La MORA
Bayeux tapestry

THE MORA EXPERIMENT

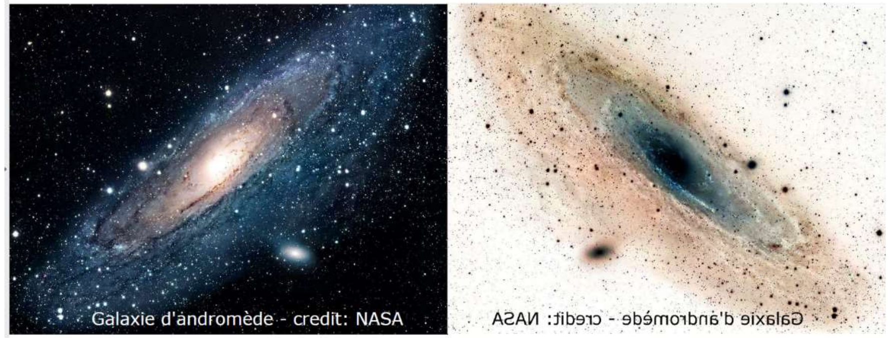
Matter's Origin from RadioActivity

News from IGISOL

P. Delahaye, GANIL

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, and more recently Λ_b baryon decay is not enough to account for the large matter – antimatter asymmetry

Physics beyond the Standard Model !

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**

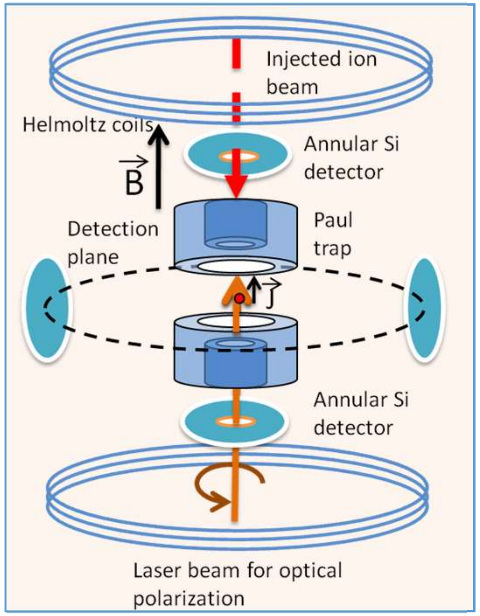
State of the art techniques from ISOL facilities

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

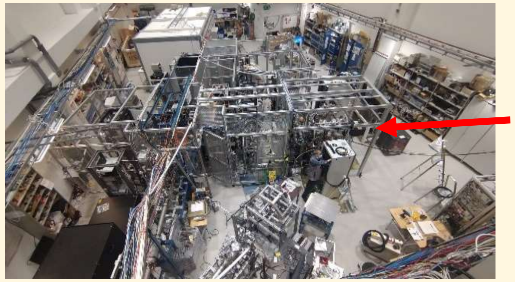
New trap and new detection setup:
off-line commissioning at LPC Caen and GANIL

Completed in automn 2021

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



- **Innovative laser polarisation techniques at** JYFL



MORA installation at JYFL/IGISOL (completed!)

Proof of principle of polarization
First *D* measurement

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**

Search for new physics via the *D* correlation measurement

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MATTER'S ORIGIN FROM RADIOACTIVITY

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

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

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

$D_{^{19}Ne}$=(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
- 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)

