

# Trapping and polarization of $^{23}\text{Mg}$ ions for CP violation searches in nuclear beta decay

**MORA**

**Matter's Origin from RadioActivity**

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**GANIL**



# CP violation and the Matter-antimatter imbalance in the Universe

## Why is there more matter than antimatter in the universe?

- Big Bang → equal matter & antimatter expected
- To explain the matter–antimatter asymmetry in the universe, three conditions must be satisfied (Sakharov, 1967):
  - Violation of baryon number
  - Violation of C and CP symmetries
  - Departure from thermal equilibrium

A. D. Sakharov, «Violation of CP invariance, C asymmetry, and baryon asymmetry of the universe,» *JETP Letters*, vol. 5, p. 24, 1967.

- CP violation is observed in **K**, **B**, and **D** mesons within the Standard Model.
- It is insufficient to explain the matter–antimatter asymmetry.
- Indicates the need for new physics beyond the Standard Model.



# Search for new physics via the $D$ correlation measurement

$$w(\langle \vec{J} \rangle | E_e, \Omega_e, \Omega_\nu) dE_e d\Omega_e d\Omega_\nu = \frac{F(\pm Z, E_e)}{(2\pi)^5} p_e E_e (E_0 - E_e)^2 dE_e d\Omega_e d\Omega_\nu$$

$$\times \frac{1}{2} \xi \left[ 1 + a \frac{\vec{p}_e \vec{p}_\nu}{E_e E_\nu} + b \frac{m}{E_e} + \frac{\langle \vec{J} \rangle}{J} \cdot \left( A_\beta \frac{\vec{p}_e}{E_e} + B_\nu \frac{\vec{p}_\nu}{E_\nu} + D \cdot \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right) \right]$$

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

$D$  is T-odd  $\rightarrow$  non-zero  $D$  implies CP violation

Correlation	Correlation coefficient	Symmetry (P,T)
Beta-neutrino angular	$a$	P-even, T-even
Fierz interference	$b$	P-even, T-even
Beta asymmetry	$A_\beta$	P-odd, T-even
Neutrino asymmetry	$B_\beta$	P-odd, T-even
<b><math>D</math> correlation</b>	<b><math>D</math></b>	<b>P-even, T-odd</b>

## Search for New Physics

- Direct constraints on CP-violating Wilson coefficients in the nucleon-level EFT  $\sim 10^{-4}$  measurement
- Probe specific BSM Models, like L-R symmetric model and Leptoquark model  $\sim 10^{-5}$  measurement
- Measure Final State Interactions, predicted by the SM

# MORA: Best candidates for $D$ measurement

$$D \equiv \sin(\varphi_{AV}) \cdot \underbrace{\frac{2\rho}{1+\rho^2} \cdot \left(\frac{J}{J+1}\right)^{1/2}}_{F(X)} \quad \rho \sim \frac{C_A M_{GT}}{C_V M_F}$$

From neutron measurement (emiT):  $\varphi_{AV} = 180.013^\circ \pm 0.028^\circ$  (68% CL)

T. E. Chupp, R. L. Cooper, K. P. Coulter, et al. Phys. Rev. C 86, 035505 (2012)

Neutron and mirror nuclei (N=Z-1): strong mixed (GT+ Fermi) transitions between analog states

	n	<sup>19</sup> Ne	<sup>23</sup> Mg	<sup>35</sup> Ar	<sup>39</sup> Ca
<b>Sensitivity <math>F(X)</math></b>	0,43	-0,52	-0,65	0,41	0,71
<b><math>D_1</math> (<math>\times 10^{-4}</math>)</b>	0,11	2,31	2,64	0,43	-0,47
<b><math>D_2</math> (<math>\times 10^{-4}</math>)</b>	0,02	0,17	0,16	0,01	-0,02

$$D_n = (-0.94 \pm 1.89 \pm 0.97) \cdot 10^{-4} \quad D_{^{19}\text{Ne}} = (1 \pm 6) \cdot 10^{-4}$$

emiT collaboration, PRL 107, 102301 (2011),

Calaprice, Hyp. Int. 22(1985)83

Best measurement so far, *statistics limited*

$$D_{FSI}(p_e) = \left( D_1 \cdot \frac{p_e}{p_{e\max}} + D_2 \cdot \frac{p_{e\max}}{p_e} \right) \times 10^{-4}$$

Callan and Treiman, Phys. Rev. 162(1967)1494.  
Chen, Phys. Rev. 185(1969)2003.

