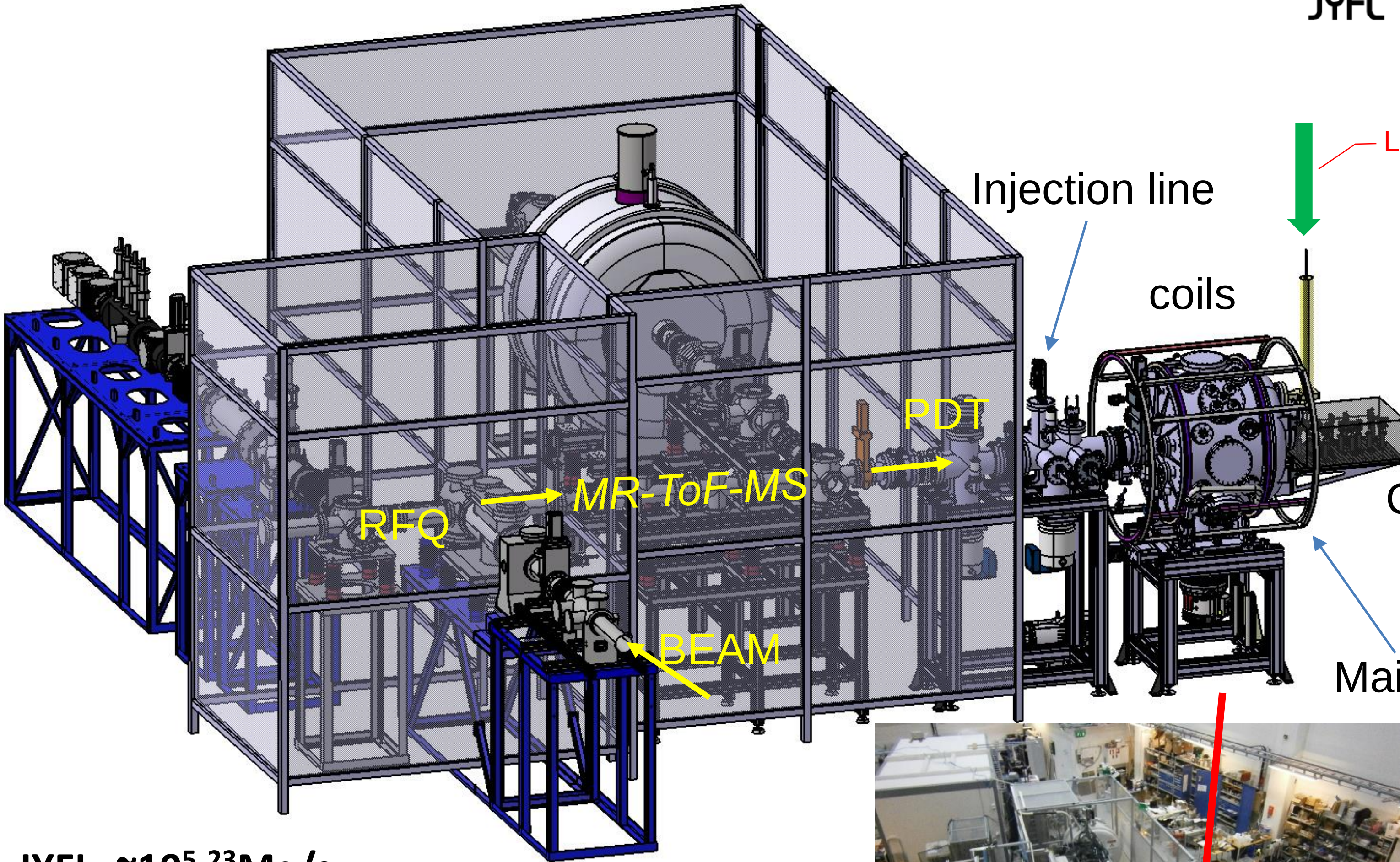
To: **11mm** (MORA + environment)

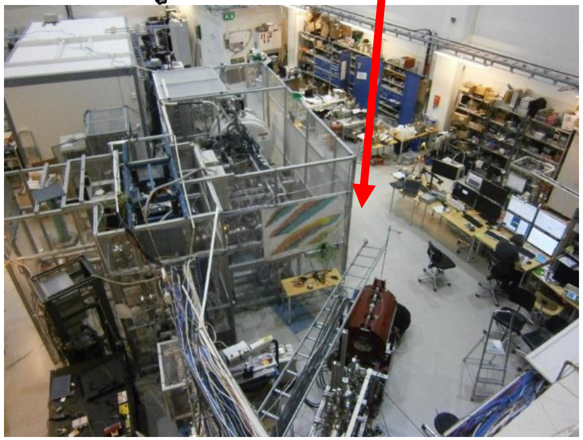
- ➢ **Negligible evaporation losses**
- ➢ **pseudo-potential depth x 5**

- Systematic effects $\lesssim 10^{-5}$
  - D_n measurement, dominated by statistics, give hints
  - Tests and simulations of the detection setup are just starting
    - GEANT 4 simulations for electrons
    - Home made simulations for dynamics of trapped ion and recoil ion trajectories

