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

MORA

Matter's Origin from RadioActivity

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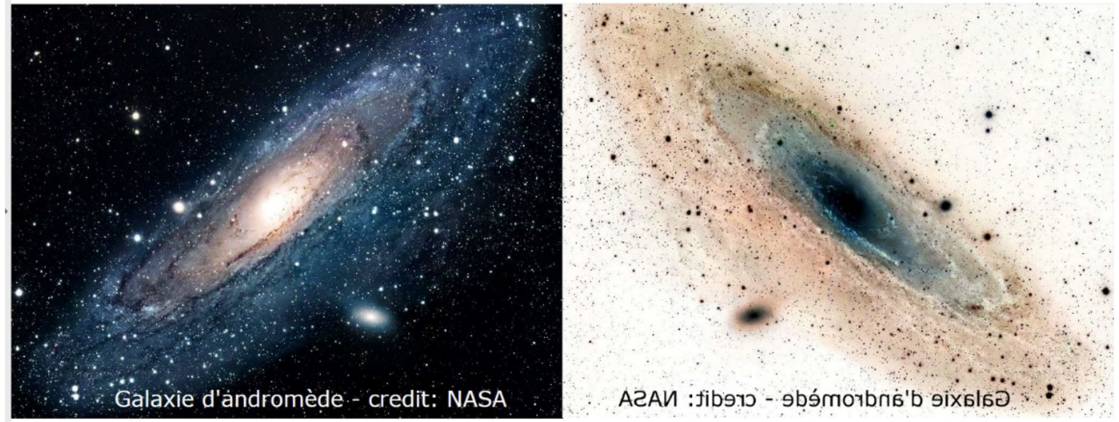
CP violation and the Matter-antimatter imbalance in the Universe

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

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$$w(<\vec{J}>|E_e,\Omega_e,\Omega_\nu)dE_e d\Omega_e d\Omega_\nu = \frac{F(\pm Z, E_e)}{(2\pi)^5} p_e E_e (E_0 - E_e)^2 dE_e d\Omega_e d\Omega_\nu$$
$$\times \frac{1}{2}\xi \left[1 + a\frac{\vec{p_e}\vec{p_\nu}}{E_e E_\nu} + b\frac{m}{E_e} + \frac{<\vec{J}>}{J}.\left(A_\beta \frac{\vec{p_e}}{E_e} + B_\nu \frac{\vec{p_\nu}}{E_\nu} + D.\frac{\vec{p_e}\times\vec{p_\nu}}{E_{eE_\nu}} \right) \right]$$

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

D is T-odd → 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_β	P-odd, T-even
Neutrino asymmetry	B_β	P-odd, T-even
***D* correlation**	D	P-even, T-odd

Search for New Physics

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

MORA: Best candidates for *D* measurement

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

From neutron measurement (emiT): $\varphi_{AV} = 180.013° \pm 0.028°$ (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	^{19}Ne	^{23}Mg	^{35}Ar	^{39}Ca
Sensitivity *F(X)*	0,43	-0,52	-0,65	0,41	0,71
D_1 (x10^{-4})	0,11	2,31	2.64	0,43	-0,47
D_2 (x10^{-4})	0,02	0,17	0,16	0,01	-0,02