# MORA: in-trap laser polarization

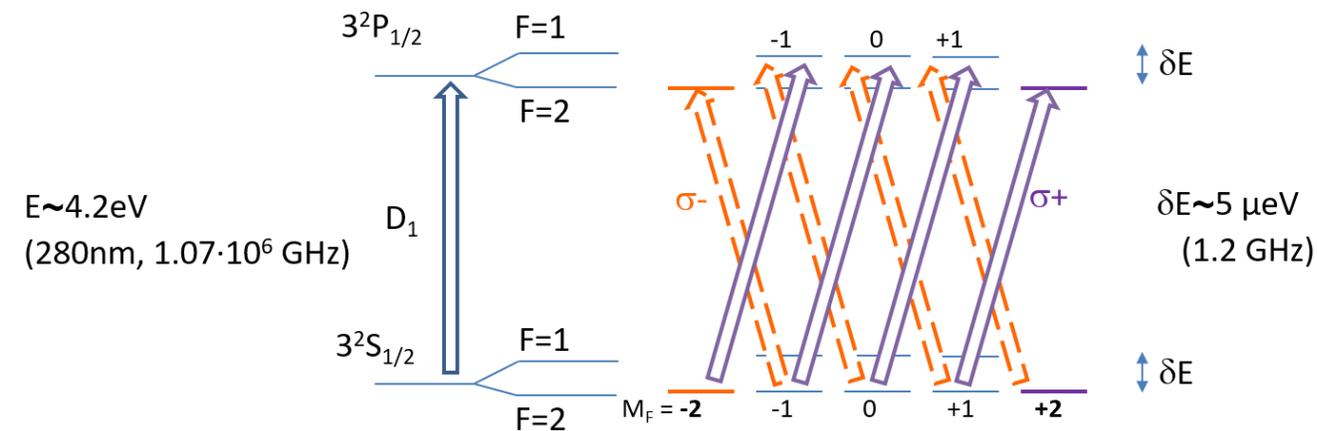
## Proof of principle is the first objective at JYU