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

Never accessed by a direct measurement in *D*

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

Precision measurement of the *D* correlation

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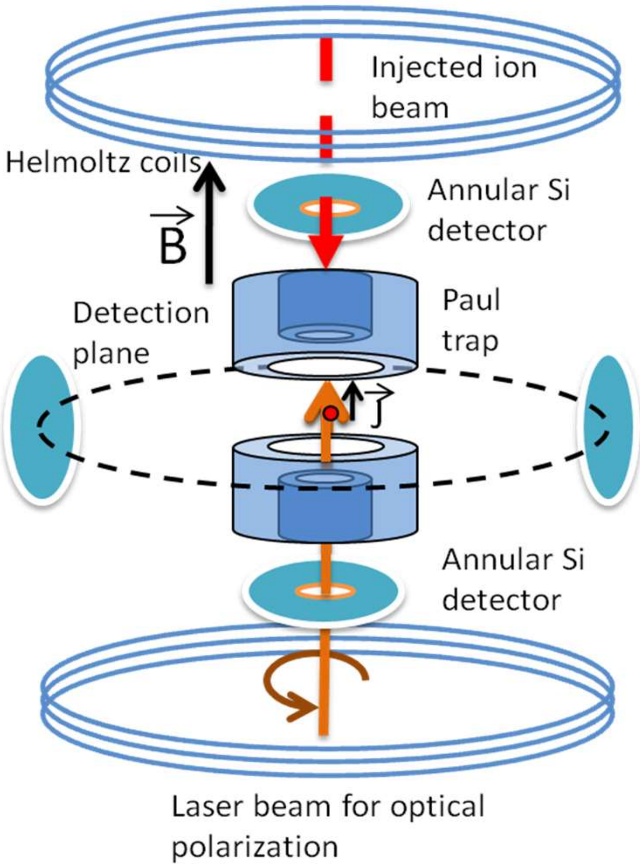
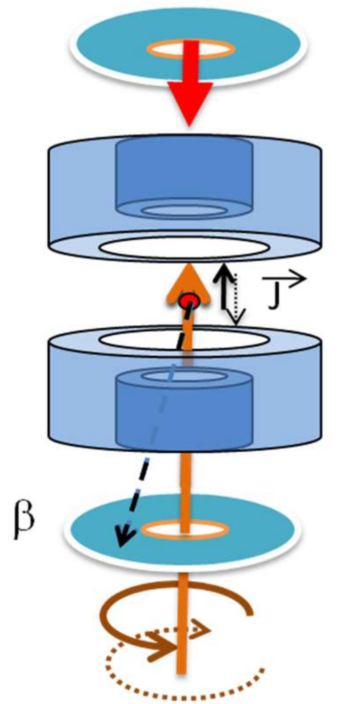
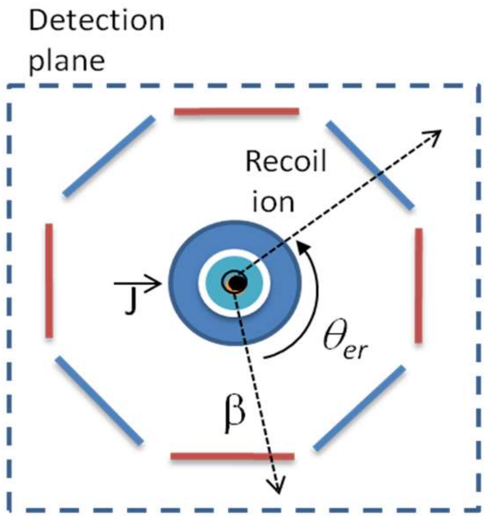


Detection setups



P measurement

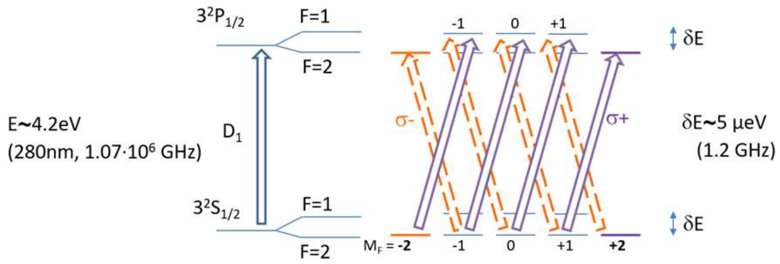


D correlation

MORA: in-trap laser polarization

- 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

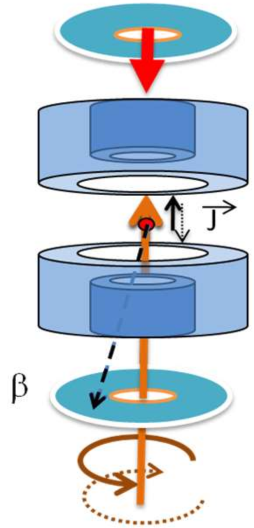


Transitions excited using trippled Ti:Sa laser pulses
λ~280nm σ+ polarization, ~4GHz width