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

Best measurement so far, *statistics limited*

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

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

MORA: in-trap laser polarization

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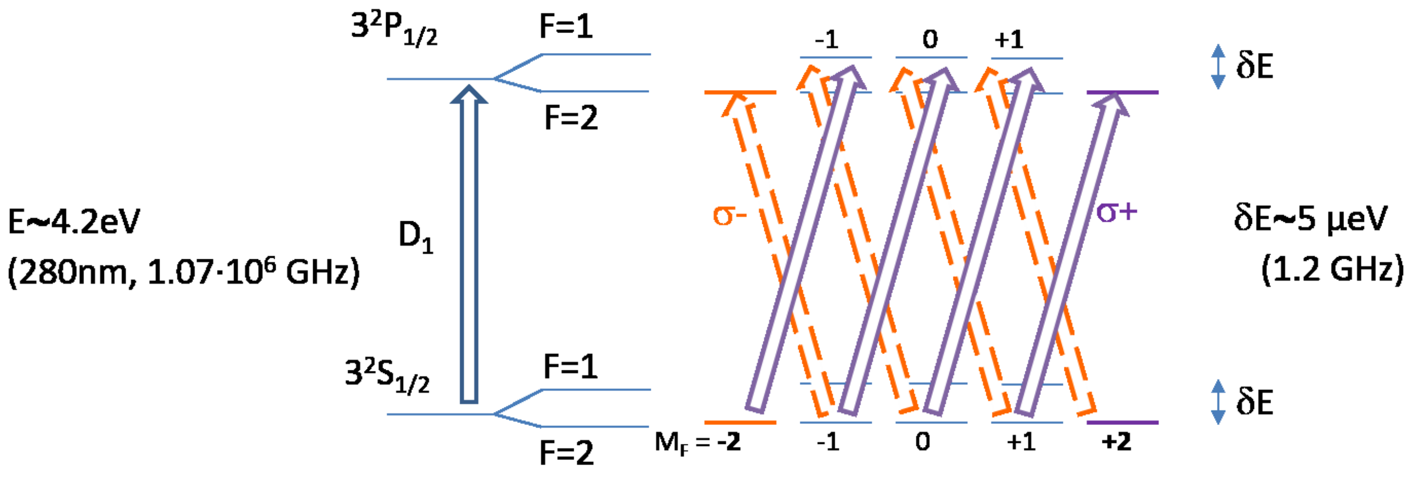
Proof of principle is the first objective at JYU

- 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=±F state

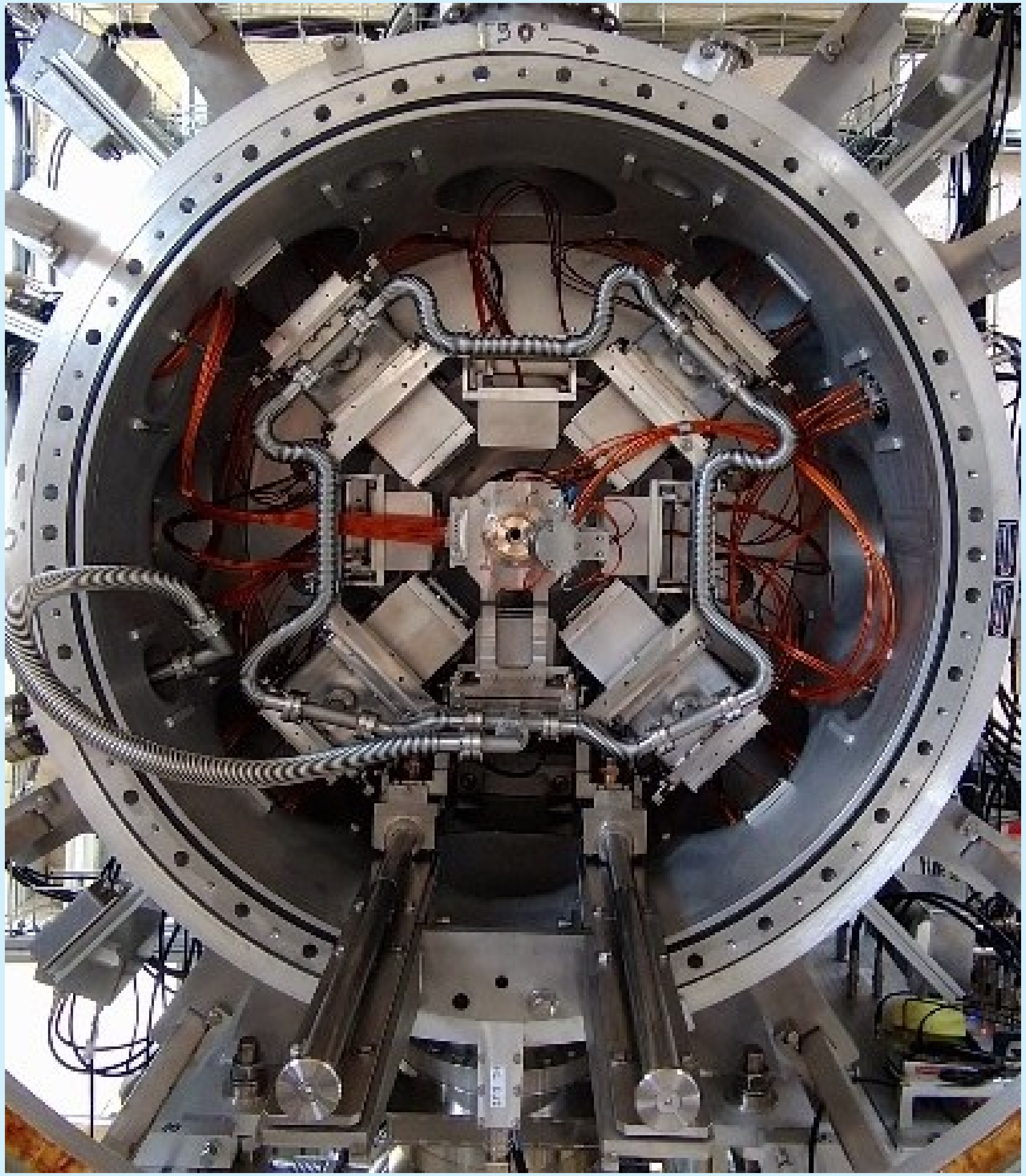
$$D\,\frac{\langle\vec{J}\rangle}{J}\cdot\left(\frac{\vec{p_e}}{E_e}\times\frac{\vec{p_\nu}}{E_\nu}\right)$$

