

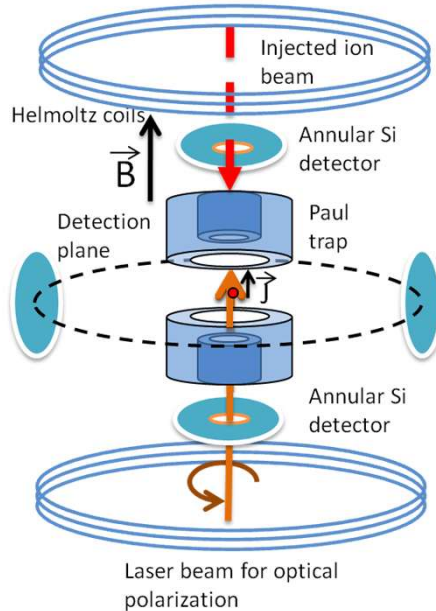
ENTRETIEN ANNUEL PROJET MORA



MORA: sonder l'origine de l'asymétrie matière antimatière par la mesure de la corrélation D dans la désintégration d'ions $^{23}\text{Mg}^+$ et $^{39}\text{Ca}^+$ piégés et polarisés

THE MORA EXPERIMENT

Matter's Origin from RadioActivity



Corrélation
$$D \frac{\vec{J} \cdot (\vec{p}_e \times \vec{p}_\nu)}{J(E_e E_\nu)}$$

**T impaire → via CPT →
Recherche de violation de CP**

Techniques de pointes

- Production de faisceaux radioactifs intenses à **GANIL**
- Refroidissement et piégeage d'ions développés au **LPC CAEN**
- Polarisation laser **innovante**



Projet financé **pour la partie équipement** par la Région Normandie
et pour les thèses, postdocs par l'ANR + **ANR ACCLAIM**



X2!

2022-2028: Tests de principe de la polarisation laser à JYFL et première mesure de D à JYFL, avec une intensité de ^{23}Mg réduite

2029-....: data taking à DESIR

ENTRETIEN ANNUEL PROJET MORA

**Organisation du projet redéfinie dans le cadre du nouveau projet ANR
« AdvanCed CaLcium radioActive Isotope Manipulation for MORA »**



Data taking à Jyväskylä, analyse, production, lasers et supervision projet

Porteur du projet: **GANIL**

Coordinateur: P. Delahaye

Design et construction du cooler buncher pour DESIR

Partenaire français:



Coordinateur partenaire : L. Hayen

Partenaires étrangers

Soutien de la campagne à Jyväskylä, développement d'un stacking trap for ACCLAIM

Hôte du projet MORA
pour 2020-2028



Coordinateur partenaire : T. Eronen

Experts en polarization laser, soutien technique pour le stacking trap



Coordinateur partenaire : R. De Groote

Experts français théorie EFT



Contact A. Falkowski

Projet MORA - ANR

Équipes concernées 2020 - 2025

Période 2020 – 2025 (Oct) ANR MORA



110 m*m



165 m*m



30 m*m

Dont 36 PhD, 6+2+2 postdoc

Dont 70 PhD, 24 postdoc

Dont 18 postdoc

Période 2025 (Oct) – 2029 ANR ACCLAIM MORA - prévisionnel



32 m*m



181 m*m



1 m*m

Dont 12 postdoc

Dont 74 + 18 PhD, 24 postdoc

+ partenaires étrangers



10 m*m + 18 PhD



20 m*m

cotutelle à confirmer par Région Normandie

Financements ANR, Région et Université

PUBLICATIONS

DEPUIS 4 ANS	ANNÉE 2023	ANNÉE 2024	ANNÉE 2025	ANNÉE 2026
Nombre de publications: 4 (+1 en 2022 +2 en 2021 +3 en 2019 +1 en 2020)	1	1	1	1+1
Nombre de communications: 15 (+5 en 2022 +5 en 2021 +5 en 2020 +4 en 2019 + 1 en 2020)	3	2	6	4
Nombre de thèses soutenues: 2	2	-	-	1
	Nishu Goyal et Sacha Daumas-Tschopp			Luis Miguel Motilla