Doppler shift/broadening due to ion motion ~1.6GHz

Collisions with He atoms (no spin) do not depolarize

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



P measurement

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

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

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

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

Remember 2021 - 2022

Off-line commissioning in LPC Caen
September 2021

^{23}Na trapped ions from alkali source

Shipping incident – trap chamber
to be repaired - October 2021

Installation in JYFL
November 2021 – injection line

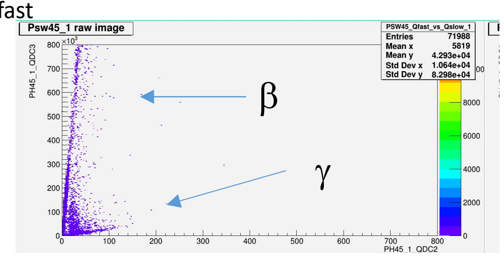
Installation in JYFL
January 2021 – trap and detectors

Commissioning in JYFL
Mid February – off-line

^{23}Na trapped ions from cooler buncher

Commissioning in JYFL
18^{th} - 20^{th} February – on-line
27-31 May 2022 – on-line

Q_{fast}



Q_{slow}

First ^{23}Mg β activity is recorded

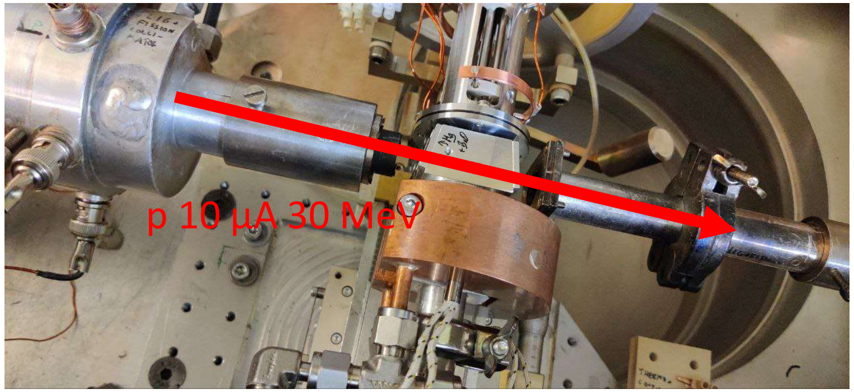
Large involvement of LPC Caen technical resources

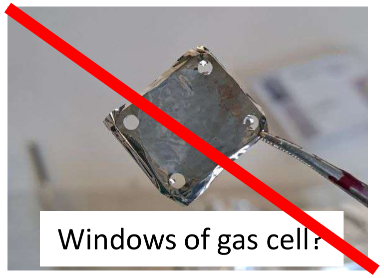
2023 - 2024

Contamination makes progress difficult!

^{23}Na:^{23}Mg$\gtrsim$1000

Origin of the stable Na contamination?





Na+ beam only appears with p beam on

- Efforts focused first on targets and windows
- He gas was also discarded
- **Gas cell material is also discarded**

Culprit: zeolite filter in cold trap??
13X sieve: $Na_2O.Al_2O_3.mSiO_2.nH_2O$

Testing charcoal and SiO2 filters instead of zeolite

→ Same impurities

Cat litter!

Dec. 2024

2023 - 2024

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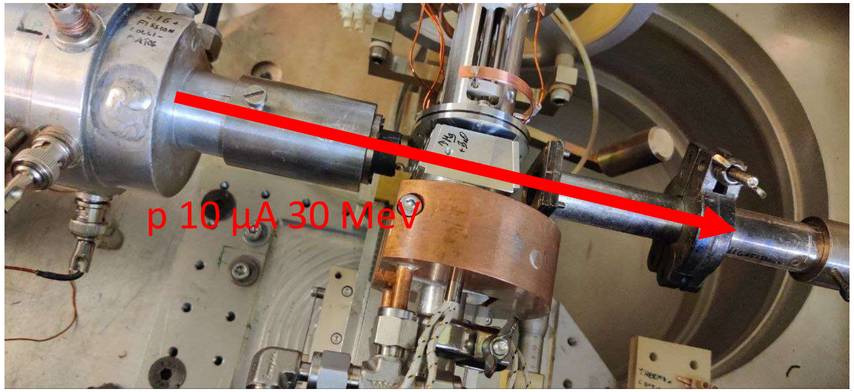

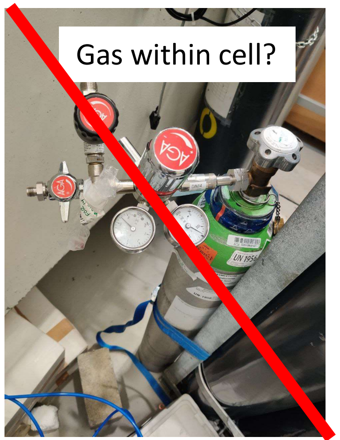

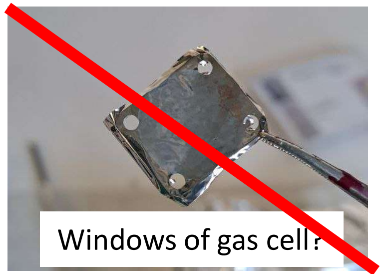

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No!

