La MORA
Bayeux tapestry

THE MORA EXPERIMENT

Matter's Origin from RadioActivity

Searching for BSM Physics with β Decay

Kick-off meeting of the

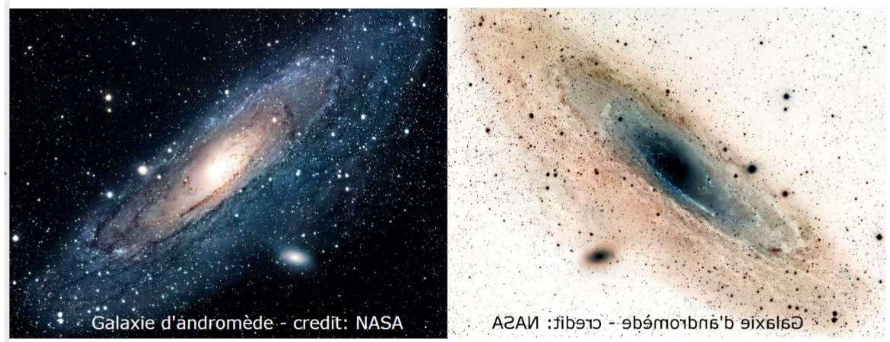
AdvanCed CaLcium radioActive Isotope Manipulation for MORA project

ACCLAIM MORA

P. Delahaye, GANIL

CP violation and the Matter-antimatter imbalance in the Universe

The big bang should have produced equal amounts of matter and antimatter



In 1967, Sakharov expresses the 3 conditions for Baryogenesis, the processus responsible for the 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.

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

CP violation observed in the K, B and D - meson decays is not enough to account for the large matter – antimatter asymmetry

Physics beyond the Standard Model !

Search for new physics via the *D* correlation measurement

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

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

T reversal odd

$$D \equiv \sin(\boldsymbol{\varphi_{AV}})\cdot\underbrace{\frac{2\rho}{1+\rho^2}\cdot\left(\frac{J}{J+1}\right)^{1/2}}_{F(X)}$$

$$\rho\sim\frac{C_A M_{GT}}{C_V M_F}$$

Best measurement so far: $\boldsymbol{D_n}$**= (−0.94 ±1.89±0.97)·10^{-4}** *emiT collaboration, PRL 107, 102301 (2011),*

$\boldsymbol{D_{19_{Ne}}}$**=(1 ±6)·10^{-4}** *Calaprice, Hyp. Int. 22(1985)83*

$$\varphi_{AV} = 180.013° \pm 0.028° \text{ (68\% CL)}$$

Search for New Physics

- **Direct constraints** on CP-violating Wilson coefficients in the nucleon-level EFT ➡ Interest for ~10^{-4} measurement
- Specific New Physics models ➡ Interest for ~10^{-5} measurement
  - via **the L-R symmetric model:**
    - M. J. Ramsey-Musolf et J. C. Vasquez, «Left-right symmetry and electric dipole moments. A global analysis,» arXiv:2012.02799 [hep-ph], 2020.
  - via **the LQ model**
    - Thorough investigation undertaken at IJClab by Adam Falkowski and Antonio Rodriguez-Sanchez
      - «On the sensitivity of the D parameter to new physics » , Eur. Phys. J. C (2022) **82**: 1134
      - Presentation at MORA workshop https://indico.in2p3.fr/event/25986/
    - Severe constraints for CP violating terms from EDM, pion decay and high energy searches
    - But D is also sensitive **to exotic non-CP violating terms via recoil-order corrections**

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- via **the L-R symmetric model:** ➡ Interest for ~10^{-5} measurement
- via **the LQ model**

Below 10^{-4}, measurement of Final State Interactions

Recoil order effect due to the weak magnetism (allowed in SM)

$$D_{FSI}\sim Z\alpha\frac{E_e}{M}\cdot A\left(\mu_f-\mu_i\right)$$ Callan and Treiman, Phys. Rev. 162(1967)1494.

Never accessed by a direct measurement in *D*

Search for new physics via the *D* correlation measurement

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

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

T reversal odd

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

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A measurement of *D* to the 10^{-5} level: looking for New Physics and accessing for the first time FSI

Edoardo Alviani and Adam Falkowski: ***On the Coulomb corrections in nuclear beta decay*** arXiv:2412.17702 [hep-ph]

MORA in a nutshell

THE MORA EXPERIMENT
Matter's Origin from RadioActivity

D correlation measurement in ^{23}Mg, ^{39}Ca decays to the 10^{-5} level with some beam, laser and trapping R&D