Articles

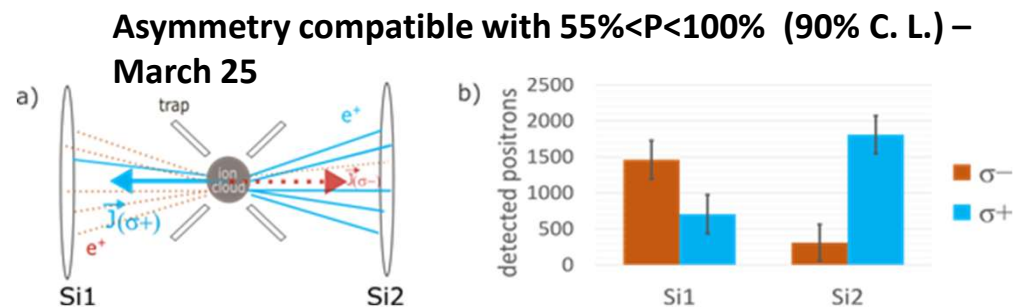
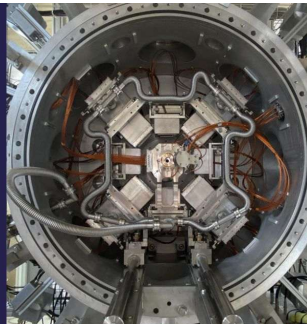
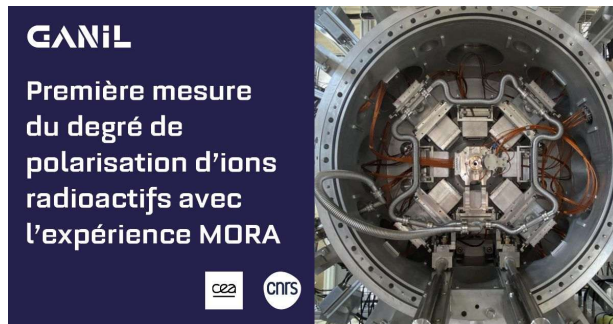
- N. Goyal et al., detection of recoil ion in the beta decay of laser oriented trapped radioactive isotopes for the MORA project, J. Phys:Conf. Ser. 2586 012142 (INPC 2022) <https://doi.org/10.1088/1742-6596/2586/1/012142>
- A. Falkowski, M. González-Alonso, A. Palavrić, A. Rodríguez-Sánchez, Constraints on subleading interactions in beta decay Lagrangian, arXiv:2112.07688 <https://doi.org/10.48550/arXiv.2112.07688> JHEP 02 (2024) 091
- A. Falkowski, A. Rodríguez-Sánchez, On the sensitivity of the D parameter to new physics, arXiv:2207.02161, <https://doi.org/10.48550/arXiv.2207.02161>
- N. Goyal, A. Singh, S. Daumas-Tschopp et al., *Performance of the MORA apparatus for testing time-reversal invariance in nuclear beta decay*, Eur. Phys. J. A (2025) 61: 221, <https://doi.org/10.1140/epja/s10050-025-01694-3>
- P. Delahaye and L. M. Motilla Martinez, *Matter's Origin from the RadioActivity of trapped and laser oriented ions (status and perspectives)*, (29 Sept. 2026), in Brian Foster (ed.), Oxford Research Encyclopedia of Physics (New York, NY, online edn, Oxford Academic, 29 July 2019 -), <https://doi.org/10.1093/9780197851753.003.0141>, accessed 19 Oct. 2026.
- L. Motilla S. Vanlangendonck et al., *Sensitivity of the MORA apparatus to the Beta Assymetry*, INPC 2025 proceedings, to appear in IOP conference proceedings

Communications – latest 2023/2026

- L. M. Motilla: Ganil colloquium 2026+23 - INPC 2025 – EuNPC 2025 - Platan 2024 – PhyNuBE 2023 Aussois
- M. Jbayli: GDR Inf 2025
- T. Eronen: TCP 2026 – ARIS 2025 (invitation)
- P. Delahaye (invitations): SMI 2027 - Mazurian Lake conf. 25 – ESNT Saclay 25 - EURORIB 2024 - Les Houches CP2023

FAITS MARQUANTS 2025 - RAPPEL

Breakthrough - **IN2P3 highlight**: in-trap polarisation demonstration March 25



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

Purity of $^{23}\text{Mg}^+$ beam has significantly been improved: $^{23}\text{Na}:^{23}\text{Mg} \sim 2$ at the end of the beamtime – July 25