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

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

<sup>23</sup>Mg hyperfine structure

$F=I+J$

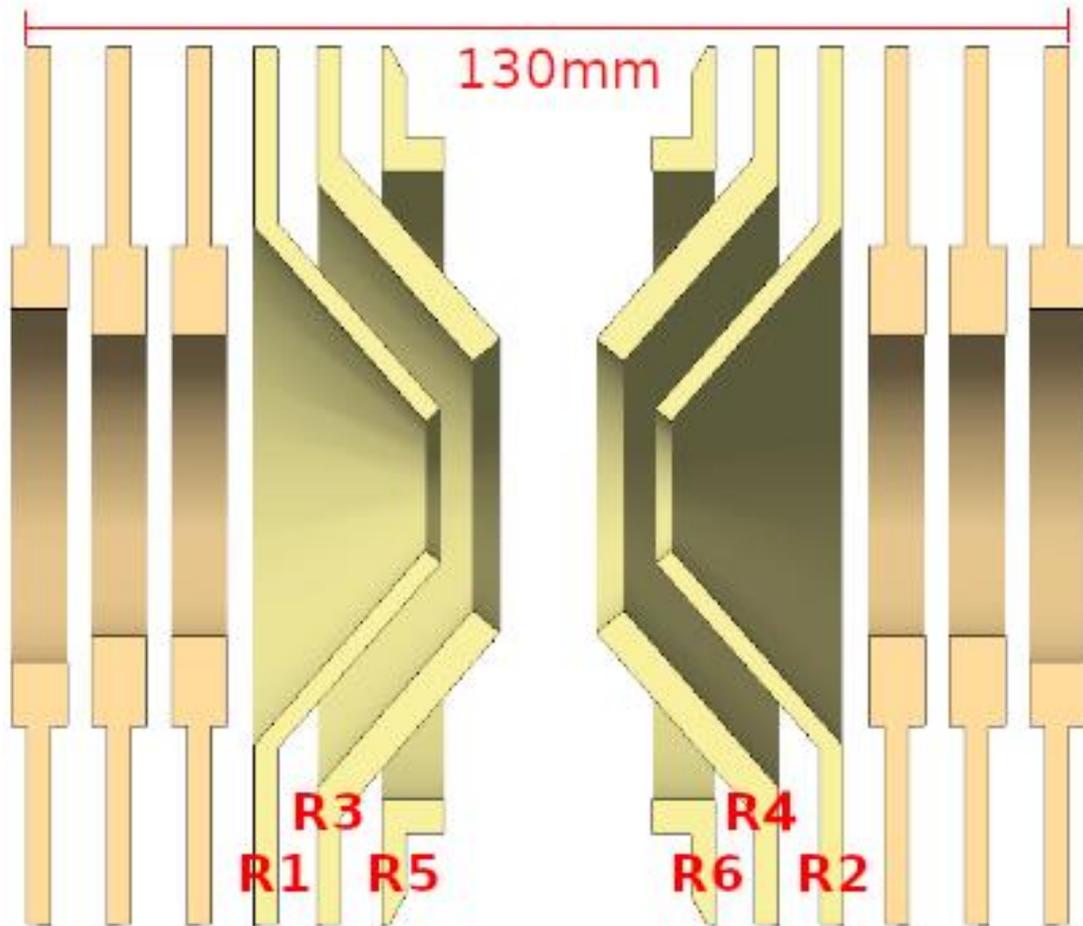


- Pump the ions to  $m_F = \pm 2$  for spin  $J$  polarization
- $D_1$  transition excitation with a circular polarized laser to increase(decrease) the projection number  $m_F$
- <sup>39</sup>Ca has a more complex structure to polarize than <sup>23</sup>Mg (2 lasers vs 1 laser)
- <sup>23</sup>Mg is the best candidate for the first experiments at IGISOL
  - Easy to produce and polarize
  - High sensitivity to FSI and new physics

# MORA apparatus

# MORA Trap

Paul Trap developed in LPC caen

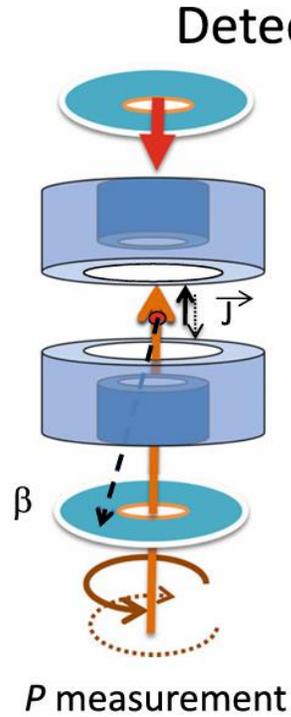
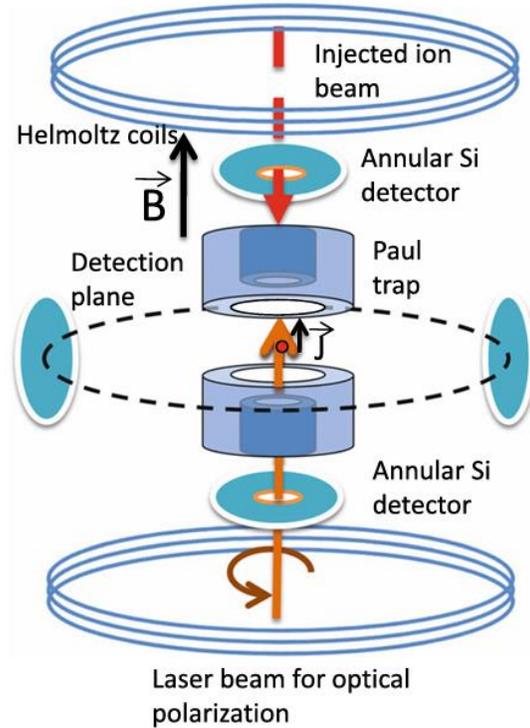