Proof of principles

2020-2023





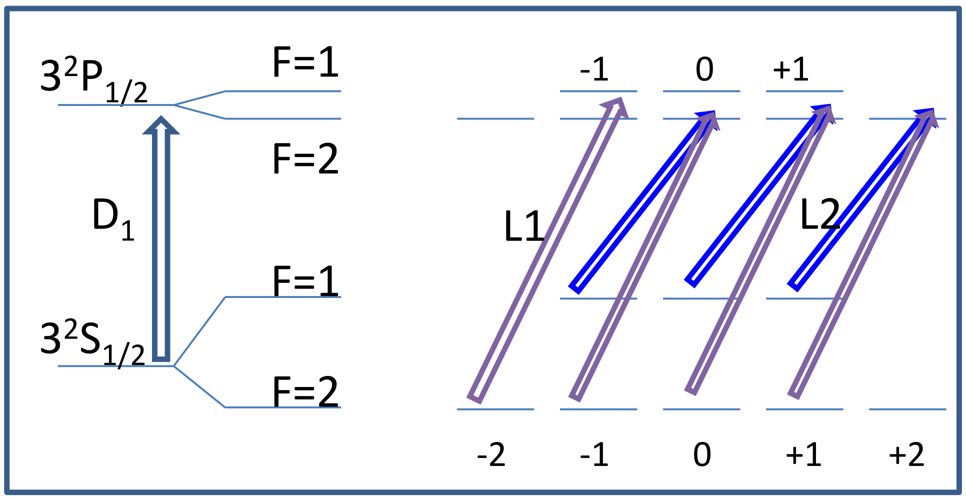
JYFL: ~10^5 ^{23}Mg/s
Laser setup readily available

1) Polarization degree measurement ~% level
2) *D* correlation measurement ~ $5\cdot10^{-4}$ level

Optical pumping

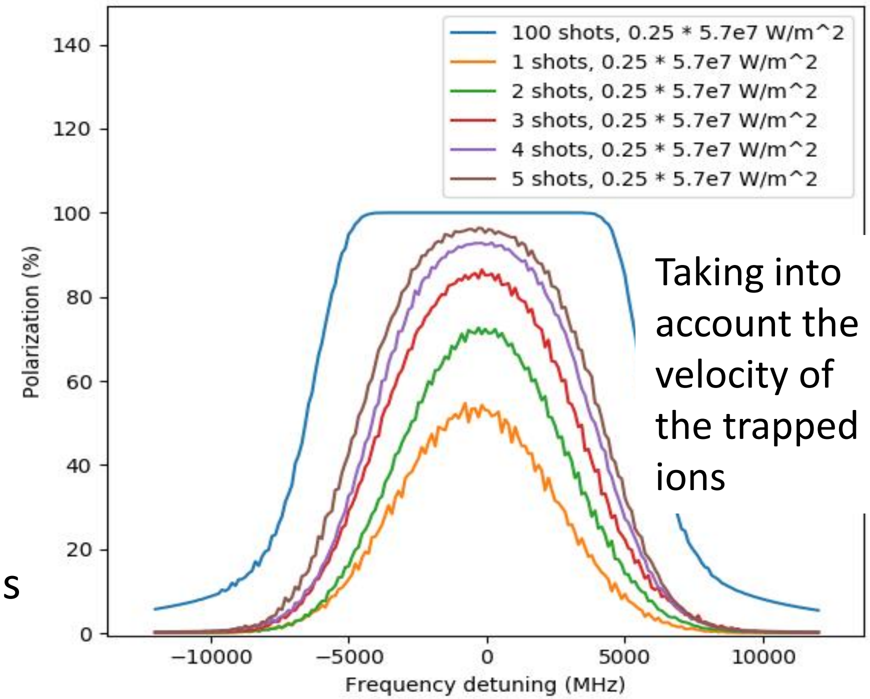
- The nuclear spin I interacts with the atomic one J → F=I+J
- σ+ or σ- light to scan the hyperfine structure forces ions in the $m_F=\pm F$ state

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



L1+L2 lasers excited using trippled Ti:Sa laser pulses
λ~280nm σ+ polarization

Transition probabilities: numerical simulations
R. de Groote, X. Fléchard and W. Gins



