Search for CP violation in nuclear beta decays: the MORA project

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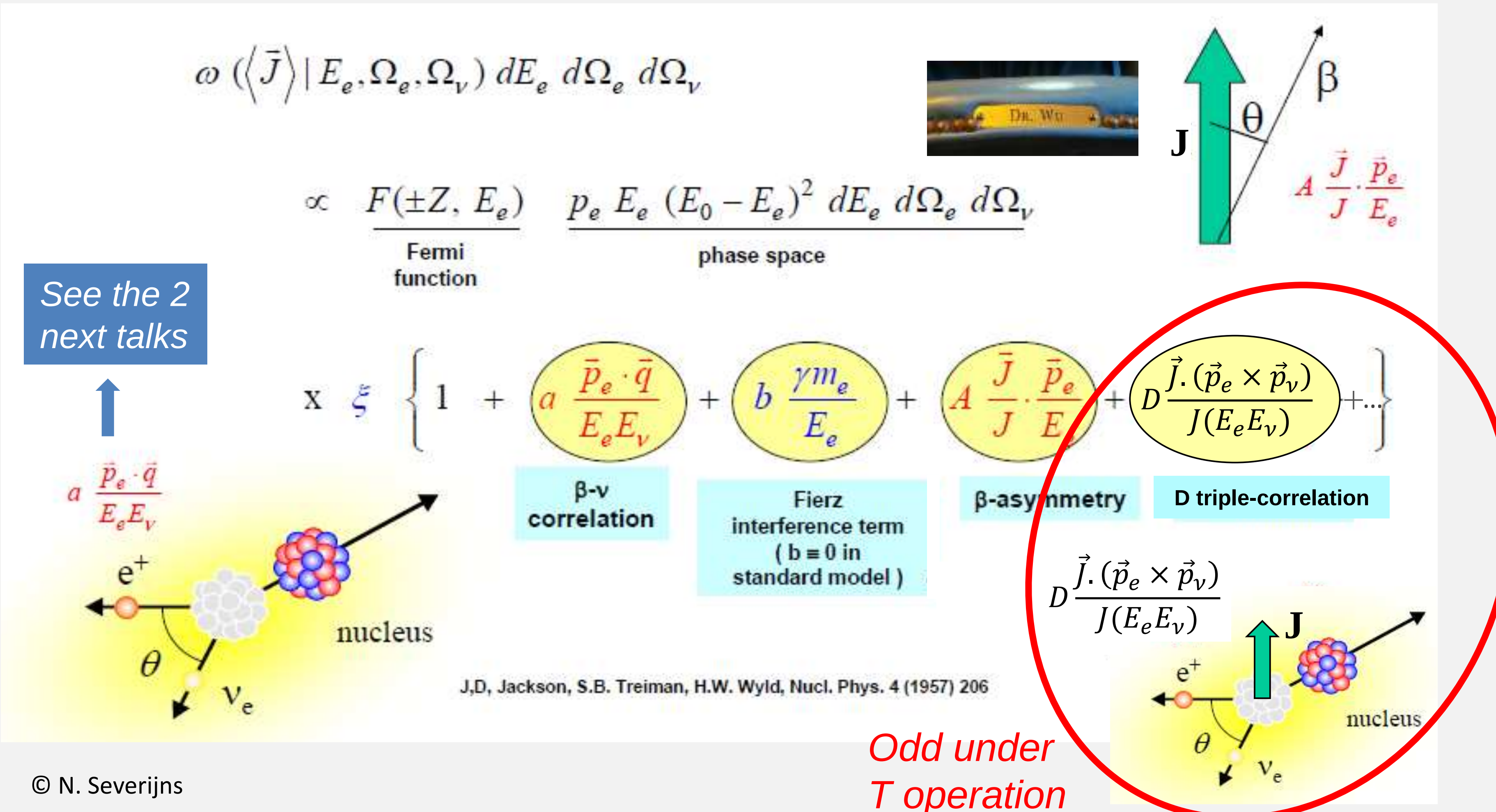
Search for CP violation in nuclear β decay: How?

M. Gonzales-Alonso "Fundamental interaction studies with nuclear beta decay", Monday Sept 09 2019

- Nuclear β decay: sensitive tool to test SM complementary to HE physics
- @ low energy, "traces" of New Physics (NP) are hidden in correlations:



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Search for CP violation in nuclear β decay: How?

- Correlations between 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)	-0.4078 (7)	-0.5142 (10)	0.5563 (16)

⇨ *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
$D_{FSI}(X)$	1.2×10^{-5}	1.5×10^{-4}	1.2×10^{-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)*

- Final precision of 2×10^{-5} on *D* *A. Falkowski, LPT Orsay, private communication*
  → probing a new particle of ~ 500 TeV: out of reach of colliders !!