## Trap Setup

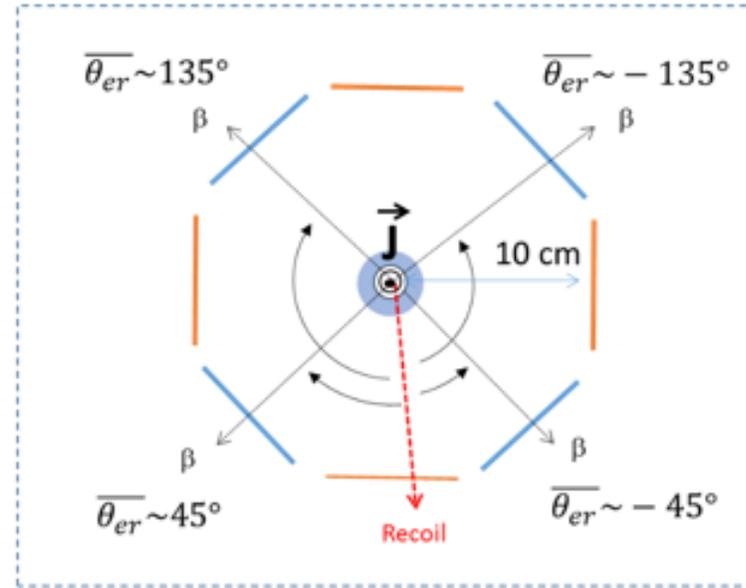
- 6 electrodes: R1–R2 (RF end caps), R3–R4 (injection/ejection), R5–R6 (correction)
- Einzel lenses only for injection/extraction
- Buffer gas:  $^4\text{He}$  ( $\sim 10^{-5}$  mbar) for cooling & Doppler effect reduction for better trapping efficiency



# Detection setup



## Detection setups



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

- Polarization monitoring thanks to **beta asymmetry**:  $A_\beta$
- 2 **annular Si** detectors in the line axis for polarization measurement

$$\frac{N_{\beta+}^\uparrow - N_{\beta+}^\downarrow}{N_{\beta+}^\uparrow + N_{\beta+}^\downarrow} \propto A_\beta \cdot P$$

$\sim 10^2$  ions / cycle

- Extract **D correlation** from  $\beta$ -recoil coincidences.  
 $\vec{J} \cdot (\vec{p}_e \times \vec{p}_\nu)$  is equivalent to  $\vec{J} \cdot (\vec{p}_e \times \vec{p}_r)$ .  $\rightarrow$  measure **recoil ions**.
- Alternating **phoswich** ( $\beta$ ) and **RIDE** (recoil ion) detectors every  $45^\circ$