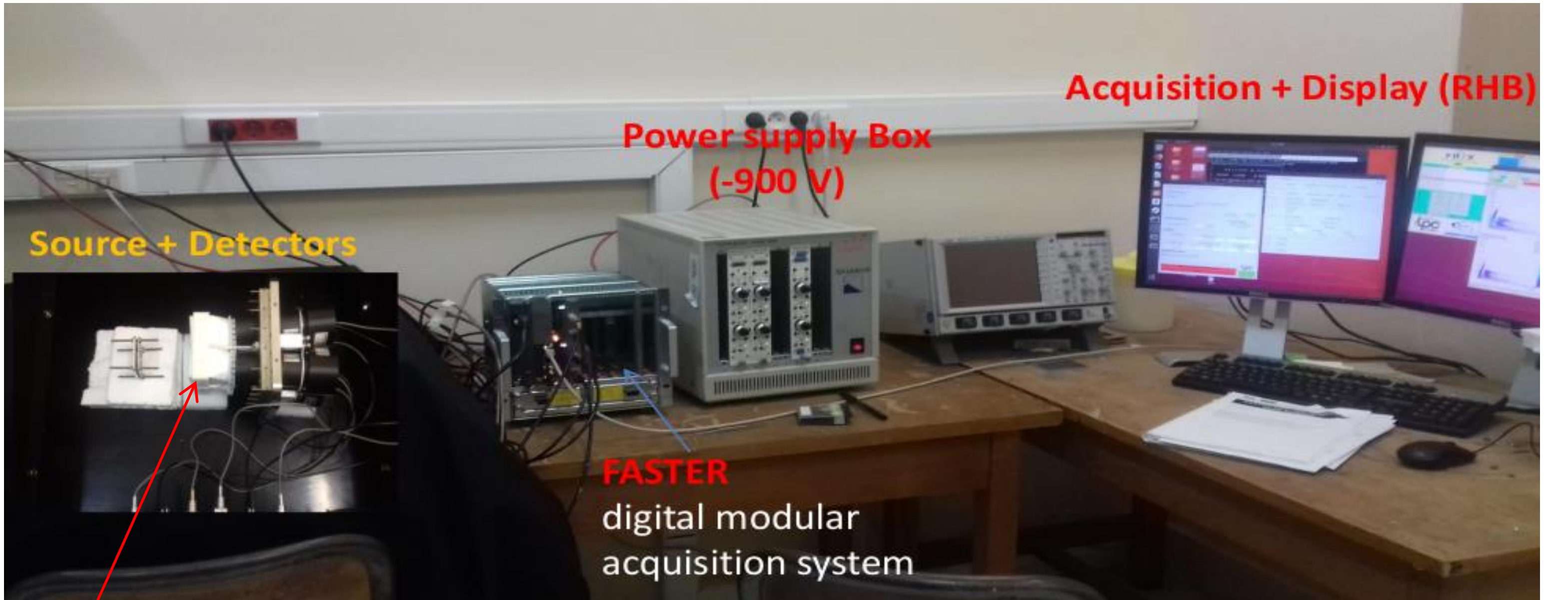
Taking into account the velocity of the trapped ions

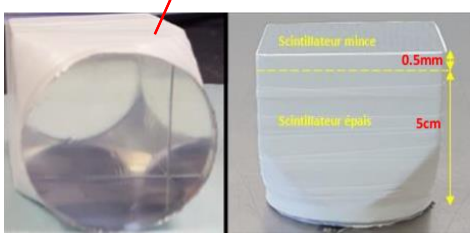
Collisions with He atoms (no spin) do not depolarize
With the power available at JYFL
More than 99% achievable in 1ms
Probable limitation: laser light polarization

Experience from COLLAPS

Examples!
^{31}Mg: G. Neyens et al, PRL 94, 022501 (2005)
$^{21\text{-}32}$Mg: D. T. Yordanov et al, PRL 108, 042504 (2012)

Phoswich detectors tests



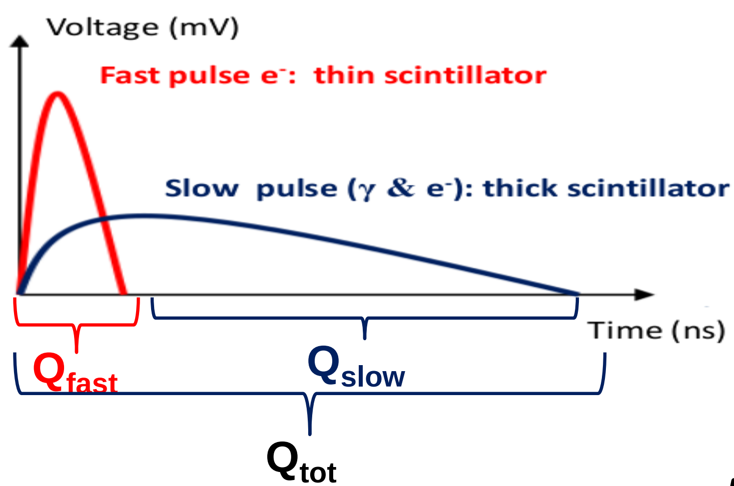


Phoswich detector :

combination of two plastic scintillators :

- thin scintillator (0.5 mm , τ=1.8 ns)
- thick scintillator (5 cm , τ=285 ns)

(+ Mylar + Téflon)



=> beta, gamma discrimination

M. Benali

Phoswich detectors tests

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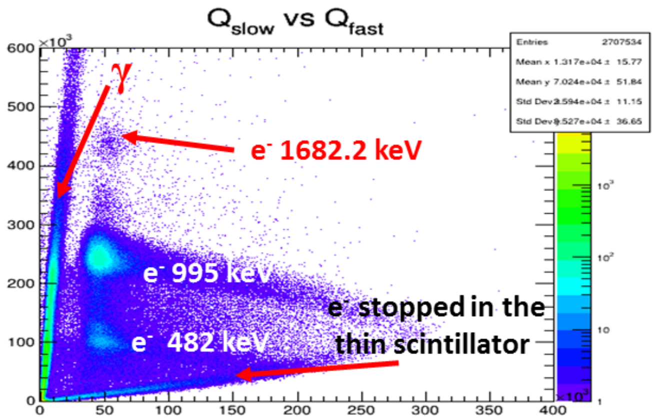
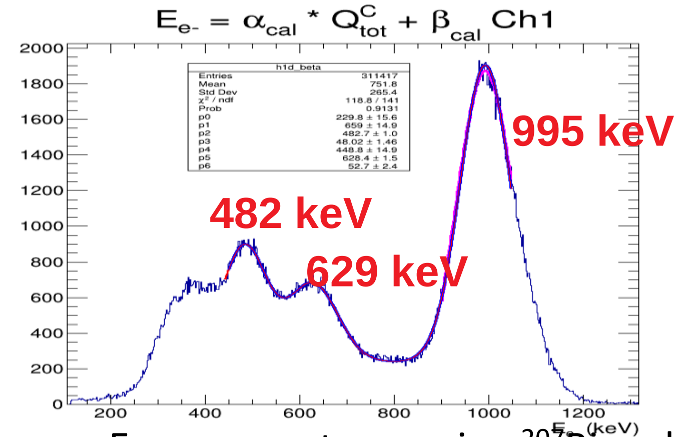
❖ Detectors calibration using ^{207}Bi (β,γ) and ^{137}Cs (β)