State of the art techniques from ISOL facilities

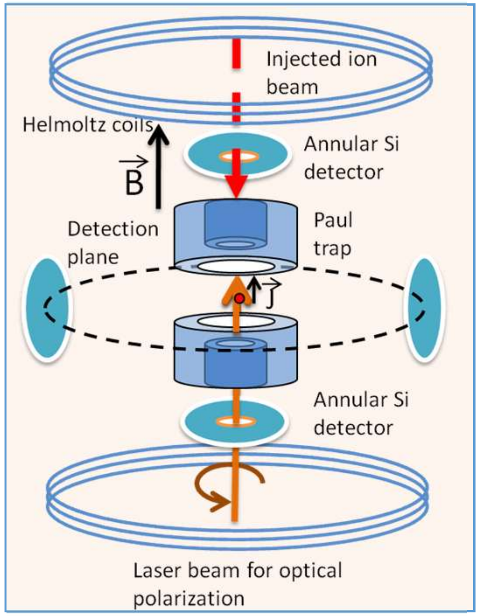
- **Ion cooling and trapping originally developpped for**

LPCTrap

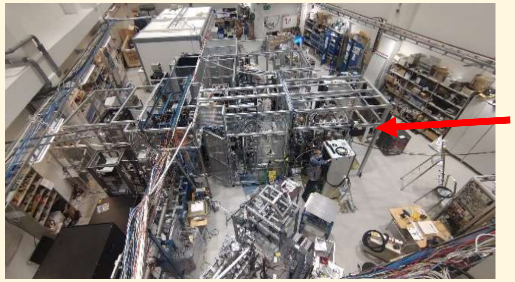
New trap and new detection setup:
off-line commissioning at LPC Caen and GANIL

Completed in automn 2021

- **Theoretical studies with state-of-the-art EFTs**



- **Innovative laser polarisation techniques at**



MORA installation at JYU/IGISOL (completed!)

Proof of principle of polarization
First D measurement ~10^{-4}

Started in Feb 2022

With experts from:

ISOLDE, KU LEUVEN (Nuclear and Radiation Physics), MANCHESTER 1824 (The University of Manchester)

Back to GANIL/DESIR, making use of the intense and purified ISOL beams from SPIRAL 1/ S3-LEB: **2028**

MORA: Best candidates for *D* measurement

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$$D \equiv \sin(\varphi_{AV}) \cdot \underbrace{\frac{2\rho}{1+\rho^2} \cdot \left(\frac{J}{J+1}\right)^{1/2}}_{F(X)}$$

Sensitivity to CP violating phase between V and A currents

Search for New Physics

- **Direct constraints** on CP-violating Wilson coefficients in the nucleon-level EFT
- via **the L-R symmetric model**
- via **the LQ model**

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 ($\times 10^{-4}$)	0,11	2,31	2.64	0,43	-0,47
D_2 ($\times 10^{-4}$)	0,02	0,17	0,16	0,01	-0,02

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

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: Best candidates for *D* measurement

$$D \equiv \sin(\varphi_{AV}) \cdot \underbrace{\frac{2\rho}{1+\rho^2} \cdot \left(\frac{J}{J+1}\right)^{1/2}}_{F(X)}$$

Sensitivity to CP violating phase between V and A currents

Search for New Physics

- **Direct constraints** on CP-violating Wilson coefficients in the nucleon-level EFT
- via **the L-R symmetric model**
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Neutron and mirror nuclei (N=Z-1): strong mixed (GT+ Fermi) transitions between analog states