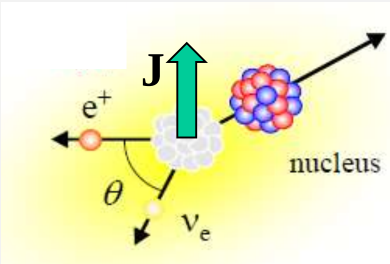
- n-EDM measurement seems to have a higher sensitivity….
  but → not for all possible extensions of SM (LQ models)
  → interpretation less direct *González-Alonso et al. PPNP104 (2019)*

⇨ *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)*

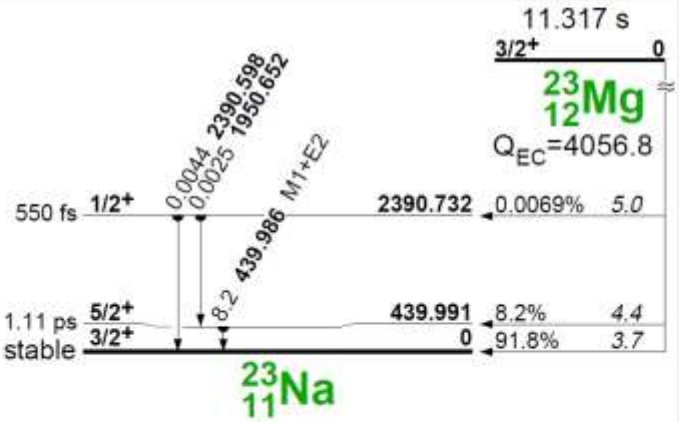
THE MORA PROJECT
MATTER'S ORIGIN FROM RADIOACTIVITY

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

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

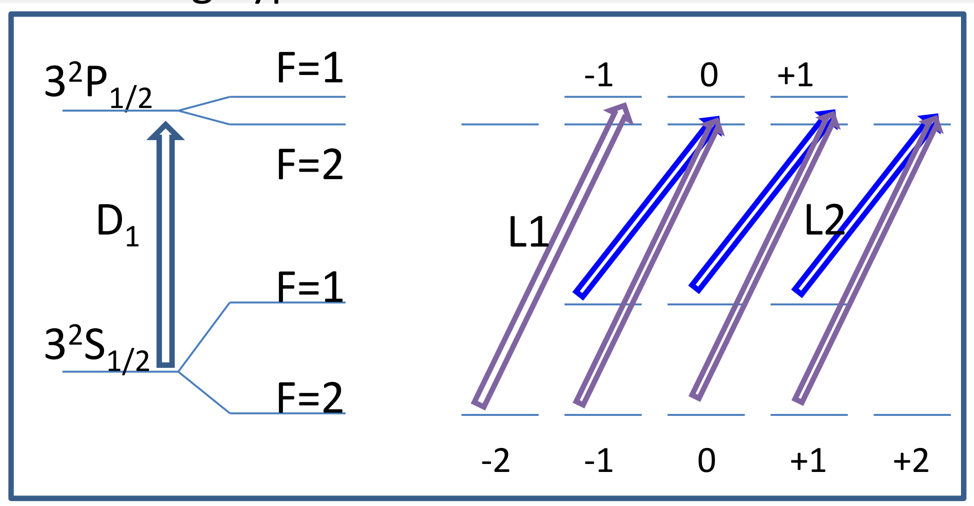
- The pros …

- 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 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 $m_F=\pm F$ 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

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

- … and cons

Solution

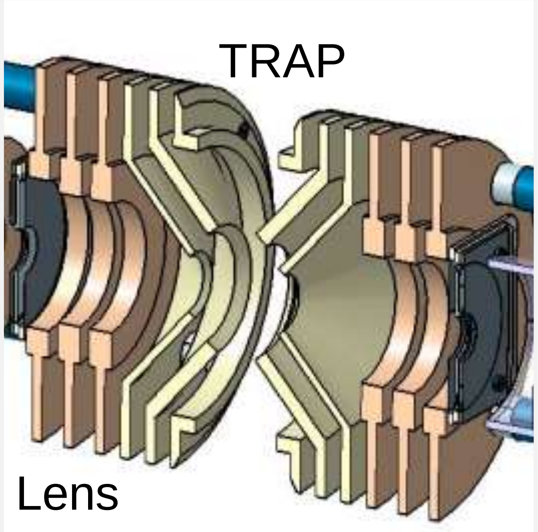
- Production rates & contamination
  > 10^5 pps @ JYFL, measured in Oct 2018
  with > 200 x more stable $^{23}Na^{1+}$