✓ Done



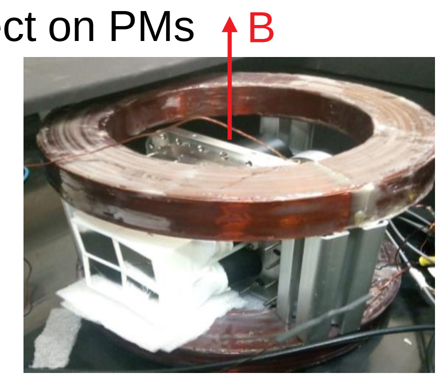


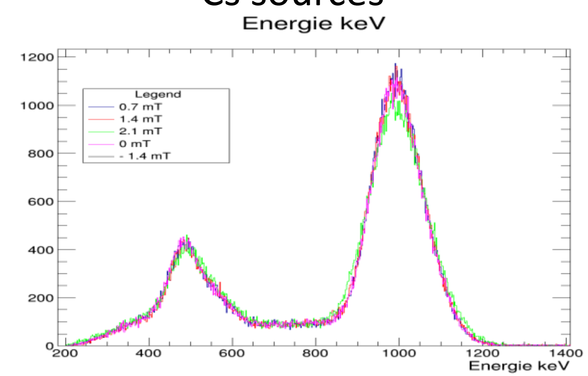
Energy spectrum using ^{207}Bi and ^{137}Cs sources

❖ Study of the magnetic field effect on PMs

✓ Done

(effect of magnetic field on signal resolution and PMs gain)





❖ Detector test in a secondary vacuum

✓ Done

❖ GEANT 4 simulations

➢ in progress

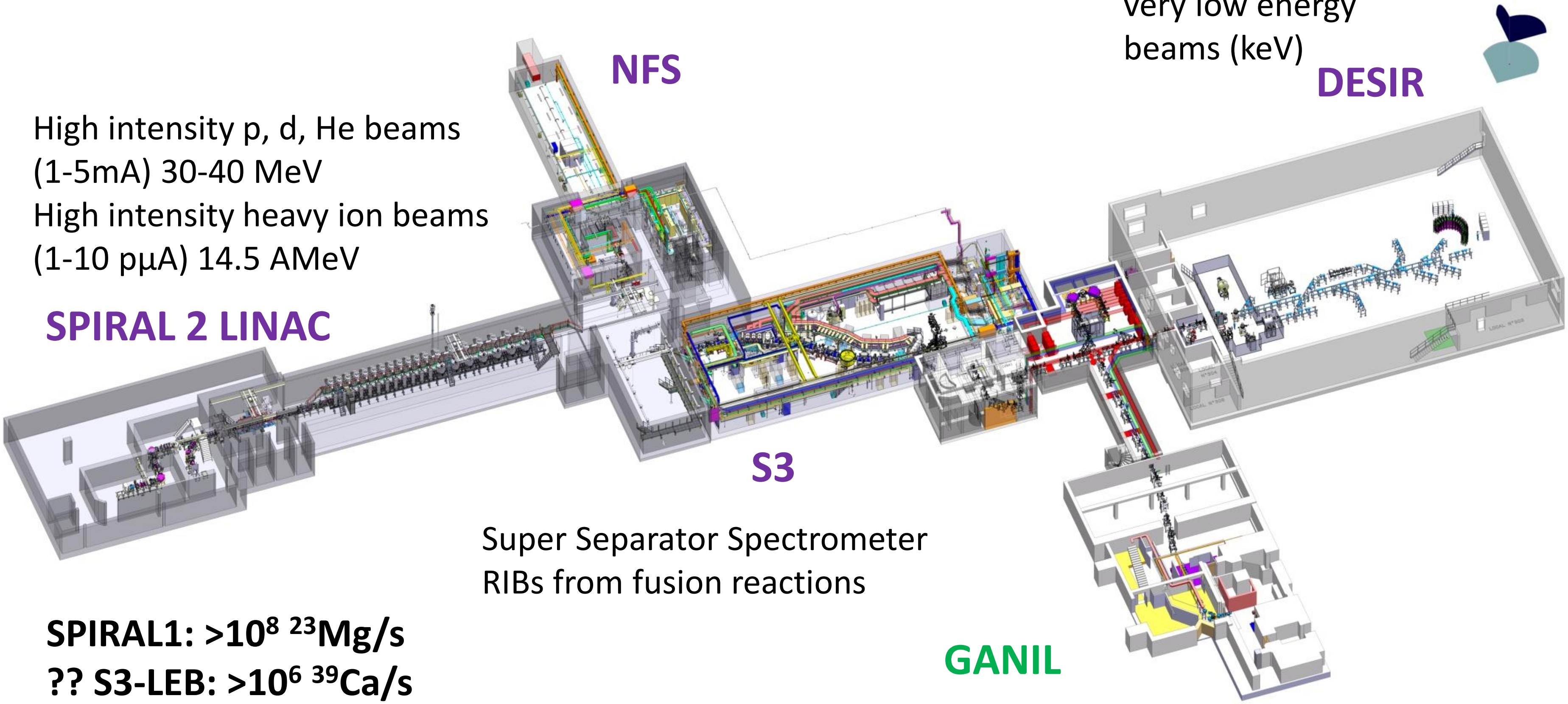
Stable resolution by varying the magnetic field