MORA: Alkali earth elements for in trap laser ion polarization

1st candidate; 10^5 pps from JYFL
>10^8 pps from SPIRAL 1

2^{nd} candidate, R&D for ISOL production required

	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

ACCLAIM MORA

- Up to 10^7 pps requested
- Laser polarisation with 2 lasers
- >50% beam purity

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

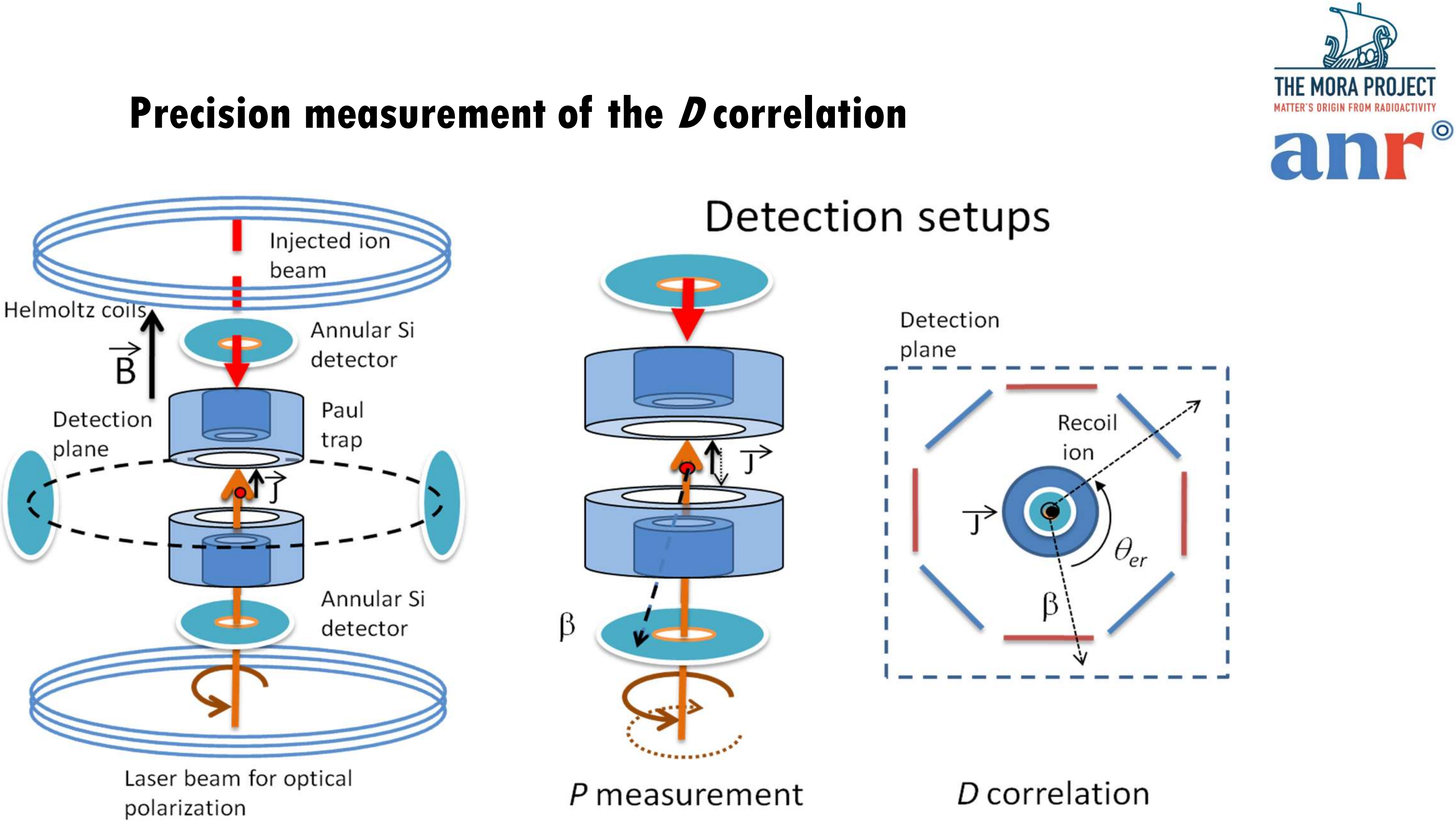
Best measurement so far, *statistics limited*

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

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

^{39}Ca + ^{23}Mg are required to look both for New Physics and FSI

Precision measurement of the *D* correlation

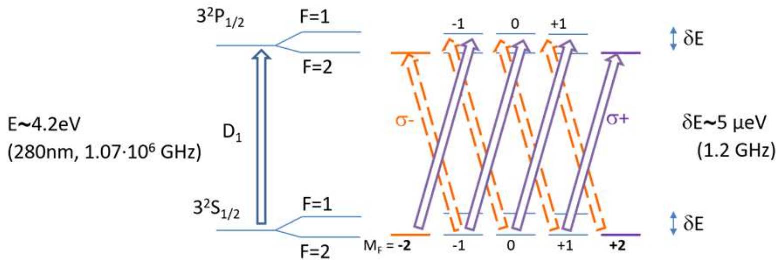


MORA: in-trap laser polarization

Innovative technique! Proof of principle was 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 $m_F=\pm F$ state

^{23}Mg hyperfine structure



Transitions excited using trippled Ti:Sa laser pulses
λ~280nm σ+ polarization, ~4GHz width

Doppler shift/broadening due to ion motion ~1.6GHz

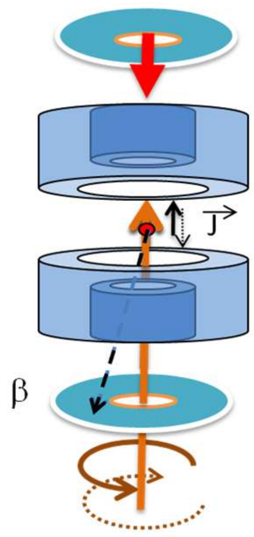
Collisions with He atoms (no spin) do not depolarize