→ 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. to be published

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

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MATTER'S ORIGIN FROM RADIOACTIVITY

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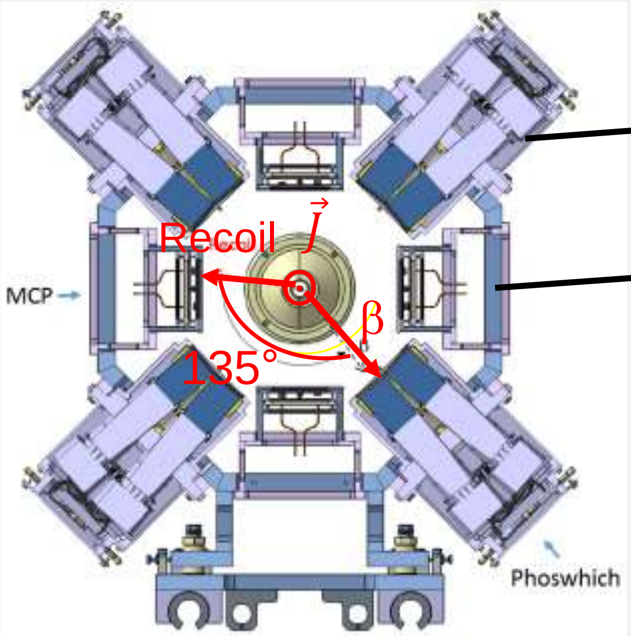
  2) Use of MR-ToF-MS ?

- $T_{1/2}$ ~ 11 s
- LPCTrap capacity: ~ 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)*

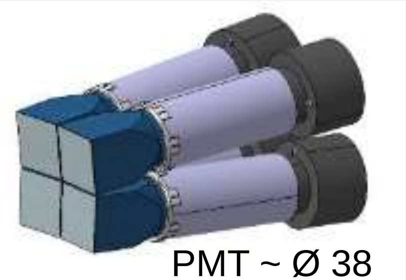
4x4 "Phoswich" detectors for β particles