^{23}Mg hyperfine structure

F= I+J



- Pump the ions to m_F = ± 2 for spin J polarization
- D_1 transition excitation with a circular polarized laser to increase(decrease) the projection number m_F
- ^{39}Ca has a more complex structure to polarize than ^{23}Mg (2 lasers vs 1 laser)
- ^{23}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

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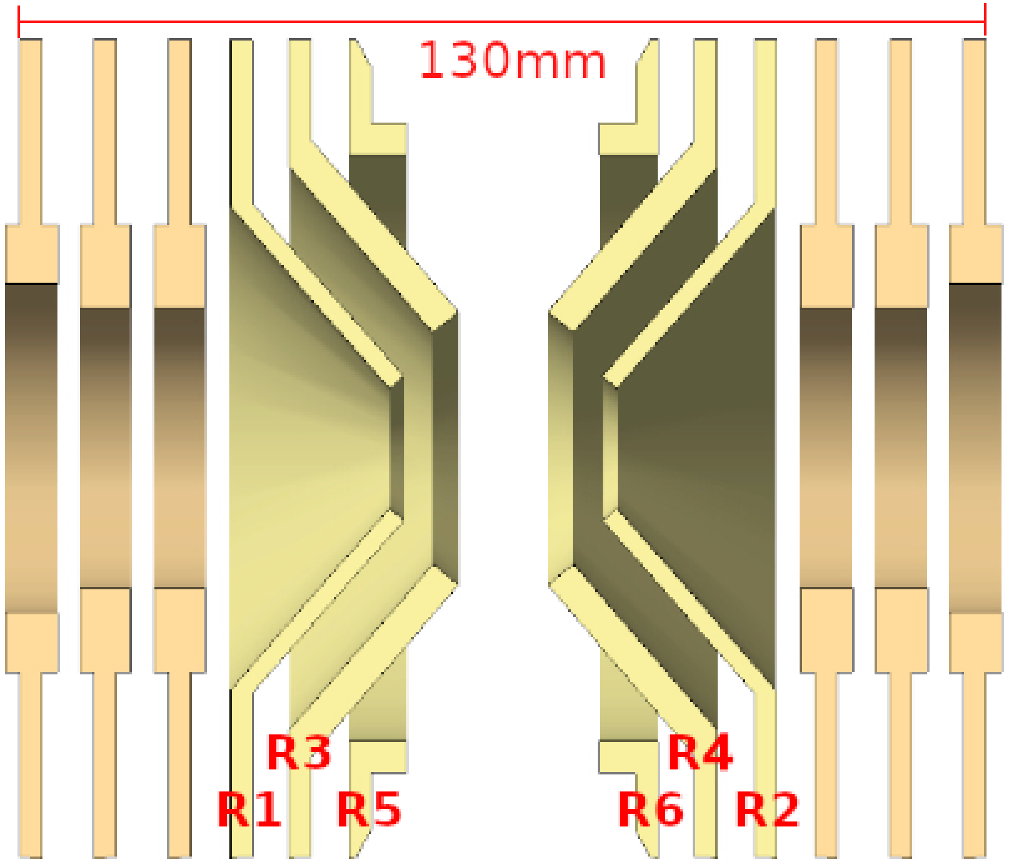
Paul Trap developed in LPC caen