With the power available at JYFL
More than 99% achievable in 1ms

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

Probable limitation: laser light polarization

Polarization monitoring thanks to β **assymetry:** A_β



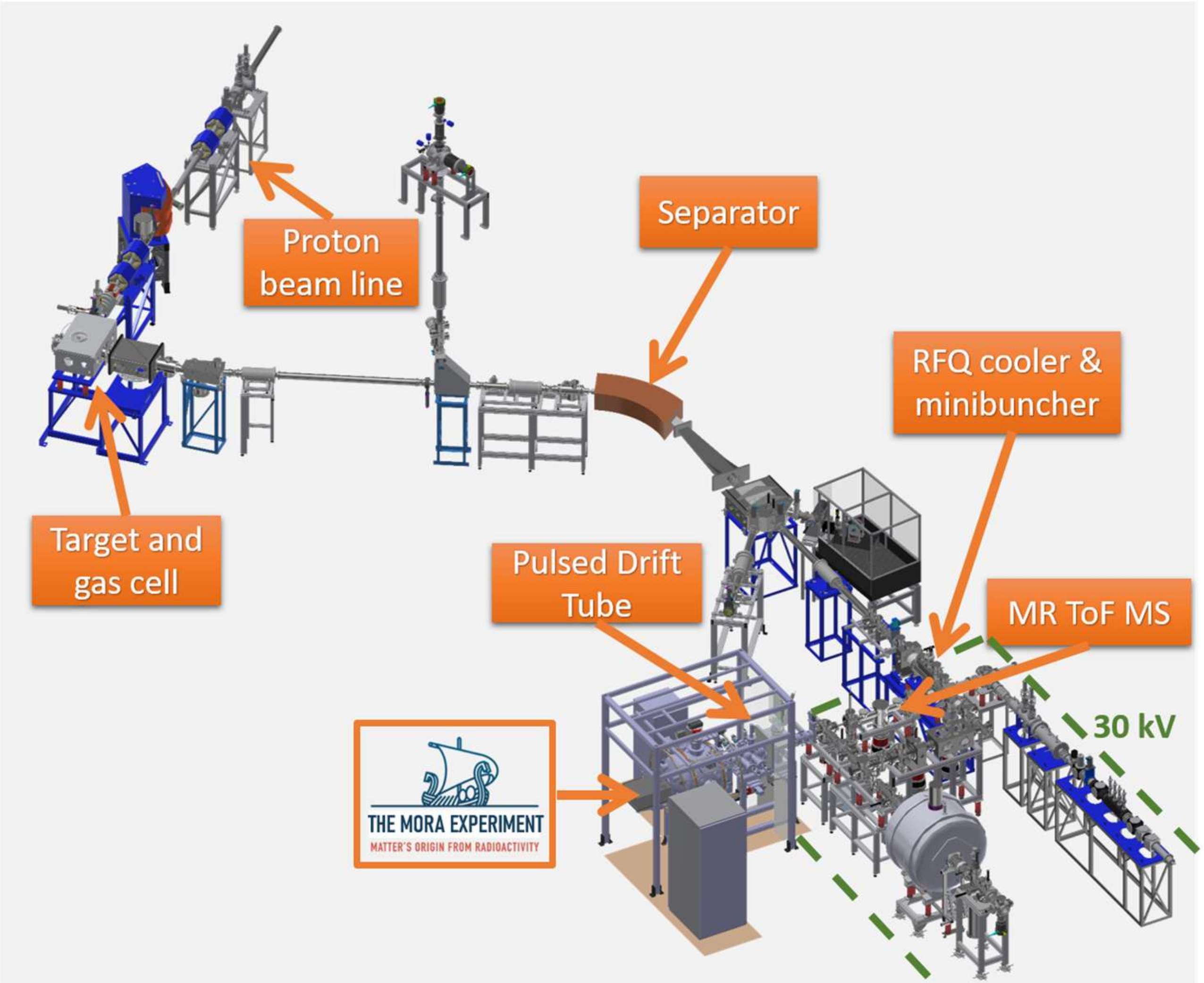
P measurement

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

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

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

^{23}Mg beam production and manipulation



- Up to **5x10^5 pps ^{23}Mg$^+$** from gas cell
- Beam comes with ^{23}Na$^+$ as isobaric contaminant after separator
  - Initially **up to 10^4 more ^{23}Na$^+$** than ^{23}Mg$^+$ (TALYS gives a factor of 2)
- Beam is cooled and bunched in RFQ cooler and minibuncher
- Minibuncher saturates **at ~10^5 ions per bunch**
- ^{23}Mg$^+$ ions in MORA: <10 bunch
- We need 10^4!

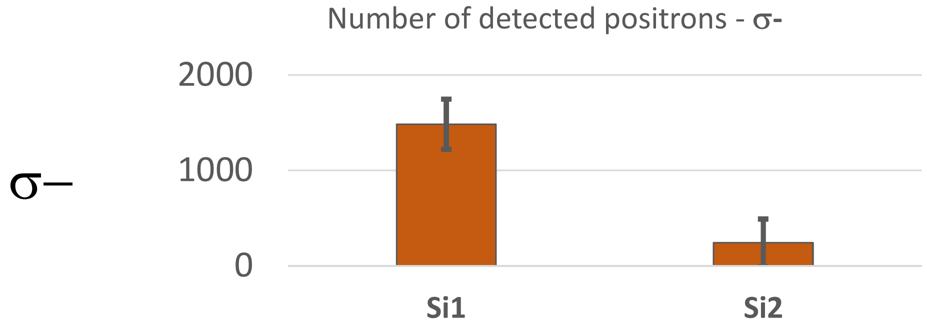
2024: The SPIG was identified as the source of the contamination