4 "RIDE" detectors for recoil ions

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

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

Plastic scintillators



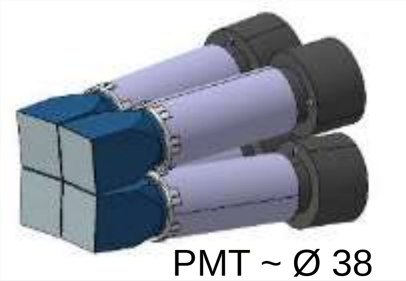
PMT ~ Ø 38

µCP 50x50
+
PSA

The Phoswich detector for β particles

- Specific design
- Fast response
- β/γ discrimination

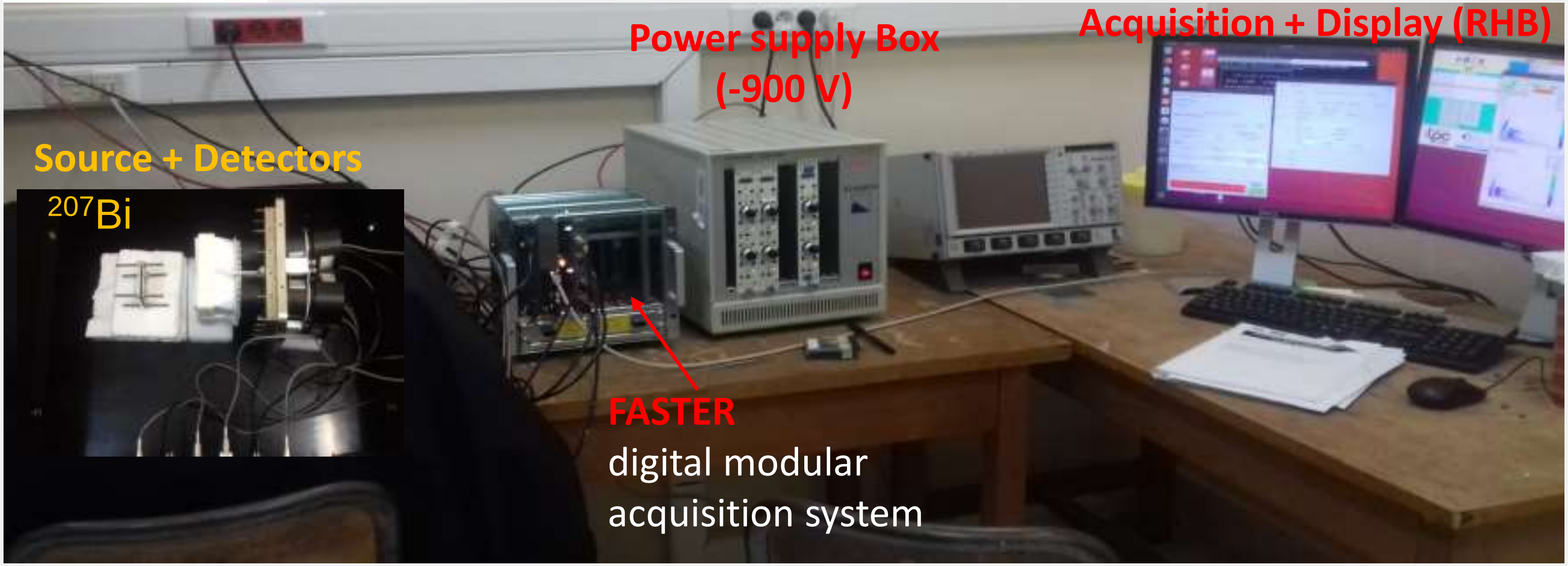
Plastic scintillators



Combination of 2 plastic scintillators: ΔE: thin (0.5 mm) & fast (τ = 1.8 ns) → "*Q_fast*"

E: thick (5 cm) & slow (τ = 285 ns) → "*Q_slow*"

Test bench

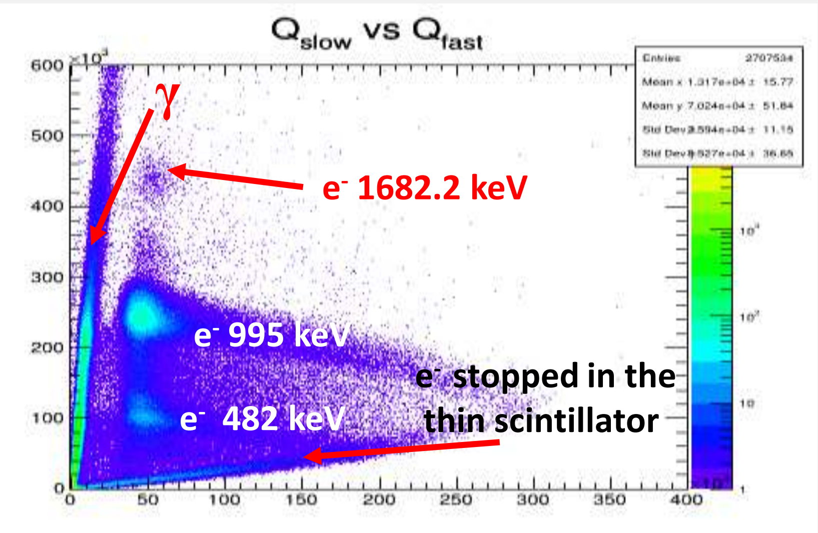


The Phoswich detector for β particles

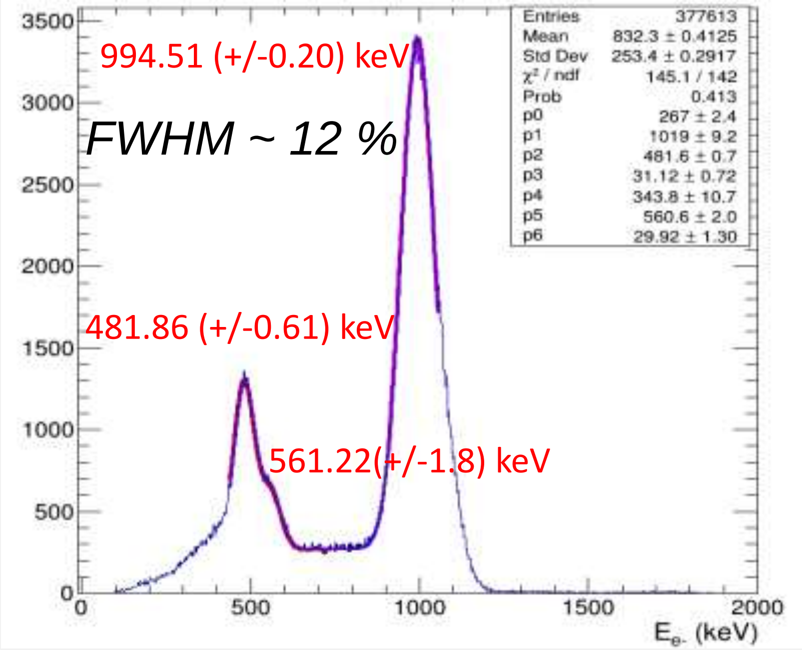
- ^{207}Bi: a rich decay scheme

Various IC electrons → weighted means: 481.7 keV (1.5%), 556.9 keV (0.6%), 994.6 keV (9.4%)