- Ready to measure D correlation in the decay of ^{23}Mg

ACCLAIM MORA: new ANR project funded

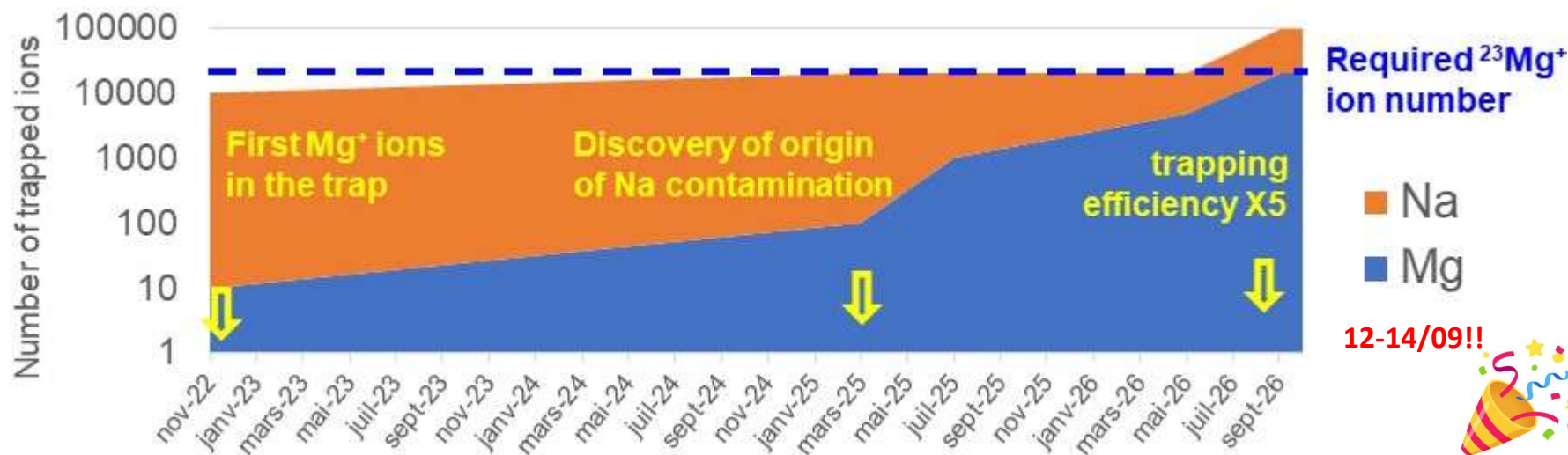
- Consolidating $^{39}\text{Ca}^+$ as promising candidate for D correlation measurement – **production test Oct. 25**
- Stacking trap with MR ToF MS and polarisation control, analysis of data 2025-2028

Acquiring data for D correlation measurement in the 10^{-4} ballpark before end of 2028

FAITS MARQUANTS 2026

Progression towards the D correlation measurement

- 20,000 trapped $^{23}\text{Mg}^+$ ions required for a $5 \cdot 10^{-4}$ measurement
 - Ratio [Na+:Mg+] now routinely reduced to <5 – satisfying!
 - Trapping efficiency from minibuncher to MORA
 - **May 26 conflicting numbers**
 - 40% measured with MCPs, with $4 \cdot 10^4$ $^{23}\text{Mg}^+$ from minibuncher theoretically enough
 - 10% from radioactivity – not enough
 - **5000 ions trapped**
 - **Sept 13-15 target test** with new diagnostics and consolidated front end
 - **combining new « abzurd » system (10fA readout) with MORA MCPs**
 - Optimisation: minibuncher **from 10^5 to $\sim 10^6$ ions per bunch (Na+Mg), transmission x trapping $\sim 10\%$**
 - Consolidated front end - better optics gives optimal yield and purity after 24h
 - **20,000 trapped $^{23}\text{Mg}^+$ ions from radioactivity in accordance with MCPs**



STATUT ET PERSPECTIVES

- **MORA looks for new interactions violating CP in nuclear β decay**
 - the D correlation measurement requires $2 \cdot 10^4$ $^{23}\text{Mg}^+$ ions in the trap
- **The innovative technique of polarisation has been demonstrated with only 100 ions in the trap**
 - **55% < P < 100% at 90 C.L.**
- **The beam purity issue at IGISOL has been tackled**
 - A factor of $[\text{Na}^+:\text{Mg}^+] \sim 10$ (3 orders of suppression) is now routinely achieved
- **The trapped ion number is in steady progression**
 - **Now the required number in $^{23}\text{Mg}^+$ decay has been reached** **12-14/09!!**
- **Perspectives include measurements with $^{23}\text{Mg}^+$ and $^{39}\text{Ca}^+$ ions**
 - at JYU/IGISOL (- 2029) with a 10^{-4} sensitivity
 - and GANIL/DESIR (2029 -) with a 10^{-5} sensitivity



New grant from ANR!