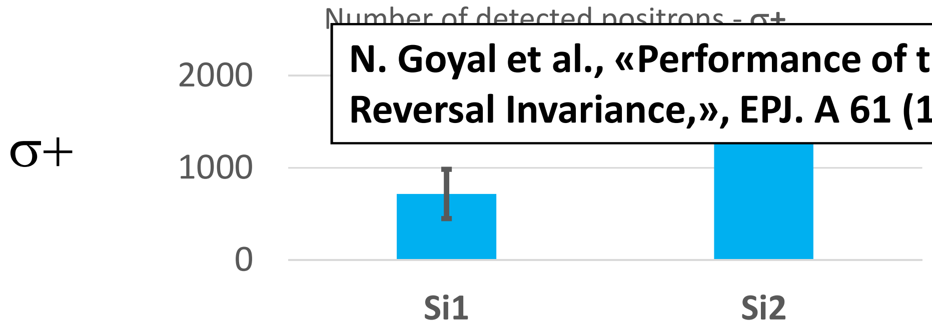
July 2025: 40,000 ^{23}Mg$^+$ in front of MORA with a modified SPIG

Experimental breakthrough – March 2025

March 25

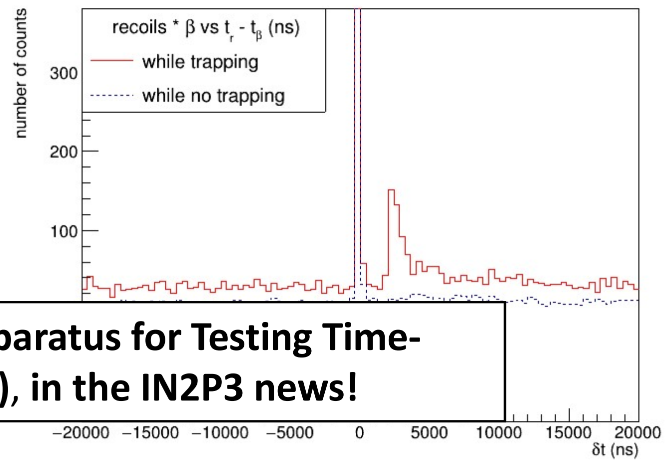
Si detectors to measure the polarisation





N. Goyal et al., «Performance of the MORA Apparatus for Testing Time-Reversal Invariance,», EPJ. A 61 (10), 221 (2025), in the IN2P3 news!

First β-recoil coincidences



Trapped ions/cycle

90±9 from Si detectors

145±55 from coincidences

First polarization measurement

- Polarization σ- : $A^{-} = \frac{nSi_1 - nSi_2}{nSi_1 + nS\ _2} = 0.72 \pm 0.25$
- Polarization σ+ : $A^{+} = -\ 0.42 \pm 0.16$
- 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.

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MATTER'S ORIGIN FROM RADIOACTIVITY

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IN2P3 highlight

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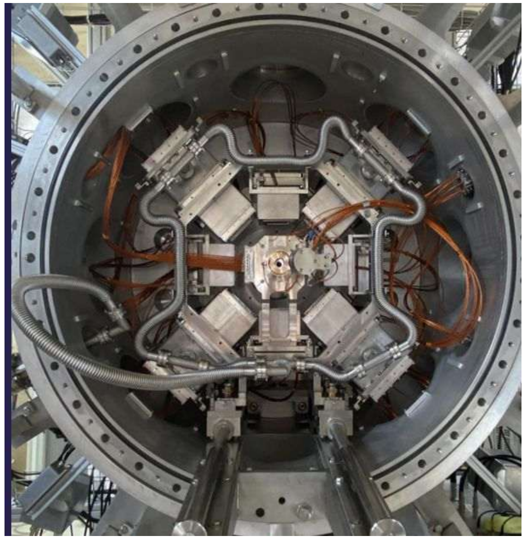
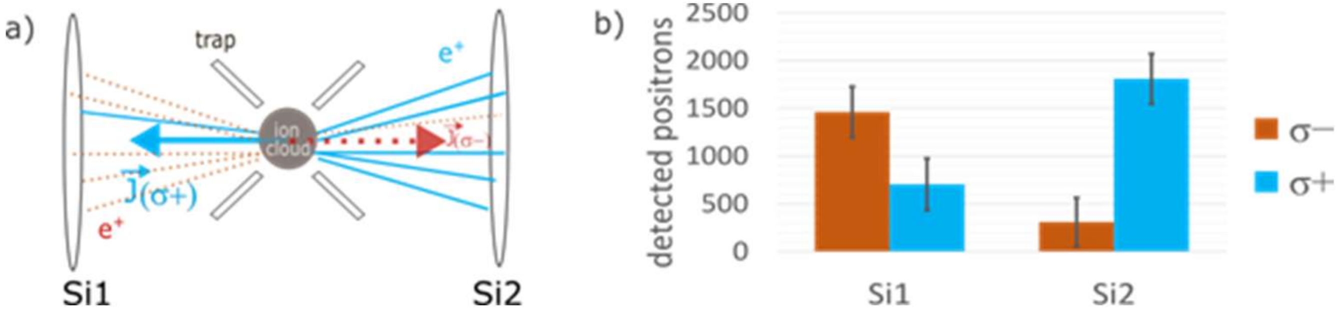