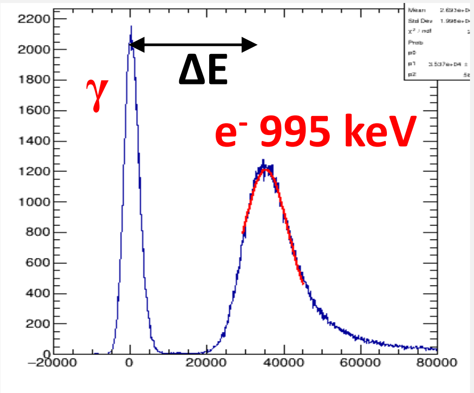
Some γ rays: 570 keV (97.76%), 1063 keV (74.5%), 1770 keV (6.87%)



After data corrections, $E = a\,Q^{c}_{tot} + b$



Good β/γ discrimination



- Opportunity to measure response functions, from 0.2 MeV up to 3.5 MeV @ATRON (Cherbourg)
- GEANT4 simulations just started

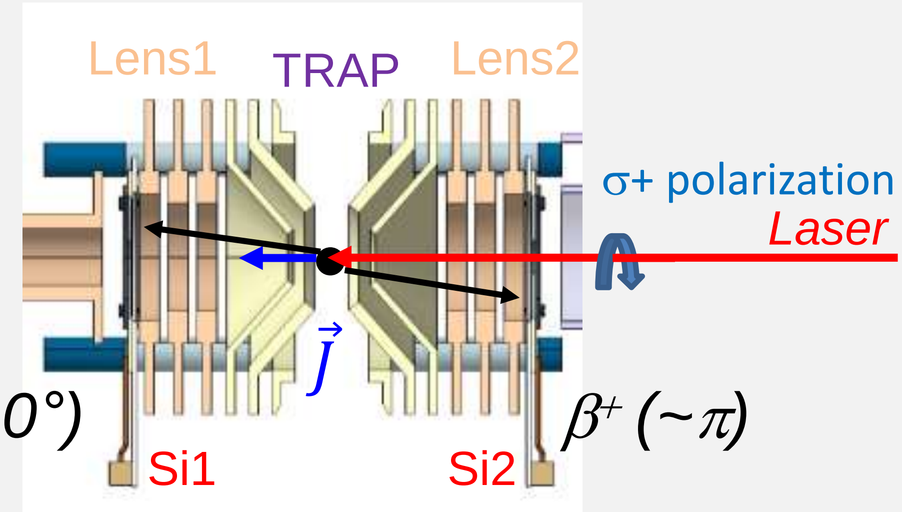
First measurement: the Polarization degree

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

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

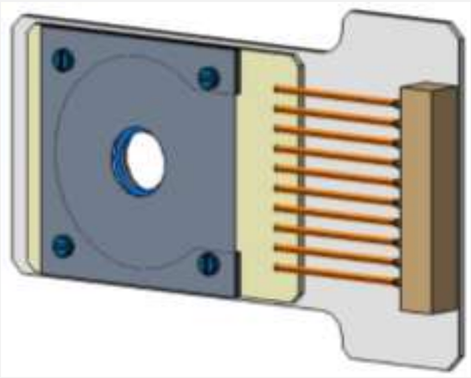
P must be ① measured ② controlled during the experiment