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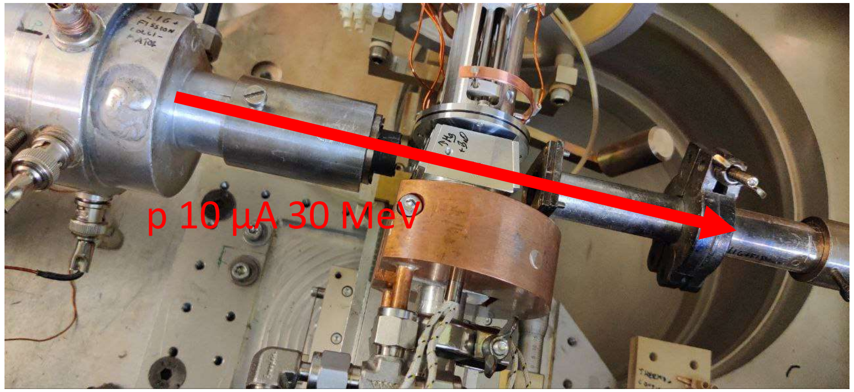

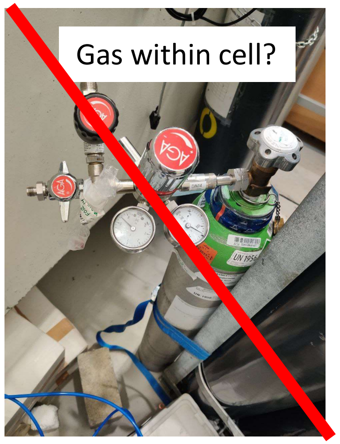

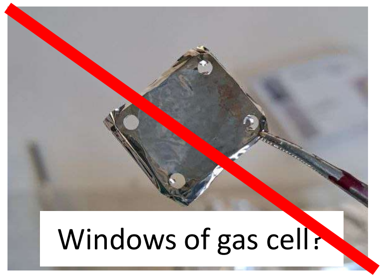

But then what is it?

2023 - 2024

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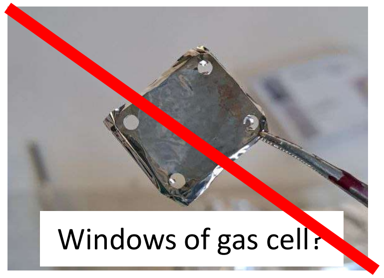

The SextuPole Ion Guide! SPIG

2023 - 2024

Contamination makes progress difficult!

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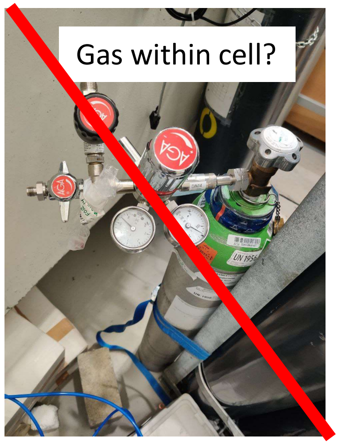
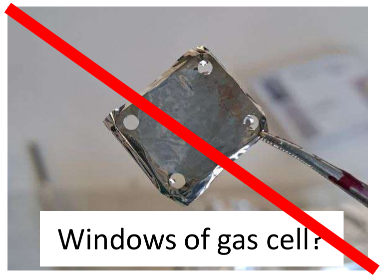
Origin of the stable Na contamination?