29.10.2025

RÉSULTATS SCIENTIFIQUES
PHYSIQUE NUCLÉAIRE

Première mesure du degré de polarisation d'ions radioactifs avec l'expérience MORA



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

Goyal et al., “Performance of the MORA apparatus for testing time-reversal invariance in nuclear beta decay,” Eur. Phys. J. A 61 (10), 221 (2025) - DOI: 10.1140/epja/s10050-025-01694-3

MORA: sensitivity challenges

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

Place and type of measurement	Trapped ions /cycle	Decays/s	Meas. time (days)	Detected coincidences (P)	σ_P stat (%)	Detected coincidences (D)	σ_D
JYFL: P - 23Mg	2,00E+04	1,23E+03	8	1,7E+05	**1,9E+00**	1,5E+06	1,0E-03
JYFL: D - 23Mg	2,00E+04	1,23E+03	32	6,7E+05	9,4E-01	6,1E+06	**5,2E-04**
JYFL: D - 39Ca	2,00E+04	1,61E+04	32	9,2E+06	2,0E-02	8,1E+07	$\boxed{\textbf{1,4E-04}}$
DESIR: D - 23Mg	5,00E+06	3,07E+05	24	1,3E+08	6,9E-02	1,2E+09	**3,8E-05**
DESIR: D - 39Ca	5,00E+06	4,03E+06	24	1,7E+09	1,5E-03	1,5E+10	$\boxed{\textbf{1,0E-05}}$

So far statistical uncertainties have dominated, over systematic uncertainties

See for ex.: $\boldsymbol{D_n = (-0.94 \pm 1.89 \pm 0.97) \cdot 10^{-4}}$

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

Provided that

- Production and purity is enough (✓ ^{23}Mg)
- Trapping capacity is attained
- Efficient laser polarization is demonstrated (✓ ^{23}Mg)
- Systematic effects are kept under control

→ Below 5.10^{-5} is feasible

Because of its shorter half life, ^{39}Ca shows promising prospects

AdvanCed CaLcium radioActive Isotope Manipulation for MORA

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- **Challenges for $^{39}Ca^{+}$**
  - **Production**
    - At IGISOL 10^5 pps ~ok
    - **10^7 pps at SPIRAL 1/DESIR is challenging** – high reactivity of vs short half-life
  - **Purity**
    - **At IGISOL ratio $^{39}K^{+}$:$^{39}Ca^{+}$ >100 - too high**
    - At DESIR HRS should solve the situation
  - **Stacking / bunching**
    - **A few 10^5 ions from minibuncher at IGISOL** – but could ideally be more
    - **Up to 10^7 ions/bunch at DESIR is challenging**
  - **Ion polarisation**
    - **At IGISOL and DESIR 1 IR + 1 Visible laser beams vs 1 UV laser for $^{23}Mg^{+}$**
  - **Ion polarisation vs systematic effects**
    - **Transverse polarization as dominant source of systematic effects**

TULIP idea - Pierre C. and Pascal

MR ToF MS capabilities - Brian

Minibuncher study - Ville

MORA RFQ buncher@DESIR - Vincent

Polarization scheme - Sai

Laser cabin @ DESIR- Coralie

Analysis - Luis Miguel

Other laser aspects- Ruben

AdvanCed CaLcium radioActive Isotope Manipulation for MORA

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- Project organization **ANR project - Sabrina**

2026 – 2029 686k€ **Advanced manipulation techniques $^{23}Mg^{+}$ & $^{39}Ca^{+}$**

	Production	Purification	Bunching	Polarisation	R. De Groote Analyse
GANIL	**1 PhD at SPIRAL 1** Design & test - TISS dedicated to ^{39}Ca			**Transverse polarization optics (65 k€)**	**1 Postdoc 24m** for the reduction of systematic effects
LPC CAEN		**Buffer trap (150k€)** purchasing components	**Buncher section** of the MORA RFQ at DESIR **(70k€)**		
JYVÄSKYLÄN YLIOPISTO UNIVERSITY OF JYVÄSKYLÄ		**Design, construction & test** with MR-ToF		**Implementation of lasers for ^{39}Ca**	
KU LEUVEN NUCLEAR AND RADIATION PHYSICS		**Technical support** design/construction		**Design support** transverse polarisation	

+40k€ missions GANIL (25) & LPC Caen (15)