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



$\beta^+ (\sim 0°)$ $\beta^+ (\sim \pi)$

Silicon detector



8 channels: 4 sectors, 2 rings

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

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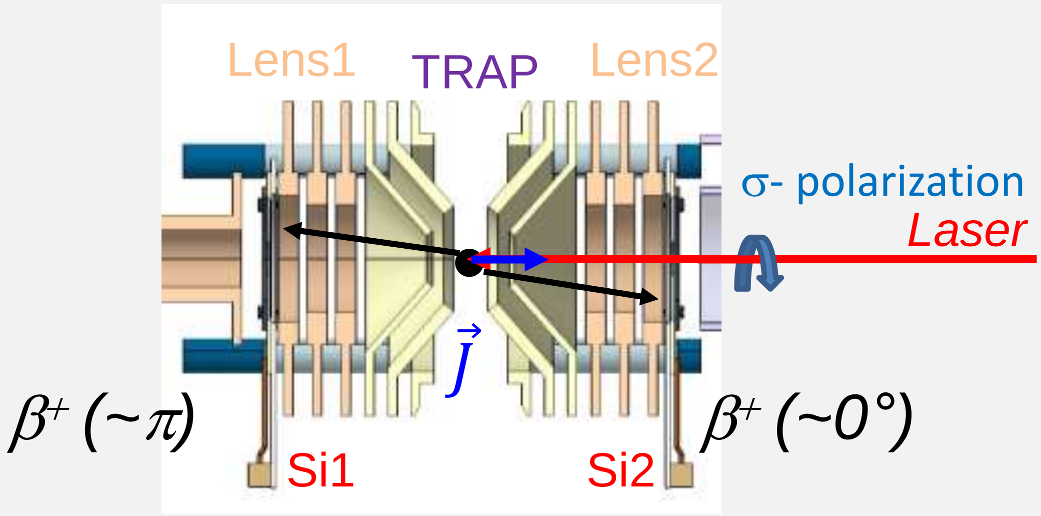
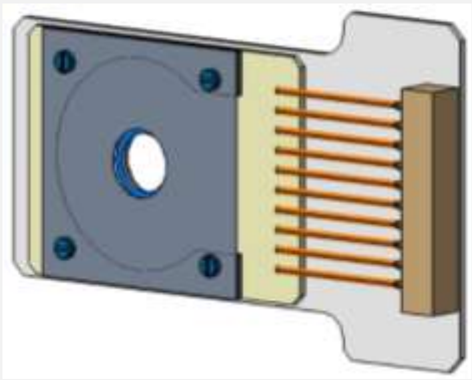