- **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}He (~10^{-5} mbar) for cooling & Doppler reduction for better trapping efficiency

Detection setup

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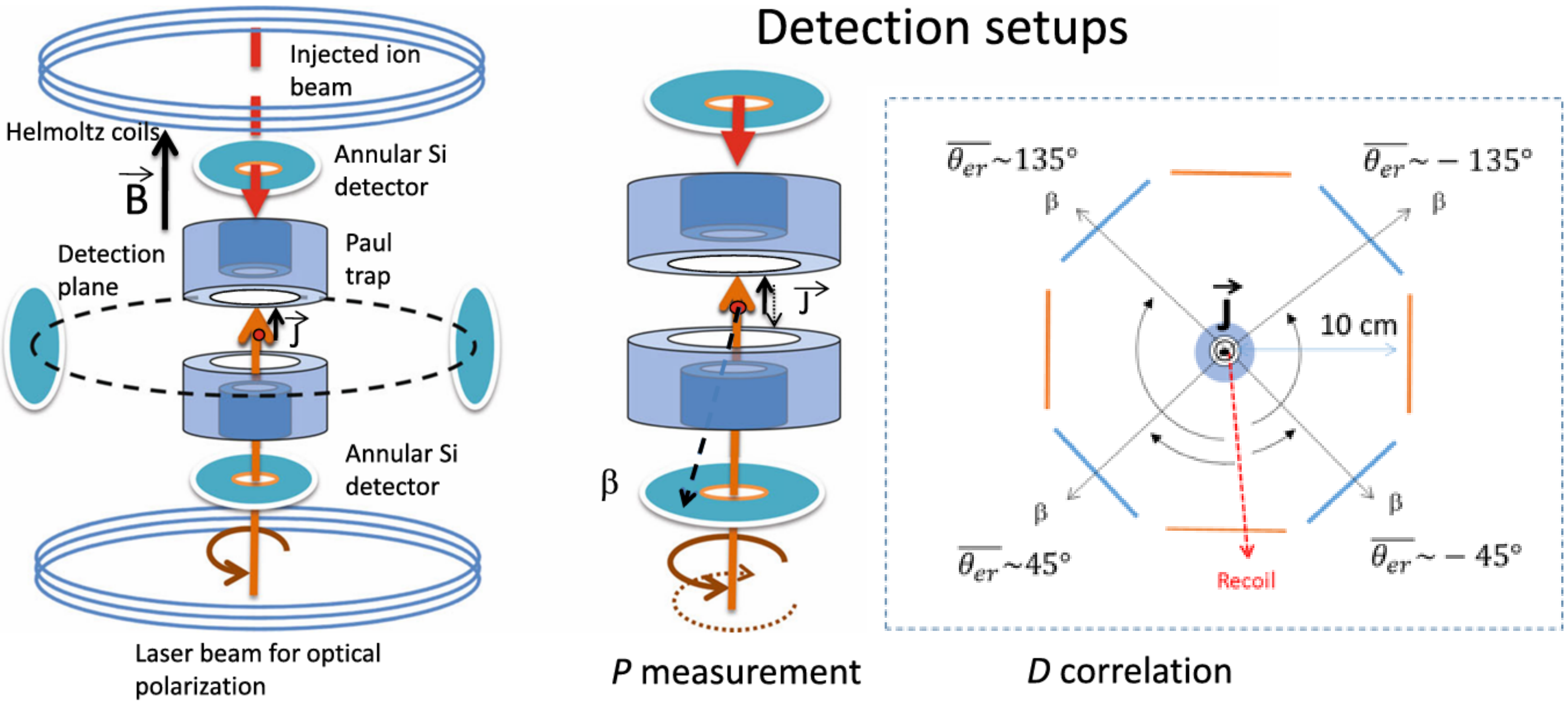
Detection setups