AdvanCed CaLcium radioActive Isotope Manipulation for MORA

- Project organization **ANR project - Sabrina**

Year	1 (starting fall 2025)				2				3				4			
Task \ Trimester	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
Project management				M1.1				M1.1				M1.1				**D1.1**
Dissemination			M1.2				M1.2				M1.2				M1.2	
Production of Ca beams at SPIRAL 1			M2.1.1					M2.1.2				M2.1.3				**D2.1**
Ca target for IGISOL				**D2.2**												
High intensity buncher for SPIRAL1 beams		M3.1.1						M3.1.2				M3.1.3				**D3.1**
Stacking trap for purified beams at IGISOL				M3.2.1				M3.2.2				M3.2.3				**D3.2**
Control of polarisation		M4.1.1						M4.1.2			**D4.1**					
Analysis of Data						M4.2.1						M4.2.2				**D4.2**
Theoretical corrections								M4.3								

Preparation
Ongoing task
Operation

AdvanCed CaLcium radioActive Isotope Manipulation for MORA

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- Project organization   **ANR project - Sabrina**

Communication

- **1 web site**
  - https://mora.ganil-spiral2.eu/
  - General info on project progression, highlights, publications
- **1 general info telegram channel**
  - Info on upcoming meetings, upcoming data taking, exchange of information between participants, etc. Open to all MORA participants.
- **1 telegram channel for experiments @ JYFL**
  - Operational channel to prepare and exchange information during data-taking. Open to participants with online participation <= 6 months.
- **Regular mails** following data taking or achieved milestones to inform on progresses.

AdvanCed CaLcium radioActive Isotope Manipulation for MORA

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Work-packages - status

To be discussed along the presentations during this meeting

Task 1 – project management

Milestone dates, communication tools and events

Task 2 – Intense Ca beam

Design of a TULIP - Target Ion Source at GANIL

Task 3 – Ion bunching, stacking and separation

High intensity buncher for DESIR

Stacking trap – work distribution

Task 4 – Polarisation and sensitivity of measurement

Transverse polarisation control with motorised mirrors

ACCLAIM MORA collaboration

Thanks a lot for your attention!

LPC CAEN

V. Bosquet
X. Fléchard
L. Hayen
E. Liénard
J. F. Cam
Y. Merrer
C. Vandamme

IJCLab Irène Joliot-Curie

A. Falkowski
E. Alviani

GANIL

P. Delahaye - P.I.
S. K. Chithakayala
P. Chauveau
F. De Oliveira
G. Frémont
H. Guérin
P. Jardin
M. Jbayli
S. Lecerf
N. Lecesne
V. Morel
L. M. Motilla
M. Tencé
J. C. Thomas

JYVÄSKYLÄN YLIOPISTO UNIVERSITY OF JYVÄSKYLÄ

I. Moore
T. Eronen
M. Reponen
Z. Ge
B. Kotte
V. Virtanen
A. Raggio
N. Rattanasakuldilok
A. Jokinen
A. Kankainen
S. Rinta-Antila

KU LEUVEN

R.P. De Groote
N. Severijns
G. Neyens
S. Vanlangendonck

IFIC

A. Rodriguez – Sanchez
M. Gonzalez-Alonso

In blue PhD and Master students hired for MORA

Backup material

Experimental breakthrough

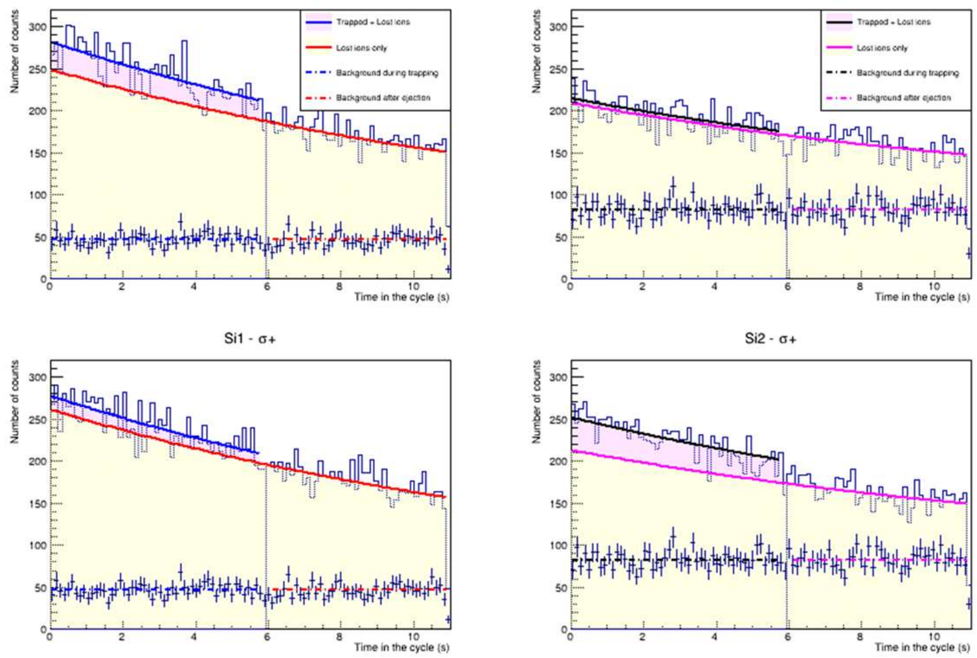
Si detectors to measure the polarisation