Silicon detector



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 @ JYFL

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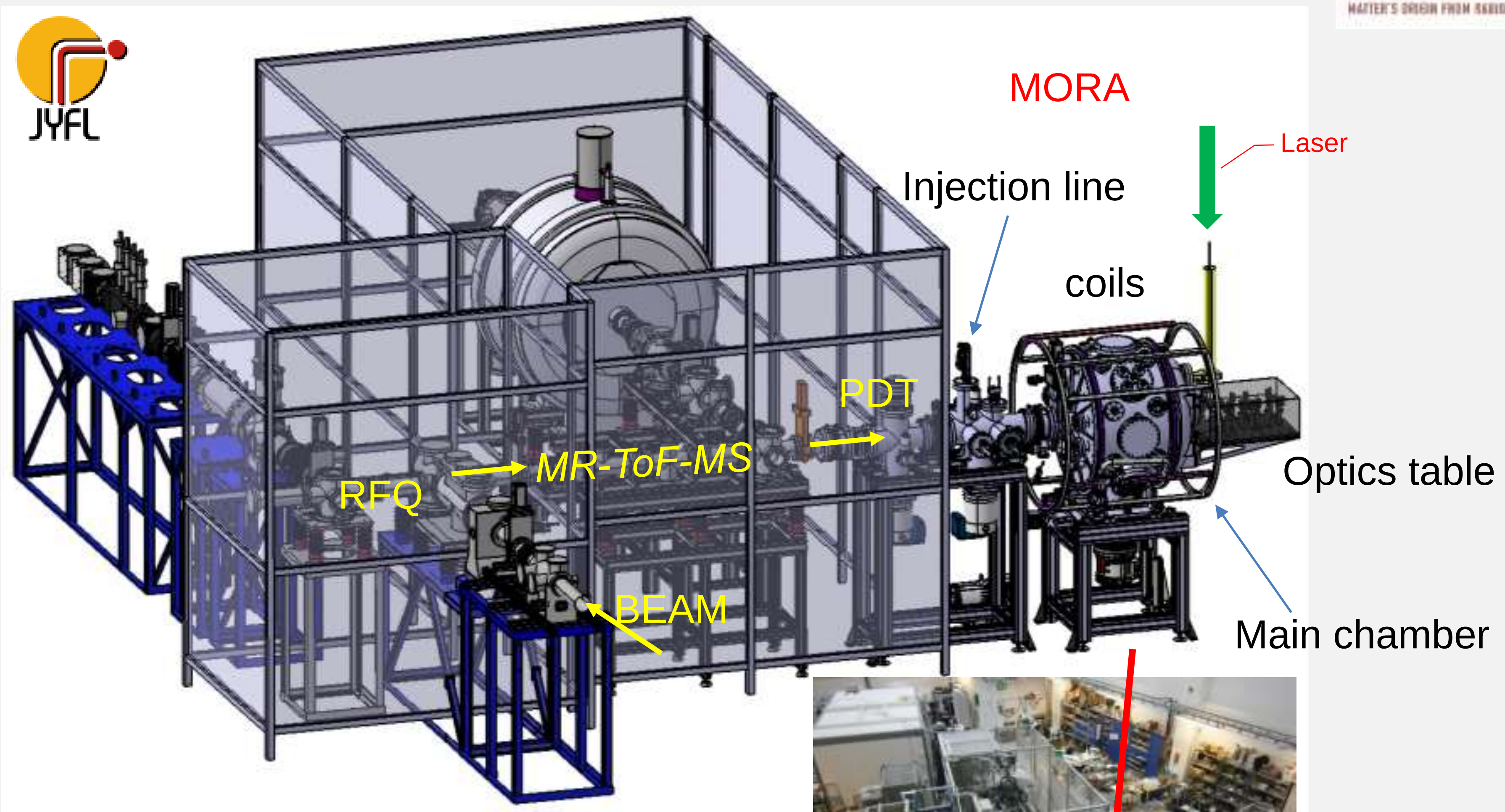
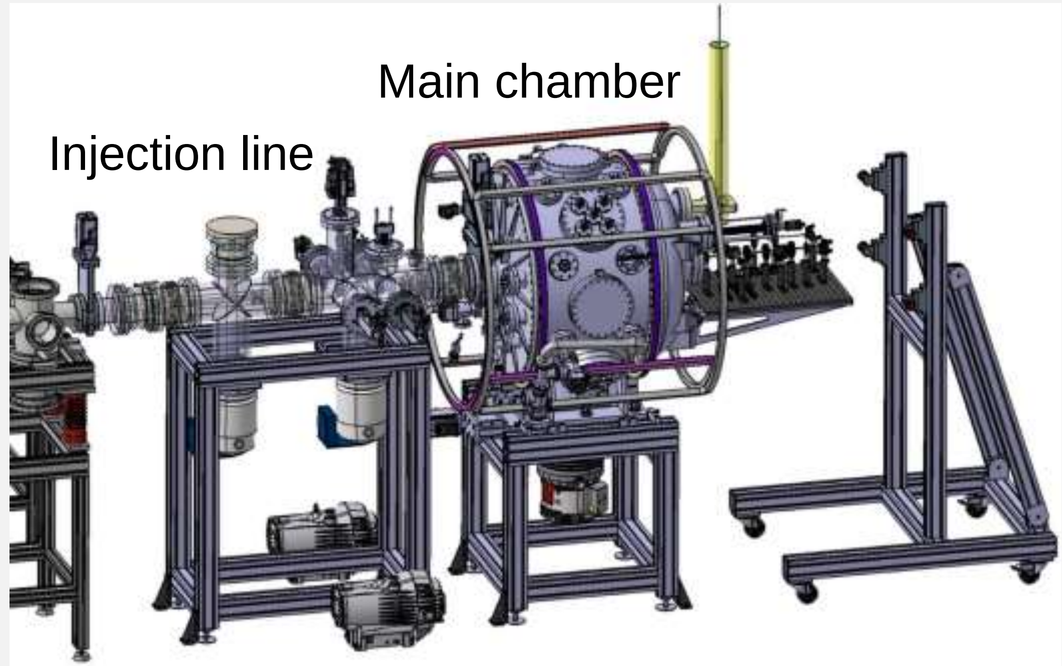
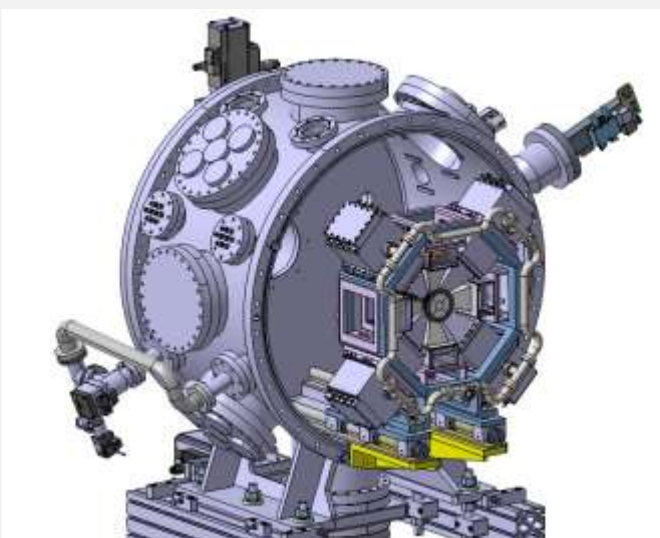