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

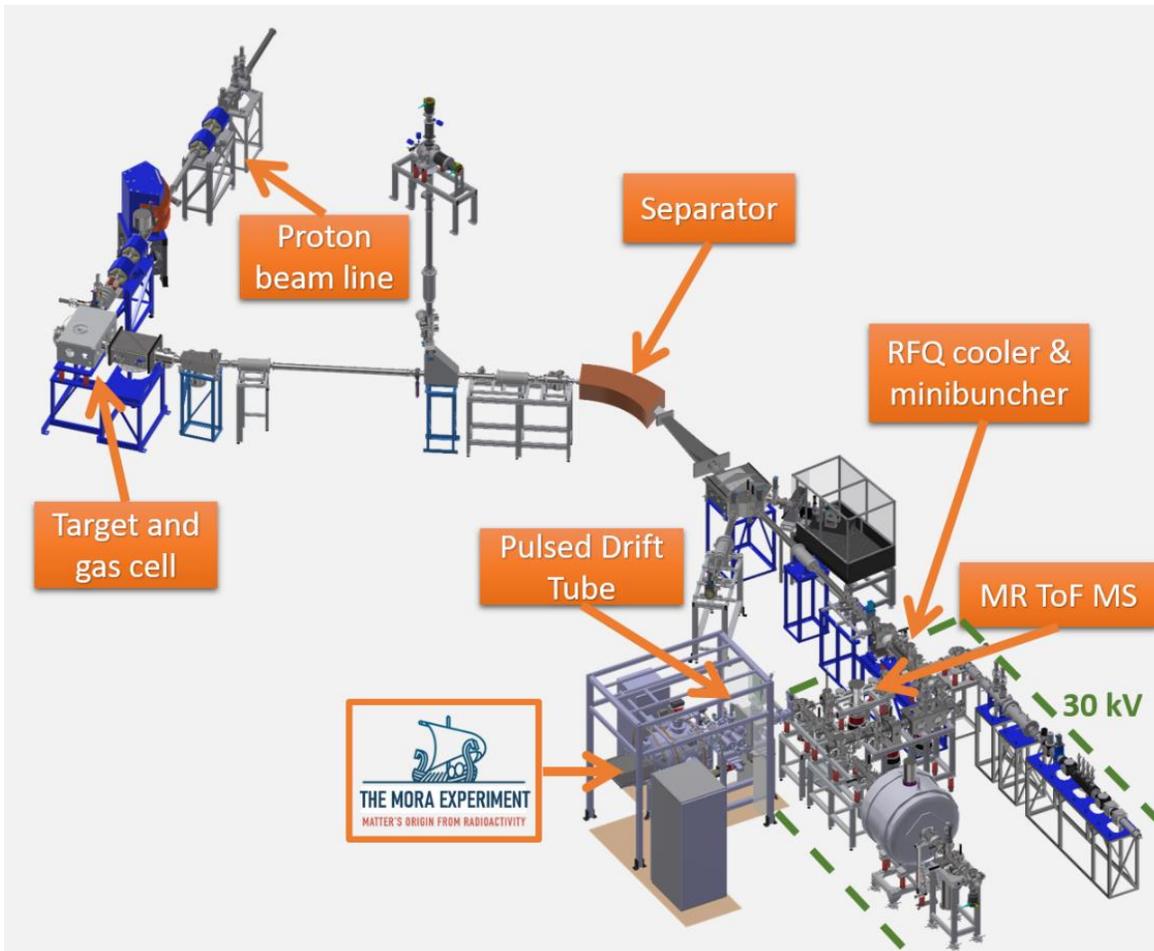
$\sim 10^4$  ions / cycle



**THE MORA PROJECT**

**Experimental Status**

# Ion production & manipulation ( IGISOL)



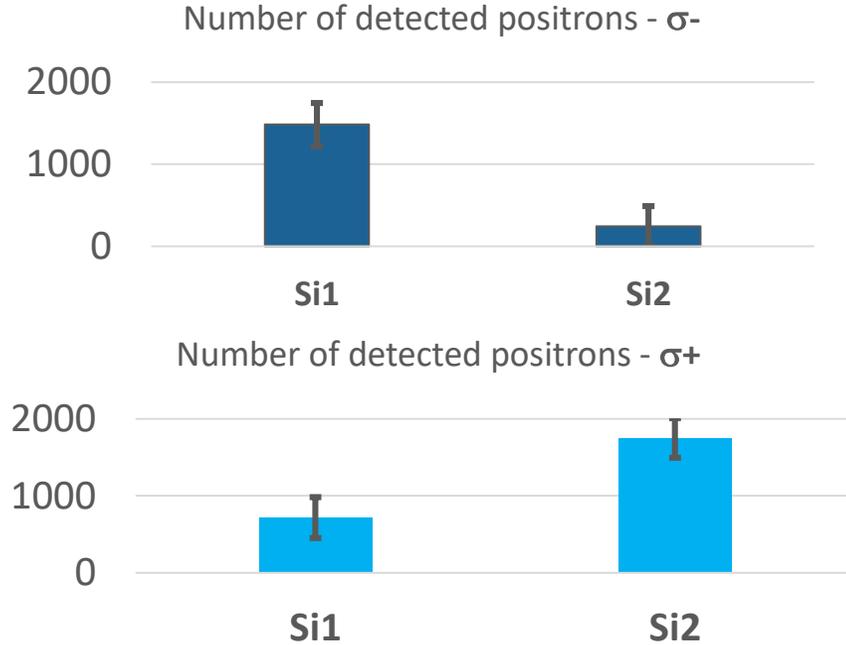
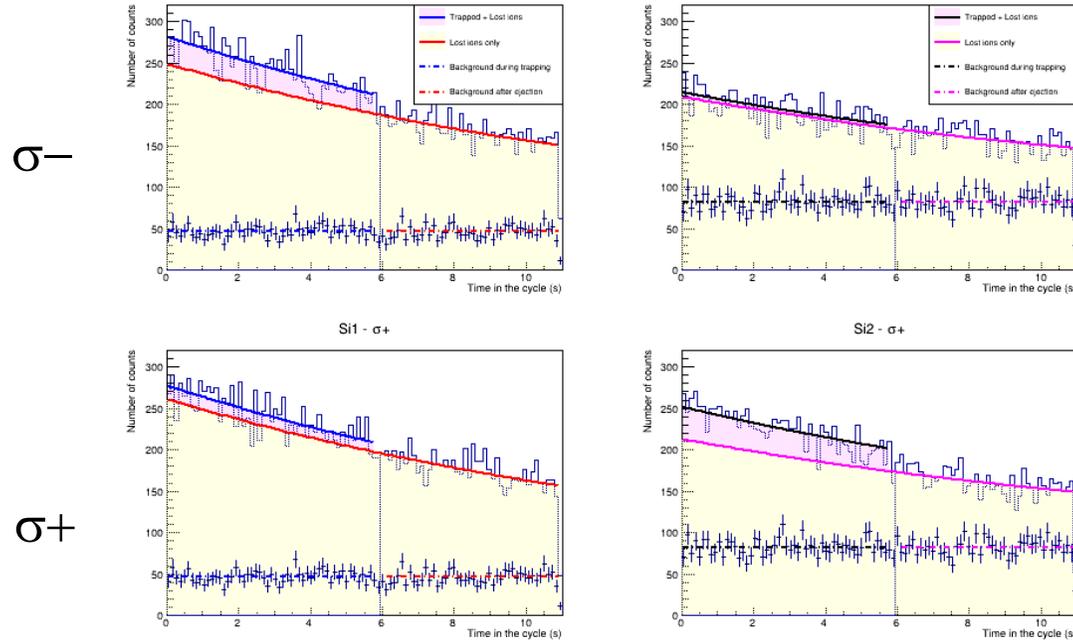
- **Radioactive ions** (e.g.,  $^{23}\text{Mg}^+$ ) produced at IGISOL using 30 MeV proton beam on Mg target
- Ions' path : Gas cell ( stops & thermalizes)  $\rightarrow$  SPIG  $\rightarrow$  mass separator  $\rightarrow$  minibuncher ( bunches & cools, saturates  $\sim 10^5$  ions/bunch).
- Up to  $5 \times 10^5$  pps  $^{23}\text{Mg}^+$  from gas cell
- Beam comes with  $^{23}\text{Na}^+$  as isobaric contaminant after separator
  - Initially up to  $10^4$  more  $^{23}\text{Na}^+$  than  $^{23}\text{Mg}^+$
  - But cross section calculations give a factor of 2
- **Polarization proof-of-principle not possible!**
- Investigation revealed the issue came from the **SPIG**: Helium ions sputtered sodium residues from the SPIG during beam time.
- SPIG cleaned with deionized water to remove residual sodium