March 25

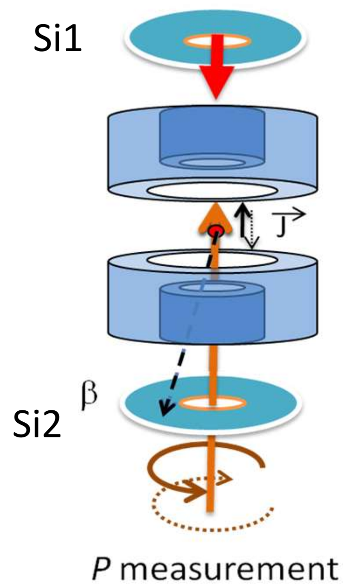
Si1 Si2

σ−

σ+



Polarisation measurement



First polarization measurement

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

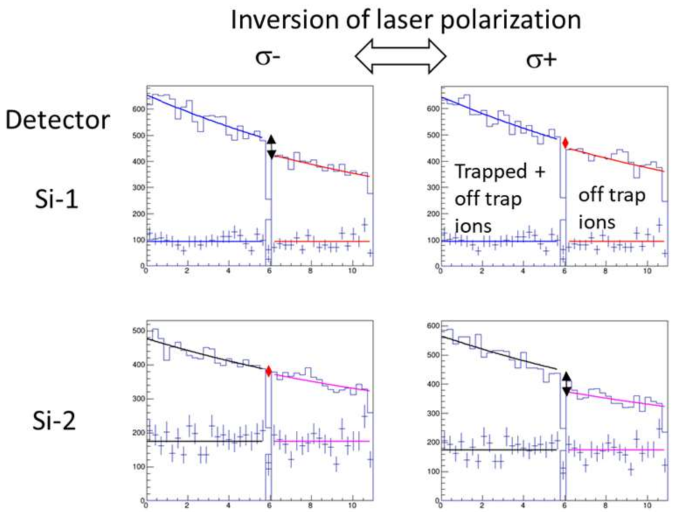
NEWS

08/04/25

Contact : Pierre Delahaye

Démonstration de la polarisation laser dans le piège de MORA

Demonstration of the laser polarisation in the trap of MORA



Le degré de polarisation des ions $^{23}Mg^{+}$ dans le piège de MORA a été mesuré à IGISOL en Finlande. C'est une première expérimentale pour cette technique innovante. Les premières estimations montrent qu'il est supérieur à 55% avec un intervalle de confiance de 90%.

The degree of polarization of 23Mg+ ions in the MORA trap has been measured at IGISOL in Finland. This is an experimental first for this innovative technique. Initial estimates show that it is greater than 55%, with a confidence interval of 90%.

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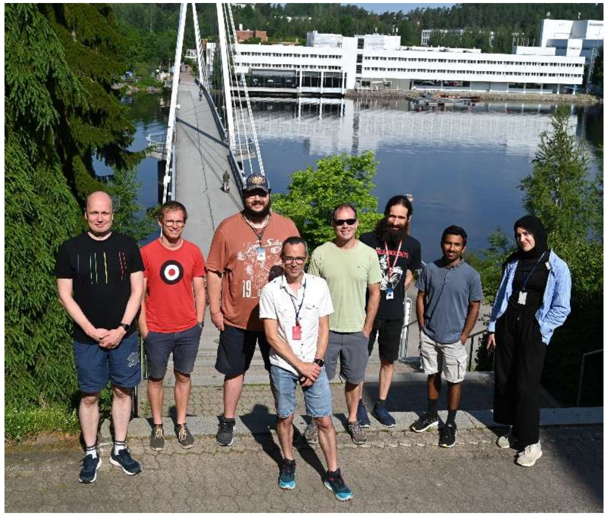
MORA a le vent en poupe!

MORA has the wind in its sails!



Un jalon clé pour MORA : à IGISOL (Finlande), la contamination du faisceau de ^{23}Mg par ^{23}Na a été réduite de trois ordres de grandeur, atteignant une pureté suffisante pour la mesure du coefficient *D*. Par ailleurs, l'ANR a confirmé le financement du projet ACCLAIM_MORA, qui étendra les mesures à l'isotope $^{39}Ca^{+}$, d'abord à IGISOL puis à DESIR.

A key milestone for MORA: at IGISOL (Finland), ^{23}Na contamination in the ^{23}Mg beam was reduced by three orders of magnitude, achieving the purity required for measuring the *D* coefficient. ANR has also confirmed funding for the ACCLAIM_MORA project, which will extend the measurements to the $^{39}Ca^{+}$ isotope, first at IGISOL and later at DESIR.