P measurement

D correlation

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

- Polarization monitoring thanks to **β assymetry:** A_β
- 2 **annular Si** detectors in the line axis for polarization measurement

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

~10² ions / cycle

- Extract **D correlation** from β–recoil coincidences.
  $\vec{J}\cdot(\overrightarrow{p_e}\times\overrightarrow{p_\nu})$ is equivalent to $\vec{J}\cdot(\overrightarrow{p_e}\times\overrightarrow{p_r})$. → measure **recoil ions**.
- Alternating **phoswich** (β) and **RIDE** (recoil ion)detectors every 45°

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

~10⁴ ions / cycle

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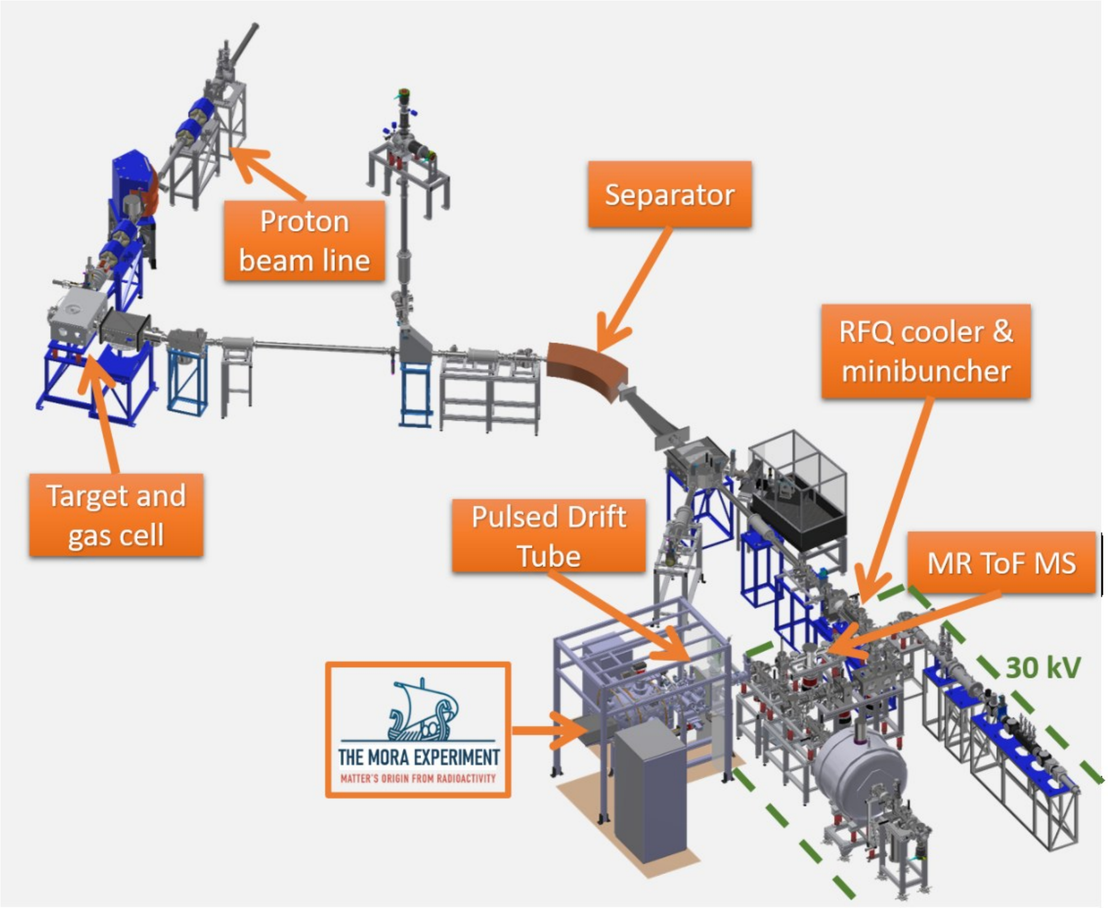
Experimental Status