# Experimental breakthrough

March 25

Si1

Si2



## First polarization measurement

N. Goyal et al, *Performance of the MORA Apparatus for Testing Time-Reversal Invariance in Nuclear Beta Decay*, arXiv:2504.16957, accepted by EPJ A

Trapped ions/cycle  
 $90 \pm 9$  from Si detectors  
 $145 \pm 55$  from coincidences

- Polarization  $\sigma^-$  :  $A^- = \frac{nSi_1 - nSi_2}{nSi_1 + nSi_2} = 0.72 \pm 0.25$
- Polarization  $\sigma^+$  :  $A^+ = -0.42 \pm 0.16$
- Full polarization of the cloud (from simulations):  $A^- = -A^+ = 0.51 \pm 0.01$

$$|A| = 0.51 \pm 0.14$$

➔ **55% < P < 100% at 90% C.L.**

# Beam time updates

- Na contamination resolved using new SPIG (baked rods to remove Na).
- First test with  $^{39}\text{Ca}$  performed.
- $^{39}\text{Ca}$  yield sufficient for D-correlation measurement.
- $^{39}\text{K}$  contamination (beam purity problem).
- Polarization not yet attempted for  $^{39}\text{Ca}$  due to limited preparation time.
- Low trap efficiency due to reliability issues at the IGISOL beamline (malfunctioning minibuncher and steering problems).
- 1 week of data acquisition scheduled (27 April – 5 May 2026)
- Proof-of-principle beam polarization of  $^{39}\text{Ca}$  later this year.



# Conclusion, outlook

- MORA aims to measure the D-correlation parameter in nuclear  $\beta$  decay to shed light on the matter–antimatter asymmetry in the universe.
- Polarization proof of principle successfully achieved with  $^{23}\text{Mg}^+$  ions.
- Further work needed to purify the  $^{39}\text{Ca}$  beam from  $^{39}\text{K}$  contamination.
- Reliability issues in the IGISOL beamline delayed the D-correlation measurement, but the problems have since been identified and are currently being resolved.
- We are almost ready for the D-correlation measurement — at least with  $^{23}\text{Mg}$ !



# MORA collaboration



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# Thank you for your attention!



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