AvanCed CaLcium radioActive Isotope Manipulation for MORA: ACCLAIM MORA

- **at JYU/IGISOL**
 - A stacking trap is being developed for cleaning beams with the MR-ToF-MS
 - A polarimeter will be commissioned for Mg and Ca

Work within the frame of a PhD in cotutelle

- **At GANIL/SPIRAL1**
 - Beam development of $^{39}\text{Ca}^+$ is undertaken within the frame of a PhD thesis

JALONS

ACCLAIM MORA Gantt chart

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																



29 Moving to DESIR

Utilisation budget année N

Dotation : Région Avril 2018 – Juillet 2020

315k€ (GANIL) + 317k€ (LPC Caen): 632 k€



Dotation : ANR Janvier 2020 – Juin 2024

149k€ (GANIL) + 169k€ (LPC Caen) + 120k€(IJCLab Orsay): 439 k€



Dotation : ANR Octobre 2025 – Sept 2029

419k€ (GANIL) + 267k€ (LPC Caen) : 686 k€

	Production	Purification	Bunching	Polarisation	Analyse
GANIL	1 PhD à SPIRAL 1 Design et test d'1 ECS dédié			Optique de polarisation transverse (50 k€)	Postdoc 24m pour la réduction des effets systématiques
		Stacking trap (150k€) pour séparation par tof à Jyväskylä	Section buncher sur le RFQ MORA à DESIR (70k€)		
		Participe au design et à la construction*			
		(*:étudiants + atelier mécanique)		Participe au design	

+40k€ missions

GANIL +



Budget pluri-annuel

2026: Budget fonctionnement 15k€

- Detecteur Magnetof - identification Mg / Na: 4k€
- Mécanique de la cavité Ti:Sa pour Ca: 2.2k€
- Cibles Mg 2.6 k€
- Tube Rhénium ionisation de surface Ca à GANIL 7.8 k€

2027: Budget fonctionnement 14.5k€

- Cible Ca/Mg : 2.5k€
- Nouveau sextupole: 10 k€
- Synchronisation RF piégeage: 2k€

Budget GANIL	2026	2027	2028	2029
Investissement	-	-	-	-
Fonctionnement	15	14.5	15	20 (retour)
Missions	11,5	12	12	12

Fonctionnement

- 27 – 28: 15k€/ans pour la détection/ électronique et maintenance du setup pendant les 2 ans de data-taking à JYFL, hors budget stacking trap et polarimétrie laser (projet ACCLAIM MORA)
- 29: retour au GANIL/DESIR 10k€ transport + 10k€ installation

Missions

- Périodes prolongées de data taking – 3 mois (~6x2 semaines) pour 2 isotopes 2027-28
- Cotutelle Jonathan Roux succède à celle de Luis Miguel, Ville Virtanen (postdoc ACCLAIM MORA) souvent à JYU pour le développement du stacking trap et polarimétrie laser
- 12 k€/an demandés pour missions à JYFL au GANIL
 - ANR Oct. 2025 – 2029 40 k€ dont 25 k€ GANIL + 15 k€ LPC Caen
 - **Accord bilatéral ACCLAB/GANIL en cours de renouvellement avec les nouvelles directions**

Financement des lasers pour MORA à DESIR: 210k€ plateforme Région à soumettre

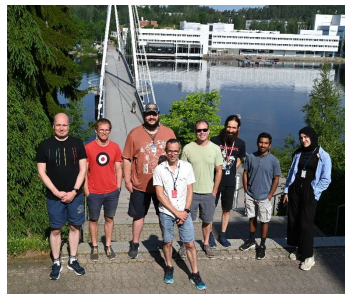
MORA: a bright future

The MORA project

2018 - 2020



Trapping in LPC



New ANR project!