Ion production & manipulation (IGISOL)



- **Radioactive ions** (e.g.,$^{23}\mathrm{Mg}^{+}$) produced at IGISOL using 30 MeV proton beam on Mg target

- Ions' path : Gas cell (stops & thermalizes) → SPIG → mass separator → minibuncher (bunches & cools, saturates ~10^5 ions/bunch).
- Up to **5×10^5 pps $^{23}\mathrm{Mg}^+$** from gas cell
- Beam comes with $^{23}\mathrm{Na}^+$ as isobaric contaminant after separator
  - Initially up to **10^4 more $^{23}\mathrm{Na}^+$ than $^{23}\mathrm{Mg}^+$**
  - 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

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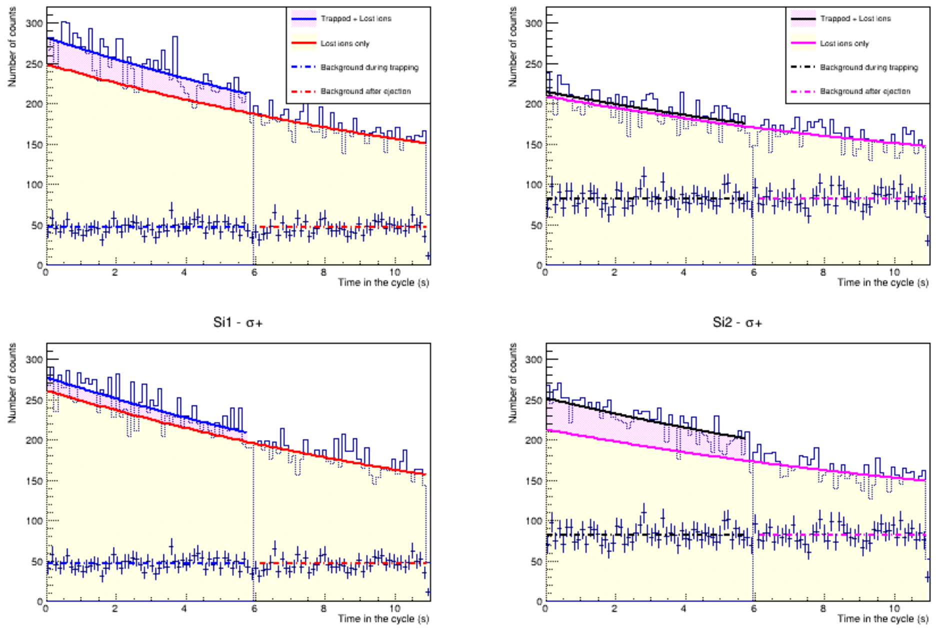
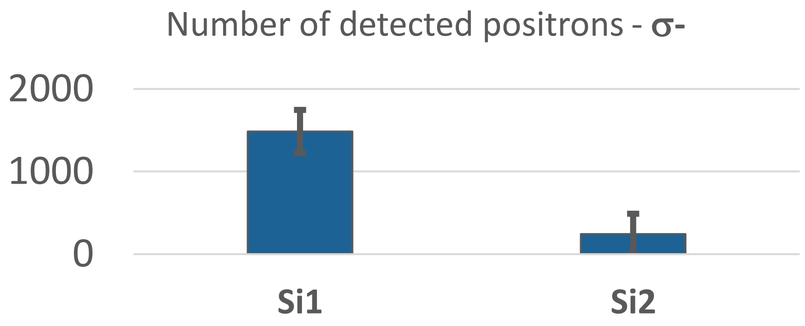
March 25