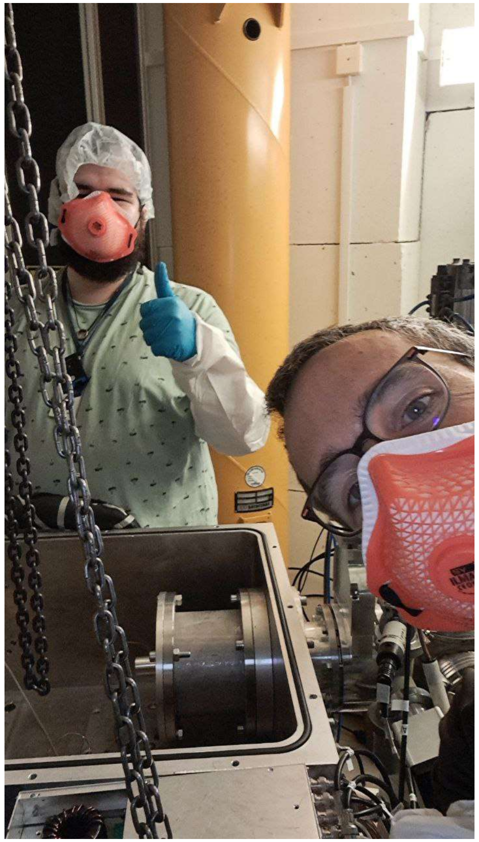
The SextuPole Ion Guide! SPIG

Sputtering of electrodes by ionized He

Explains that:

- The gas purity matters
- The Na+ can be trapped in the SPIG
- The Na+ only comes when p beam on
- …