ANR MORA

2020- 2025



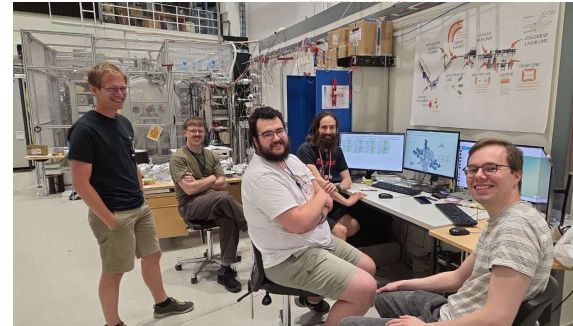
Assembly in JYFL



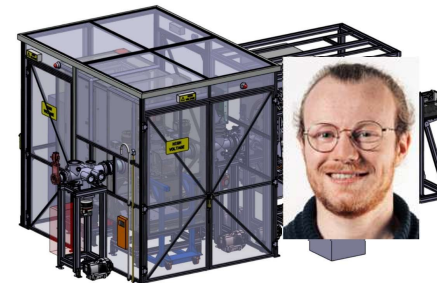
A new target ion source!

ANR ACCLAIM MORA

2025- 2029



Polarisation measurement



A new buncher!

GANIL



THE MORA EXPERIMENT
Matter's Origin from RadioActivity

...



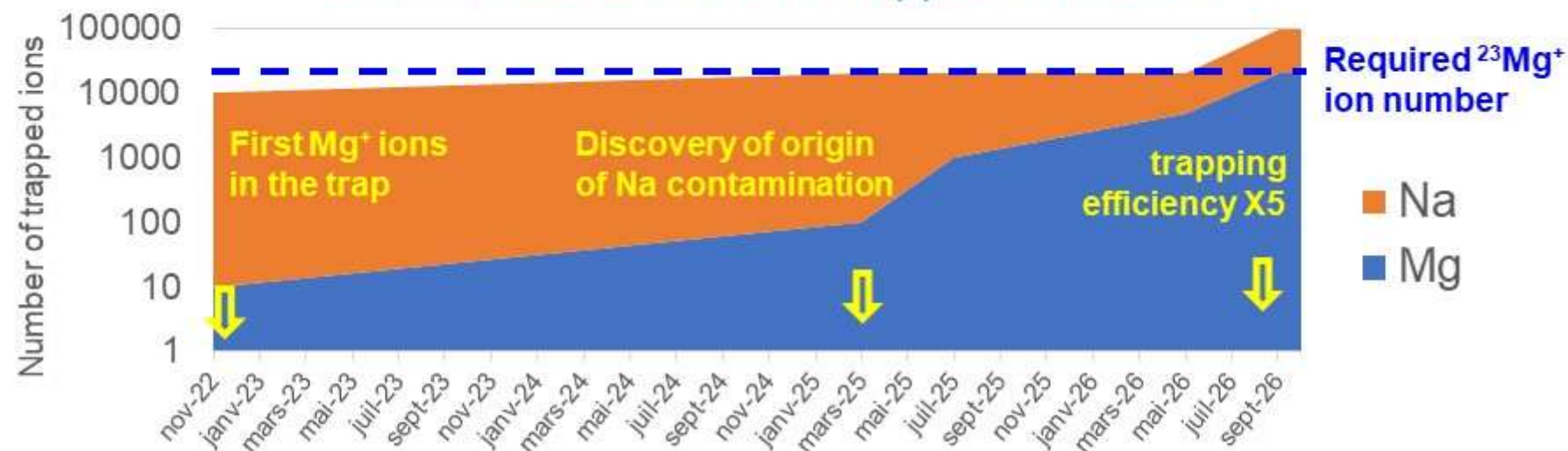
Purified beams



Analysis in progress!

20 000 ions radioactifs piégés dans MORA!

20 000 radioactive ions trapped in MORA!