M. Benali

Highest sensitivity measurements 2024-…

Neutron for Science experimental area
Up to 30 MeV n

Experimental hall for
very low energy
beams (keV)



High intensity p, d, He beams
(1-5mA) 30-40 MeV
High intensity heavy ion beams
(1-10 pμA) 14.5 AMeV

Super Separator Spectrometer
RIBs from fusion reactions

SPIRAL1: >10^8 ^{23}Mg/s
?? S3-LEB: >10^6 ^{39}Ca/s

D **correlation < $5\cdot10^{-5}$ level**

Experimental areas and cyclotrons: heavy ions (pμA) up to 95AMeV
SPIRAL 1 facility: RIBs from fragmentation

Summary/Perspectives

THE MORA PROJECT
MATTER'S ORIGIN FROM RADIOACTIVITY

- New perspectives with polarized beams with MORA at JYFL
  - **Proof of principle of the polarization to be done at JYFL**
    - Adapted IGISOL – 4 Laser setup
      - Pulsed (TiSa) or CW (Dye) laser schemes are being investigated
    - Adapted trapping setup from LPCTrap
    - Adapted detection setup carried out by GANIL and LPC Caen

    2018-2021
  - **First measurement of *D* at JYFL**
    - Best sensitivity for nuclear beta decay is probably possible
      - LoI for ^{23}Mg beam characterization

    2020-2023
  - **Theoretical efforts**
    - for defining what NP one is probing with D measurements to the 10^{-5} level
    - For reviewing D_{FSI} calculations
- *D* correlation measurement with unprecedented accuracy in SPIRAL 2
  - 1 week of beam time:
    - same accuracy as for the neutron with existing techniques
    - Better sensitivity to NP: type of transition and selection of detection plane

    2024-…
  - Sensitivity down to **the 10^{-5} level** with some beam, laser and trapping R&D
    - improvement by 1 order of magnitude on the sensitivity to NP $Im(C_V/C_A)$
    - First approach /probe of D_{FSI} for ^{23}Mg
  - Great physics with great challenges!
- Project has officially started in April 2018
- ANR funds for PhD and postdoc positions as of 2020

RÉGION NORMANDIE

AGENCE NATIONALE DE LA RECHERCHE ANR

Thanks a lot for your attention

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M. Gonzalez-Alonso

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Backup material

- Sensitivity to non zero *D* at JYFL and GANIL
- Monitoring polarization
- Further comparison to *Dn*
- Further aspects of *D* vs nEDM
- More details for 6He $a_{\beta\nu}$ experiment

Sensitivity to NP

- Aimed accuracy

$$D \cong \left(\delta \cdot P \cdot \sqrt{N_{coinc}^{+45^\circ} + N_{coinc}^{+135^\circ} + N_{coinc}^{-45^\circ} + N_{coinc}^{-135^\circ}} \right)^{-1}$$

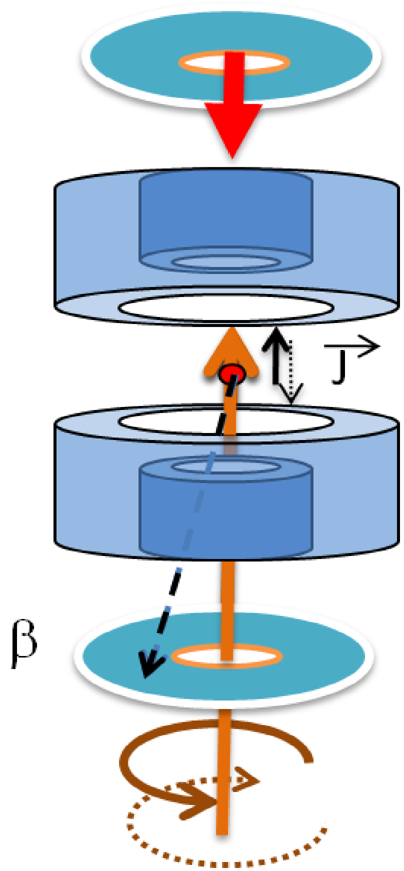
Place and type of measurement	Trapped ions /s	Decays/s	Meas. time (d)	Detected coinc. (P)	σ_P stat (%)	Detected coinc. (D)	Sensitivity on *D*
JYFL: polarization degree	2.00E+04	6.13E+02	8	1.7E+05	1.9E+00	1.5E+06	1.0E-03
JYFL: *D* correlation	2.00E+04	6.13E+02	32	6.7E+05	9.4E-01	6.1E+06	5.2E-04
DESIR: *D* correlation*	1.00E+06	3.07E+04	24	2.5E+07	1.5E-01	2.3E+08	8.5E-05
DESIR: *D* correlation**	5.00E+06	3.07E+05	24	1.3E+08	6.9E-02	1.2E+09	3.8E-05