SPIG deionized water cleaning



Experimental breakthrough

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anr®

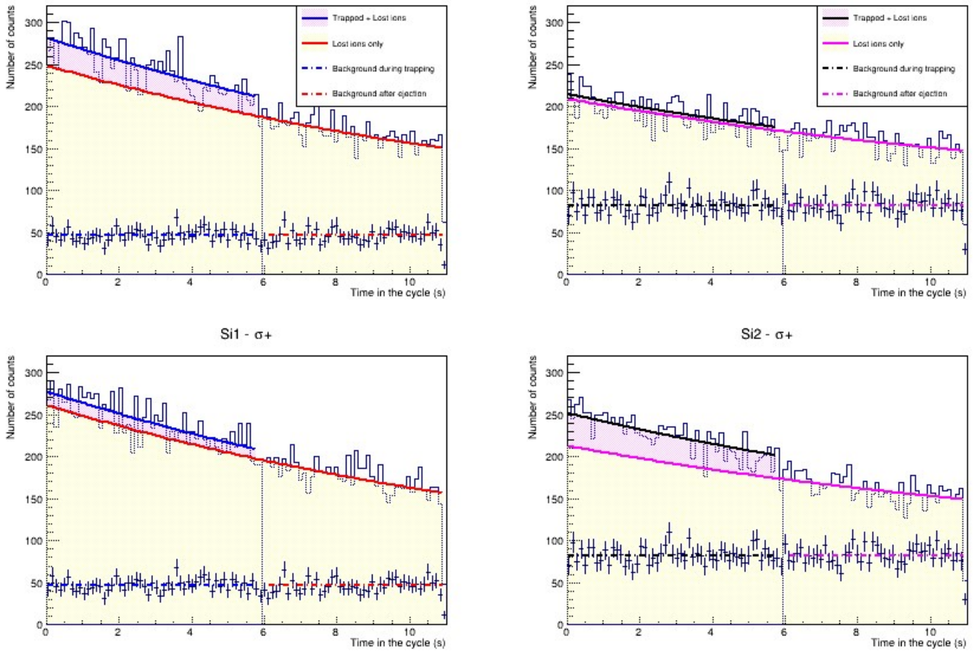
March 25

Si detectors to measure the polarisation

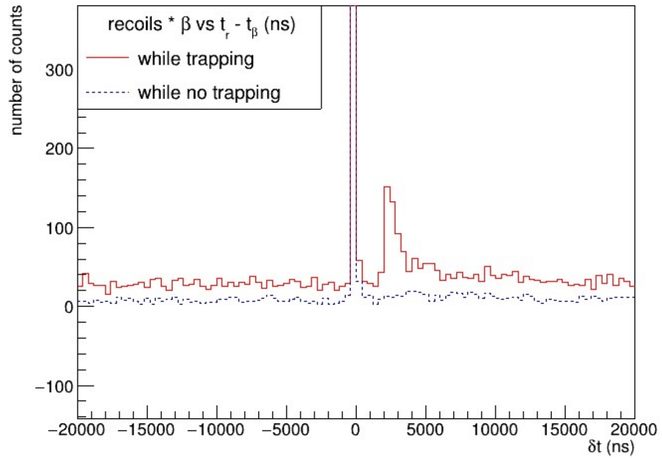
Si1 Si2

σ−

σ+



β-recoil coincidences



Trapped ions/cycle

90±9 from Si detectors

145±55 from coincidences

First polarization measurement

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

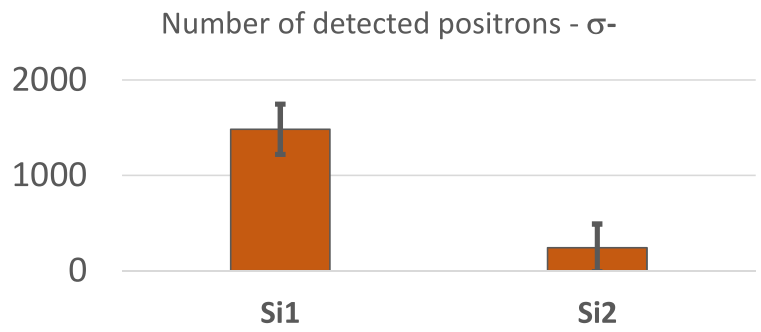
|*A*|= 0.51±0.14

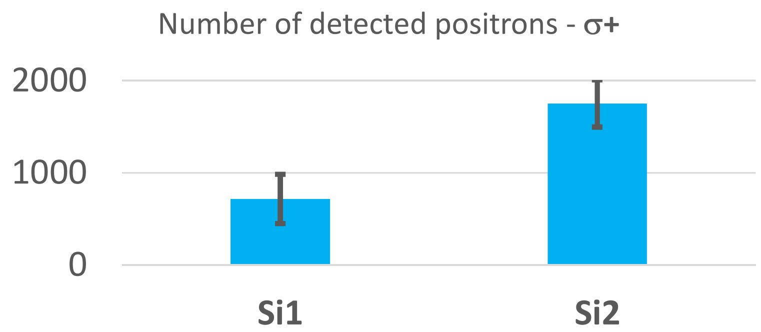
➡ **55%<P<100% at 90% C.L.**

Experimental breakthrough

March 25

Si detectors to measure the polarisation





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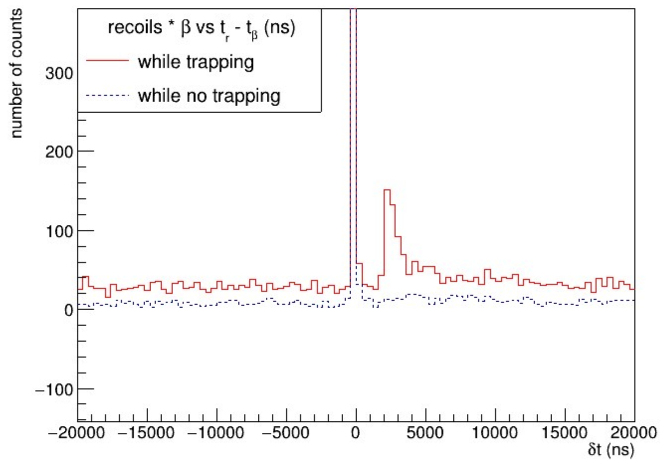