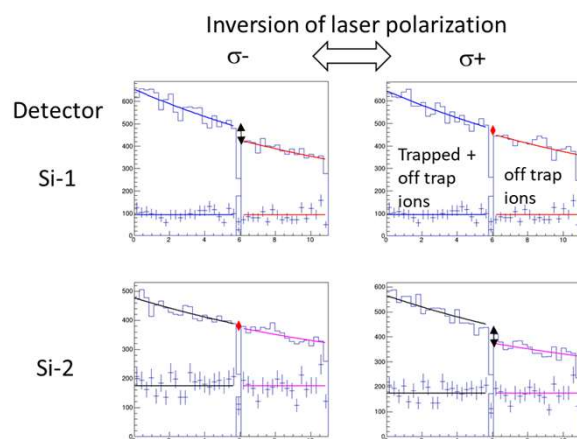
Entre le 12 et 14/09, un test réussi a permis de piéger dans MORA le nombre d'ions $^{23}\text{Mg}^+$ requis pour la mesure de la corrélation D à une précision de $5 \cdot 10^{-4}$ à l'Université de Jyväskylä. Après des années d'efforts pour réduire la contamination du faisceau et améliorer l'efficacité de piégeage, une étape importante est franchie. La campagne de mesure peut commencer, préparant les mesures à DESIR qui visent des précisions de l'ordre de 10^{-5} .

Between 12th and 14th of September, a successful test permitted to trap the required number of $^{23}\text{Mg}^+$ ions in MORA for a measurement of the D correlation with a precision of $5 \cdot 10^{-4}$ at the University of Jyväskylä. After years of efforts to reduce the beam contamination and improve the trapping efficiency, an important milestone is achieved. The measurement campaign can start, preparing measurements at DESIR, which target precisions of the order of 10^{-5} .

BACKUP

NEWS

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 $^{23}\text{Mg}^+$ 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 $^{23}\text{Mg}^+$ 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%.

NEWS

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 $^{39}\text{Ca}^+$, d'abord à IGISOL puis à DESIR.

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de la recherche
AU SERVICE DE LA SCIENCE



THE MORA EXPERIMENT
Matter's Origin from RadioActivity

 **RÉGION
NORMANDIE**

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 $^{39}\text{Ca}^+$ isotope, first at IGISOL and later at DESIR.

Search for new physics via the D correlation measurement

A non-zero D can arise from CP violation

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

T reversal odd

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

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

Best measurement so far: $D_n = (-0.94 \pm 1.89 \pm 0.97) \cdot 10^{-4}$

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

emiT collaboration, PRL 107, 102301 (2011),

Calaprice, Hyp. Int. 22(1985)83

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

Search for New Physics

- **Direct constraints** on CP-violating Wilson coefficients in the nucleon-level EFT ➡ Interest for $\sim 10^{-4}$ measurement
- Specific New Physics models ➡ Interest for $\sim 10^{-5}$ measurement
 - via **the L-R symmetric model:**
 - M. J. Ramsey-Musolf et J. C. Vazquez, «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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Below 10^{-4} , measurement of Final State Interactions

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

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

Never accessed by a direct measurement in D



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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](https://arxiv.org/abs/2412.17702) [hep-ph]



MORA in a nutshell



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

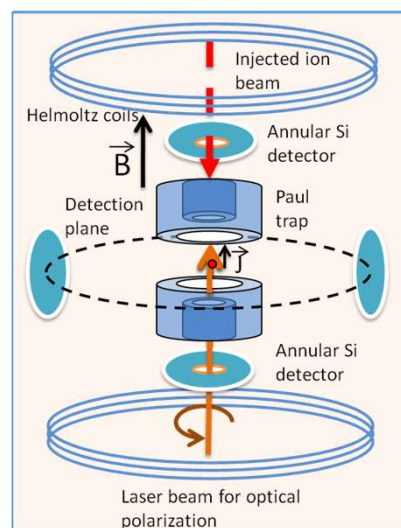
- Ion cooling and trapping originally developed for



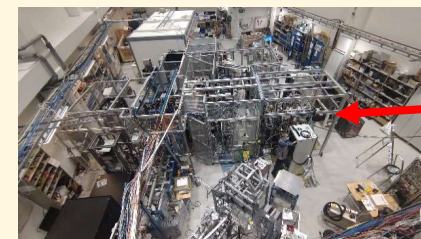
New trap and new detection setup:
off-line commissioning at and

Completed in autumn 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 $\sim 10^{-4}$