*present trapping capacity

** optimized trapping capacity

With some trapping R&D (optimized trap and RF)→ **Below 5.10^{-5} is feasible**

Monitoring of polarization



P measurement

On-line monitoring of the polarization

A_β measurement

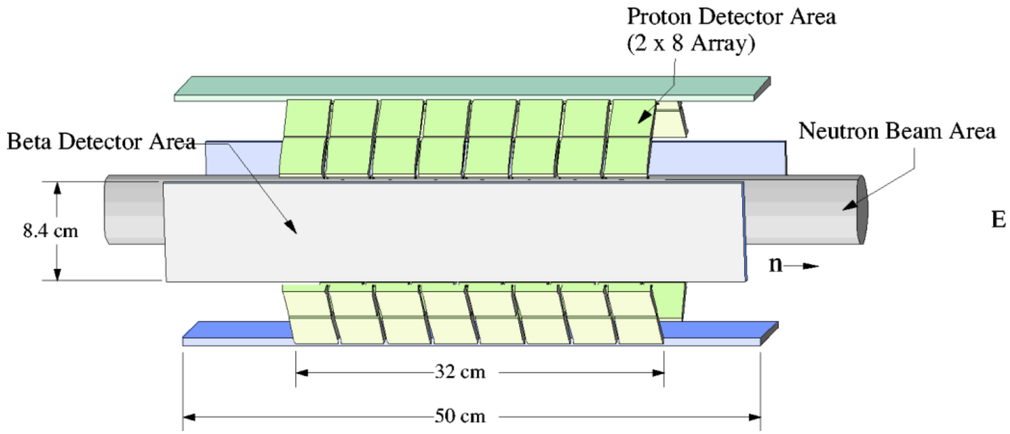
$$\frac{N_{\beta^+}^{\uparrow} - N_{\beta^+}^{\downarrow}}{N_{\beta^+}^{\uparrow} + N_{\beta^+}^{\downarrow}} \propto A_\beta \cdot P \qquad A_\beta \frac{\langle \vec{J} \rangle}{J} \cdot \frac{\vec{p_e}}{E_e}$$

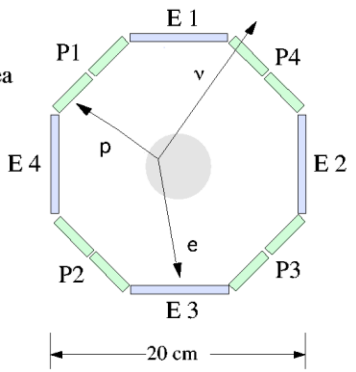
Remember: C. S. Wu et al., Phys Rev 105(1957)1413

Extended interaction time with laser light
→ Very high polarization degree
>90%: enough for the measurement of *D*!

Sensitivity to NP

- Comparison to D_n experiment





H. P. Mumm et al, Rev. Sci. Instrum. 75, 5343 (2004)
H. P. Mumm et al, PRL 107, 102301 (2011)

Sensitivity to NP

- Comparison to D_n experiment

Systematic effects

Source	Correction	Uncertainty
Background additive	−0.07	0.07
Multiplicative[a]	0.03	0.09
Electron backscattering additive	0.09	0.07
Multiplicative	0.11	0.03
Proton backscattering	0	0.03
Electron threshold nonuniformity	0.04	0.10
Proton-threshold effect	−0.29	0.41
Beam expansion	−1.50	0.40
Polarization nonuniformity	0	0.10
ATP-misalignment	−0.07	0.72
ATP-twist	0	0.24
Spin-correlated flux	0	<0.01
Spin-correlated polarization	0	<0.01
Polarization	[b]	0.04[c]
K_D	[b]	0.04
Total corrections	−1.66	0.97

[a]In Ref. [11] this entry had a typographical error.
[b]Polarization and K_D are included in the definition of $\tilde{D}$.
[c]Assumes polarization uncertainty of 0.05.

D_n= (−0.94 ±1.89±0.97) 10^{-4}

Most of the dominant effects should be highly suppressed by the trap confinement

- Beam expansion
  - From 5 cm for the neutron to ~2mm for trapped ions
- ATP= assymetric transverse polarization
  - Very good definition of the axis of polarization thanks to the lasers and magnetic field
  - negligible expansion of the cloud
  - effect can be canceled for uniform beam using 2 adjacent cell
- The proton/recoil threshold should be minimal for MCPs compared to SBDs, but will be affected from RF field to confine ions

H. P. Mumm et al, Rev. Sci. Instrum. 75, 5343 (2004)
H. P. Mumm et al, PRL 107, 102301 (2011)

Sensitivity to NP

The EDM are sensitive among others to a CP odd four fermion interaction

$$\mathcal{L}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} k_{LR} \mathcal{O}_{LR},$$

$$\mathcal{O}_{LR} \equiv i(\bar{u}_L \gamma^\mu d_L \bar{d}_R \gamma_\mu u_R - \bar{d}_L \gamma^\mu u_L \bar{u}_R \gamma_\mu d_R),$$