MORA: status

- Injection line & main chamber
  - ✓ design almost completed
- Main chamber
  - ✓ built
- Detection
  - ✓ phoswich: tests & simulations
  - ✓ RIDE – Si: design completed
- Slow control
  - ✓ just started

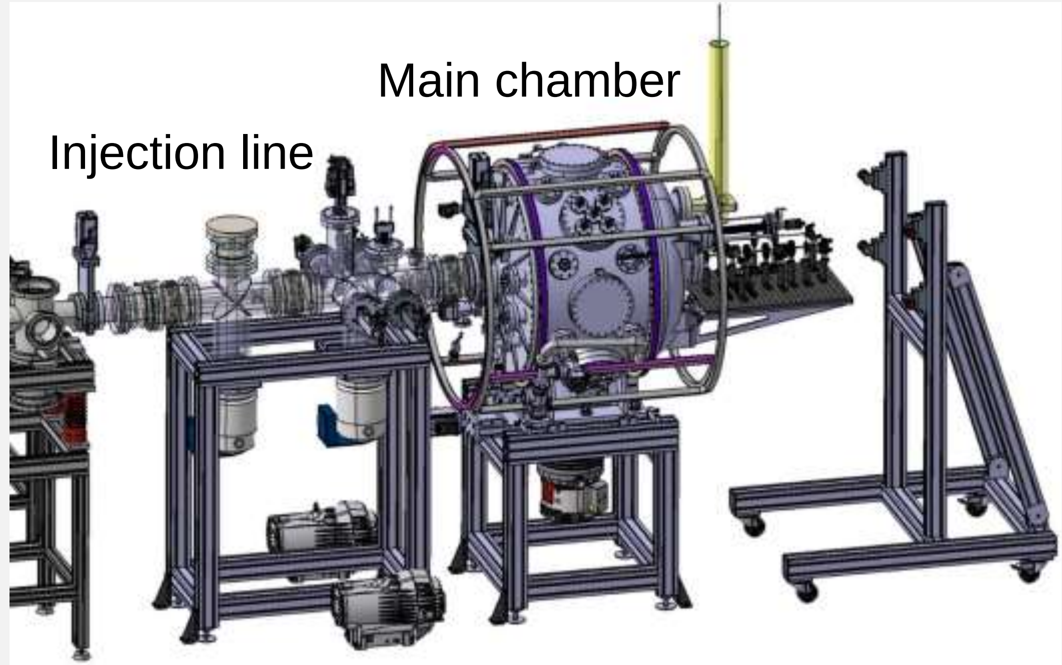


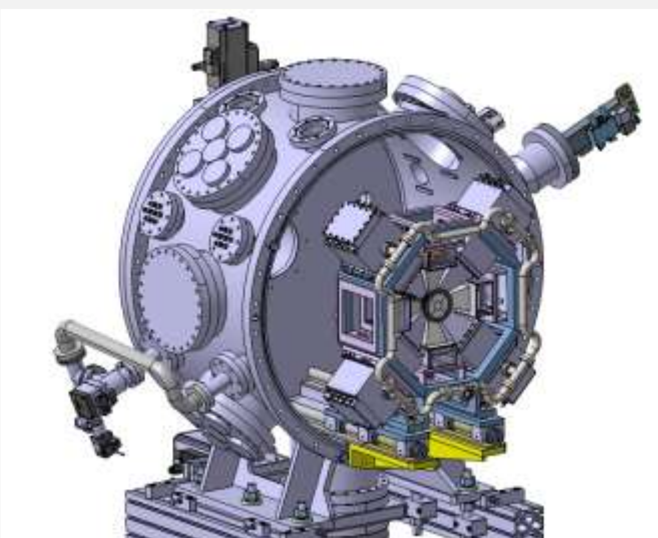


Main chamber

MORA: status

- Injection line & main chamber
  - ✓ design almost completed
- Main chamber
  - ✓ built
- Detection
  - ✓ phoswich: tests & simulations
  - ✓ RIDE – Si: design completed
- Slow control
  - ✓ just started





<u>Schedule</u>

- Setup built in spring-summer 2020
- Installed @JYFL by end 2020
- First measurements in 2021:
  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} (~1.2×10^{-4})?
(DESIR/SPIRAL1: I(^{23}Mg) > 10^8 pps)

Next candidate: ^{39}Ca ?
→ better sensitivity to NP (D_{FSI} ~ -3×10^{-5})
→ production? *perspectives@S³ (> 10^6pps?)* ...

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Thank you for your attention

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