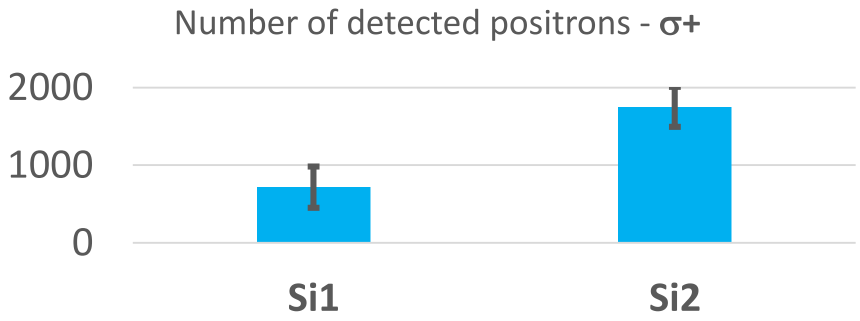
Si1 Si2

σ−

σ+







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±9 from Si detectors

145±55 from coincidences

First polarization measurement

- Polarization σ^- : $A^- = \frac{nSi_1 - nSi_2}{nSi_1 + nSi_2} = 0.72\pm0.25$
- Polarization σ^+ : $A^+ = -\ 0.42\pm0.16$
- Full polarization of the cloud (from simulations): $A^- = -A^+ = 0.51\pm0.01$

$|A| = \mathbf{0.51\pm0.14}$

55%<P<100% at 90% C.L.

Beam time updates

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- Na contamination resolved using new SPIG (baked rods to remove Na).
- First test with ^{39}Ca performed.
- ^{39}Ca yield sufficient for D-correlation measurement.
- ^{39}K contamination (beam purity problem).
- Polarization not yet attempted for ^{39}Ca due to limited preparation time.
- Low trap efficiency due to reliability issues at the IGISOL beamline (malfunctioning minibuncher and steering problems).

Conclusion, outlook

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•MORA aims to measure the D-correlation parameter in nuclear β decay to shed light on the matter–antimatter asymmetry in the universe.

•Polarization proof of principle successfully achieved with $^{23}Mg^{+}$ ions.

•Further work needed to purify the ^{39}Ca beam from ^{39}K contamination.

•Reliability issues in the IGISOL beamline delayed the D-correlation measurement, but the problems have since been identified and solved.

•We are almost ready for the D-correlation measurement — at least with ^{23}Mg!

MORA collaboration

Thank you for your attention!

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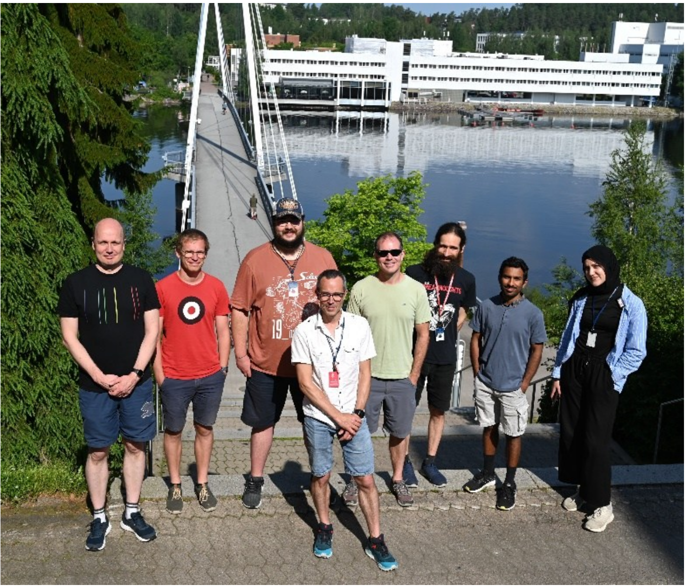

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