Ng et Tulin, Phys Rev D 85 (2012) + Seng et al, Phys Lett B 736(2014

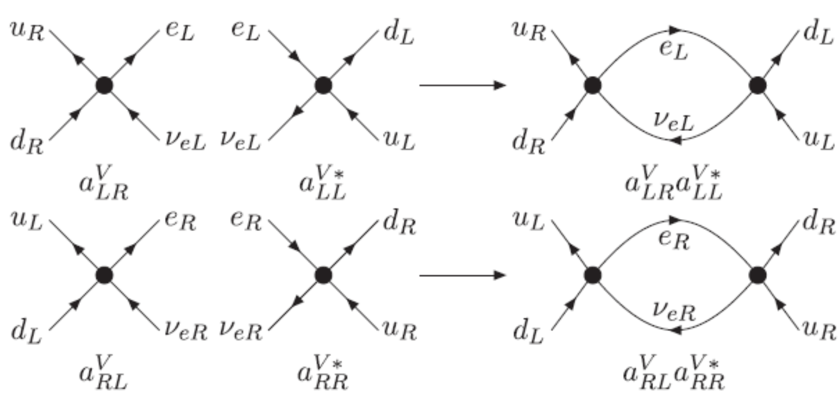


FIG. 1. *CP* violation entering $D_t = k\,\text{Im}(a^V_{LR} a^{V*}_{LL} + a^V_{RL} a^{V*}_{RR})$ automatically generates the four-quark operator $\mathcal{O}_{LR} \equiv i(\bar{u}_L \gamma^\mu d_L \bar{d}_R \gamma_\mu u_R - \bar{d}_L \gamma^\mu u_L \bar{u}_R \gamma_\mu d_R)$, which contributes to neutron, mercury, and deuteron EDMs.

That implies for
- •L-R symmetric models
- •Models with exotic fermions
- • R-parity violating MMSM

$$|D_t/\kappa| < 3 \times 10^{-6}$$

Limit is relaxed by one order of magnitude Seng et al, Phys Lett B 736(2014)
→Non adequate d_n determination from earlier meson theory

Sensitivity to NP

The EDM are also sensitive (but less!) to Leptoquarks (LQ)
LQ models were considered in the past « EDM safe »
But: Radiative corrections generate contributions to EDM

8 fermion operator in the SMEFT expansion

Ng et Tulin, Phys Rev D 85 (2012) + Seng et al, Phys Lett B 736(2014)

- For models with right-handed neutrinos:

$$|d_n| > 9 \times 10^{-22}\, e\,\mathrm{cm} \times |D_t/\kappa| \left(\frac{m_{LQ}}{300\ \mathrm{GeV}}\right)^2$$

$$|d_{\mathrm{Hg}}| > 7 \times 10^{-26}\, e\,\mathrm{cm} \times |D_t/\kappa| \left(\frac{m_{LQ}}{300\ \mathrm{GeV}}\right)^2$$

$$|d_D| > 4 \times 10^{-22}\, e\,\mathrm{cm} \times |D_t/\kappa| \left(\frac{m_{LQ}}{300\ \mathrm{GeV}}\right)^2$$

$\longrightarrow$

$$m_{LQ} > 300\ \mathrm{GeV}$$

$$|D_t/\kappa| \lesssim 3 \times 10^{-4}$$

This limit is relaxed by one order of magnitude Seng et al, Phys Lett B 736(2014)
→Non adequate d_n determination from earlier meson theory

Review: Vos et al, Rev. Mod. Phys. 87 (2015)

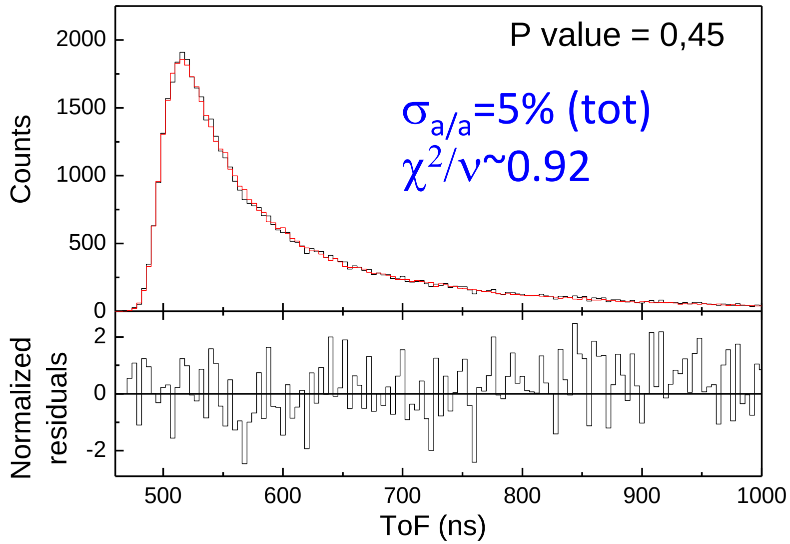
First ^{6}He experiment

Results and outcome

X. Fléchard et al ,J. of Phys. G 38 (2011) 055101

- Subtracting background
- Neutrino mass invariant $M_\nu^2 < 2.5 MeV^2c^4$

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



Main systematic uncertainties

Source	$\Delta a_{\beta\nu}$ ($x10^{-3}$)
Cloud temperature	6.8
MCPPSD calibration	1.3
Eβ	1.1
Background (acc.+off trap)	0.9
β scattering	1.9
V_{RF}	1.7
Shake - off	0.6
	...