Started in Feb 2022

With experts

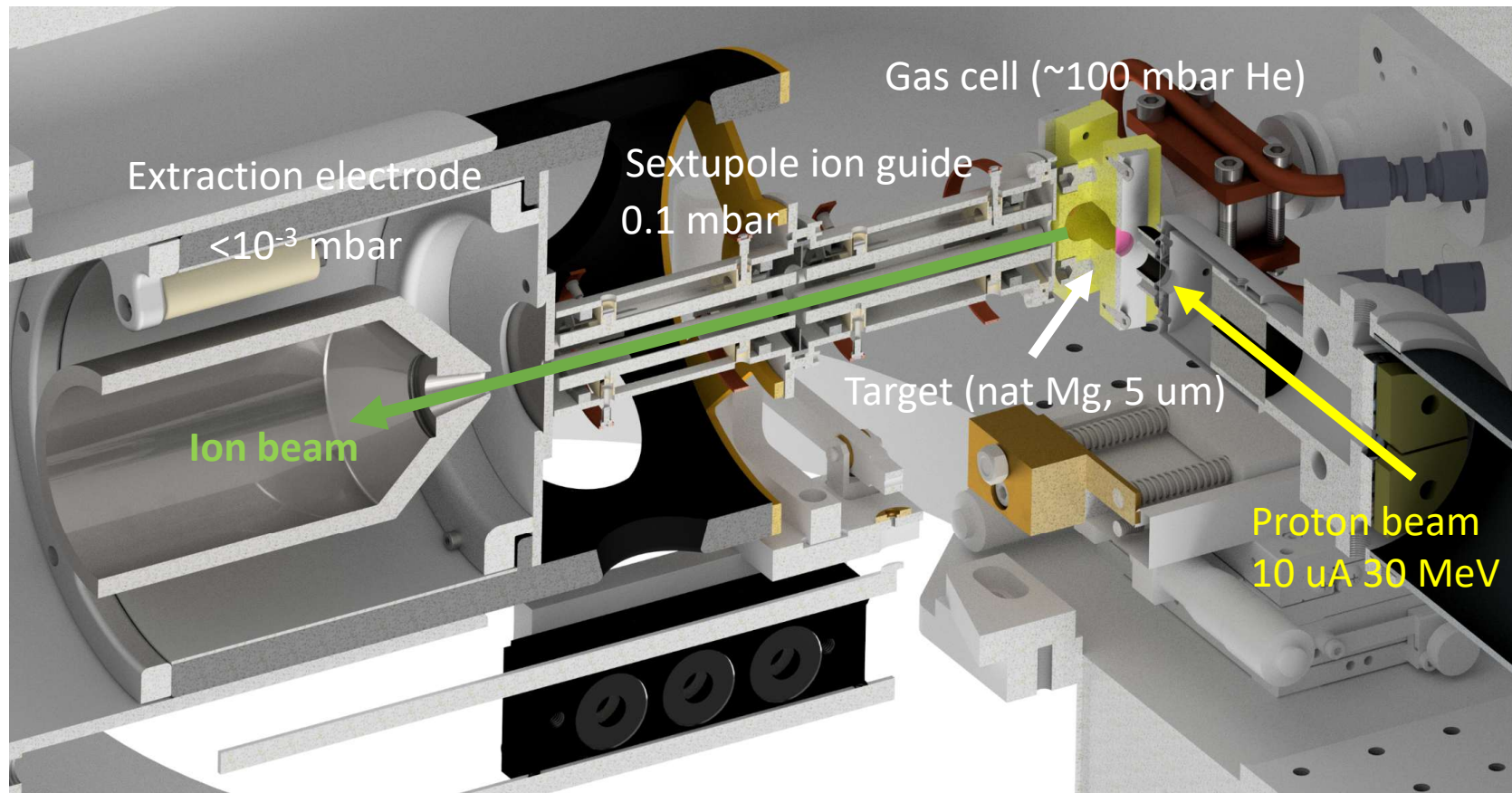
from:



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

Origin of the $^{23}\text{Na}^+$ contamination

Many possible origins: target / windows / gas cell material / ion guide / gas / extractor ...



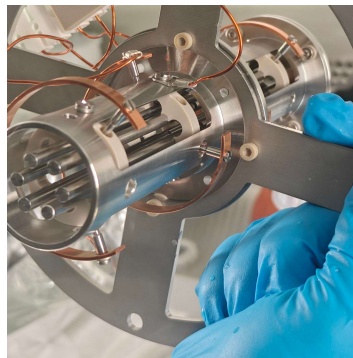
Beam contamination: a long story short

After two years of investigations... (2023 – 24)

- Origin of Na^+ : sputtering of SPIG surfaces by He^+ ions
- Suppressing Na^+ :
 - Replacement of SPIG electrodes with $>1200^\circ\text{C}$ baked Nb rods
 - Cleaning components with deionized water
 - Tuning SPIG potential to contain sputtering at the entrance of the SPIG



$>1200^\circ\text{C}$ baked Nb rods



Cleaned SPIG with Nb rods



Baking



Careful installation

$\text{Log} [\text{Na}^+:\text{Mg}^+]$



Outlook

Towards a $\sim 10^{-5}$ measurement of D at DESIR (2028-...)