Total 7.5

Reduced by statistics

May become dominant

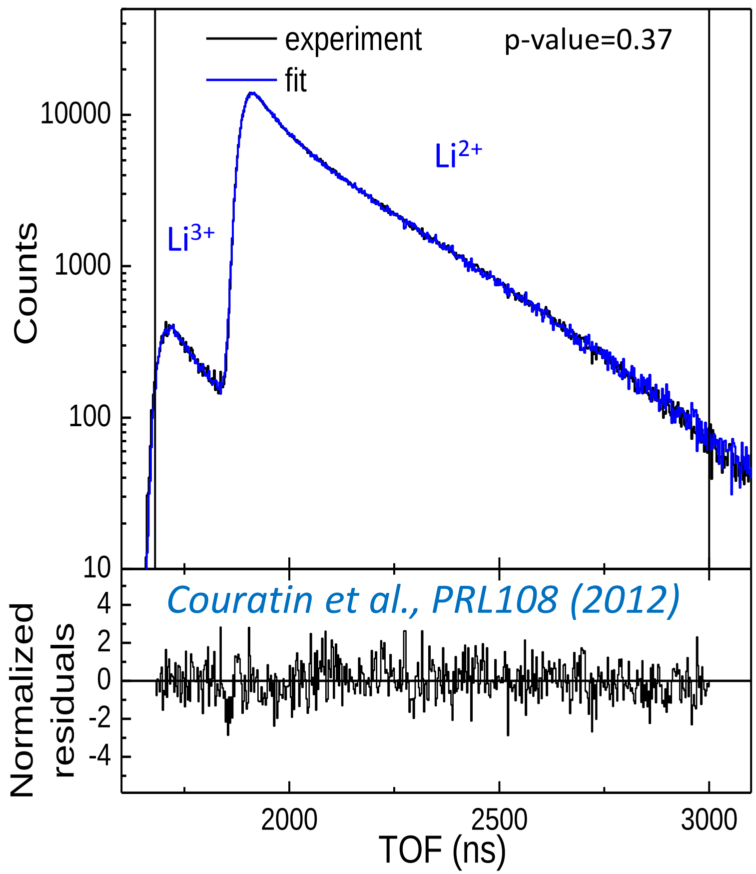
Re-measured

Shake off was only known in theory!
Arbitrary ±100%

Results of LPCTrap

^6He decay

- Experimental conditions (2010):
- $^6He^+$ Intensity ~10^8 pps
- ~ 1,5 nA of $^{12}C^{2+}$ contamination (lost in RFQ)
- ~ 1.2 10^6 « good » coincidences in ~ 4 days



- **Shake-off analysis:**
  - Complete Monte-Carlo simulation including all relevant systematic effects
  - Fit of $P_{shake\text{-}off}$ assuming $a_{\beta\nu}$ = -1/3

Systematic error budget

Source	Corr. (10^{-5})	Error (10^{-5})	Method
$a_{\beta\nu}$		4.0	[20]
β scattering	39	4.0	GEANT4
Background		3.5	present data
E_β calibration		1.7	present data
MCP efficiency	−9	1.2	present data
Total	30[a]	7.0	

[20] F. Glück, Nucl. Phys. A628, 493 (1998).

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

$\Delta P_{shake\text{-}off}$ =3.6 10^{-4}

Pshake-off (theory): 0.02322

Test of the soudain approximation
Couratin et al. PRL108 (2012)

Summary of results $a_{\beta\nu}$

Nucleus	Date	a	σ_{stat}	σ_{syst}	Publication
^{6}He	2006	-0.3335	0.0073	0.0075	σ_a/a ~ 3% *Fléchard et al. JPG38 (2011)*
	2010	-1/3 (SM)	0.0015	?	Shakeoff *Couratin et al. PRL108 (2012)*
^{35}Ar	2011	/	/	/	Shakeoff *Couratin et al. PRA88 (2013)*
	2012	0.9004 (SM)	0.0013	?	
^{19}Ne	2013	0.0438 (SM)	0.0046	?	Shakeoff *Fabian et al. , under press*

- Measurement of $a_{\beta\nu}$ for ^{6}He under analysis

  Measurement from Johnson et al. (1963!) for ^{6}He: $a_{\beta\nu}$=-.3343±.0030

  If $\sigma_{syst} = \sigma_{stat}$ $a_{\beta\nu}$=-1/3(SM)±.0021

  → Potentially constraints on $|C_T|/|C_A|$ from 7% to 5%

  + constraints from ^{8}Li decay (cf previous presentation)

- Projections for mirror nuclides

  With the ^{35}Ar measurement alone, assuming $\sigma_{syst} = \sigma_{stat}$: σ_a/a ~ 0.21%

  → Gain factor on $\rho=(C_A M_{GT})/(C_V M_F)$: σ_ρ/ρ: 5.4

  → Potentially $\sigma(V_{ud})/V_{ud}$ (2018) from 1.4×10^{-3} to $9.\times10^{-4}$

  Including latest ^{37}K measurement at TRINAT