- High Resolution Separator (>20,000 Resolving power demonstrated!)
 - Other purification tools: PIPERADE, MR ToF MS
- $^{23}\text{Mg}^+$ at required rate > 10^8 pps from SPIRAL1 at GANIL
- $^{39}\text{Ca}^+$ beam development to reach > 10^7 pps - part of the ACCLAIM project
 - Bunching scheme developped at LPC Caen



Photos: courtesy B. Blank

Delivery: 5th of Sept!

Cf. talk of F. Farget

Recommendations

- The scientific council recommends the team to evaluate carefully the possible show-stoppers and to clarify the breakdown structure and plan of the project at the University of Jyväskylä.
- Thanks to the progressive and **nearly complete removal of contamination in 2025** the **showstoppers** for the measurement of the polarization degree and D correlation **are now being retired**, at least for ^{23}Mg . The main source of contamination (sputtering of stable traces of Na in the sextupole ion guide – SPIG - of IGISOL) has been identified and is cured by association of techniques (new SPIG in Nb, specific beam optics settings).
- As an important milestone **the polarisation proof-of-principle has been achieved** in March 25 and published in EPJ A (review article on the MORA apparatus):
 - Performance of the MORA apparatus for testing time-reversal invariance in nuclear beta decay
 - <https://link.springer.com/article/10.1140/epja/s10050-025-01694-3>
 - **We want to present this achievement as a Fait Marquant CNRS/CEA**
- **The AdvanCed CaLcium radioActive Isotope Manipulation for MORA (ACCLAIM MORA) ANR project** accepted this year (686 k€) consolidates the cases of ^{23}Mg and ^{39}Ca at Jyväskylä with a detailed plan for these two isotopes for the next 3 years.
 - ACCLAIM MORA provides funds for developping **a universal cleaning methods of beams using the Multi-Reflexion Time-of-Flight Mass Spectrometer** at IGISOL (stacking trap for fast cleaning cycles, 150 k€)
 - **A second addendum has been submitted in Sept. 2025** for proposing an organization of the remaining time at Jyväskylä to do high impact measurements during 2026-2028/29.
 - It will be complemented by a last addendum in Sept. 2026
 - The addendums include beam time for testing the purification technique and other objectives specific to ACCLAIM MORA (transverse polarisation control thanks to dedicated laser optics).

- Regarding the next step at DESIR, namely the measurement for ^{39}Ca , the scientific council recommends the realization of a detailed study in a timely manner of the various requirements including the financial aspects, and in coordination with the management of IN2P3.
- The **ACCLAIM MORA project prepares the MORA campaigns at GANIL**, especially with ^{39}Ca
 - ACCLAIM provides funds for a **PhD thesis dedicated to the ^{39}Ca beam development** using a novel utilisation of the TULIP target ion source with fragmented beams over the next 4 years
 - ACCLAIM provides funds (70k€) for the developpement of a **high intensity buncher integrated in the RFQ cooler** being developped by LPC Caen using funds from DESIR for the installation of MORA at DESIR
- **ACCLAIM does not fund the laser system** that will be necessary at DESIR (~ 500 k€) **for MORA but other possibilities are explored within IN2P3**
 - The laser system has been suggested by the Physics Division of GANIL and DESIR management as a part to be funded by the FAIR-SPIRAL 2 agreement
 - As this laser system is redundant with other projects (Louis Lalanne, Laser spectroscopy at DESIR) complementary sources of support could come from ANR/ERC

SUMMARY

- the plans for MORA are getting clearer at Jyväskylä because of the recent success with reducing the contamination of ^{23}Mg to its lowest level.
- We achieved an important milestone with the proof-of-principle of the Laser polarization (fait marquant proposé)
- The ACCLAIM MORA project consolidates plans for ^{39}Ca at DESIR by providing resources to a solid international consortium gathered around clear objectives
- Some work remains to identify resources for the lasers at DESIR (Accord FAIR - SPIRAL 2 or other sources)