Trapped ions/cycle
90±9 from Si detectors
145±55 from coincidences

$|A|$= 0.51±0.14

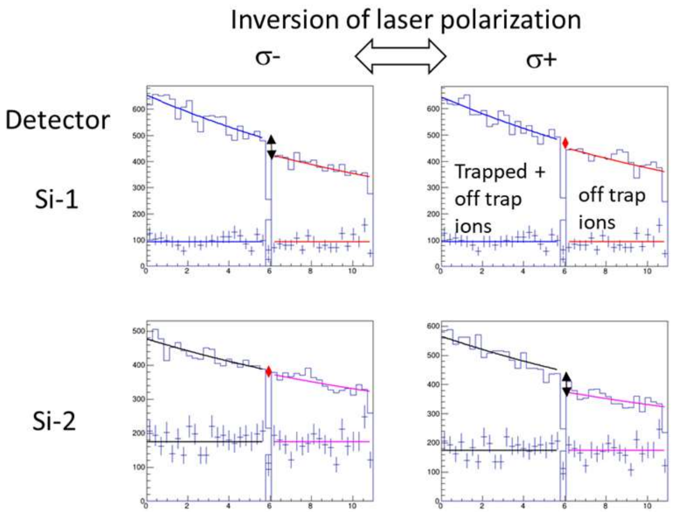
➡ **55%<P<100% at 90% C.L.**

Conclusions

- **First major milestone attained!**
  - 78%<P<100% at 90 C.L.
  - More data to come
- **Progressing towards the *D* correlation measurement**
  - 10^4 ions in the trap: still 2 orders of magnitude of contamination to fight against
  - Testing baked and cleaned Nb rods for the SPIG
  - Recovering high $5 \cdot 10^5$ pps $^{23}Mg^+$ yield
    - Proton beam tuning, new thin Mg target
  - Careful beam separator settings to suppress neighboring masses (^{22}Ne…)
- **Exploring $^{39}Ca^+$ at IGISOL and GANIL**
  - New ANR project: AvanCed CaLcium radioActive Isotopes Manipulation for MORA - **ACCLAIM MORA**

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%.

MORA collaboration

Thanks a lot for your attention!

LPC Caen

E. Liénard
M. Benali
V. Bosquet
S. Daumas-Tschopp
L. Hayen
Y. Merrer
X. Fléchard
G. Quéméner
A. De Roubin

KU LEUVEN

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

IFIC

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GANIL

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S. K. Chithakayala
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M. JBayli
N. Lecesne
R. Leroy
L. M. Motilla
B.M. Retailleau
A. Singh
J. C. Thomas

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The University of Manchester

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I. Moore
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W. Gins
V. Virtanen
J. Romero
A. Raggio
A. Jaries
A. Jokinen
A. Kankainen
S. Kujanpää
M. Stryjczyk
S. Rinta-Antila

ISOLDE

M. Kowalska

In blue PhD and Master students hired for MORA

Thanks a lot!

THE MORA PROJECT
MATTER'S ORIGIN FROM RADIOACTIVITY
anr

Highlights 2023 - 2024

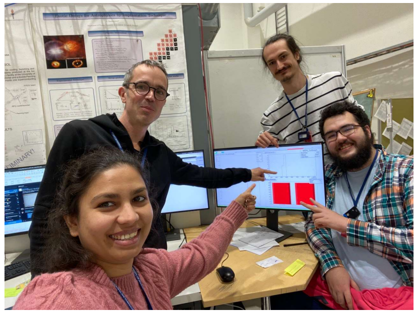
Not only contamination…

Stability problems resolved

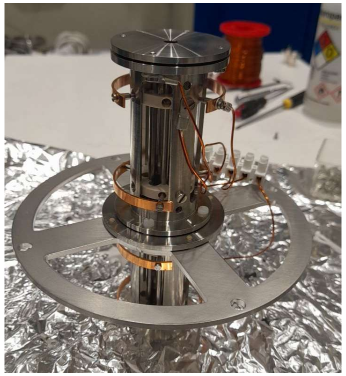
Dec. 2024

Some happy events in 2023-2024

Piégeage des ions ^{23}Na ions pendant 11s

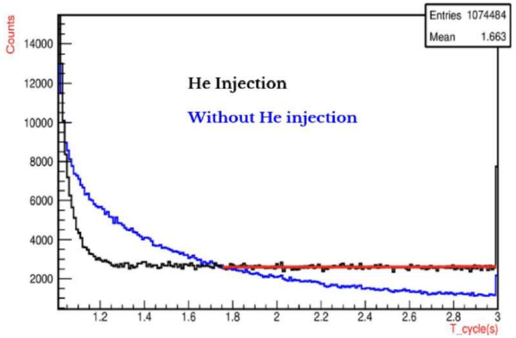


Soutenances de thèses



Origine de la contamination

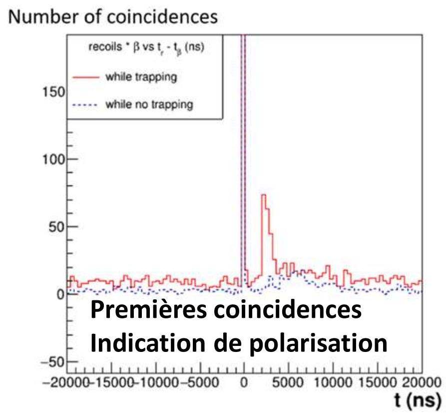
Evaporation des ions ^{23}Na piégés sur détecteurs d'ions de recul



Temps de piégeage~4min

Happy students at Les Houches School

+ Platan24, EMIS23, TCP22

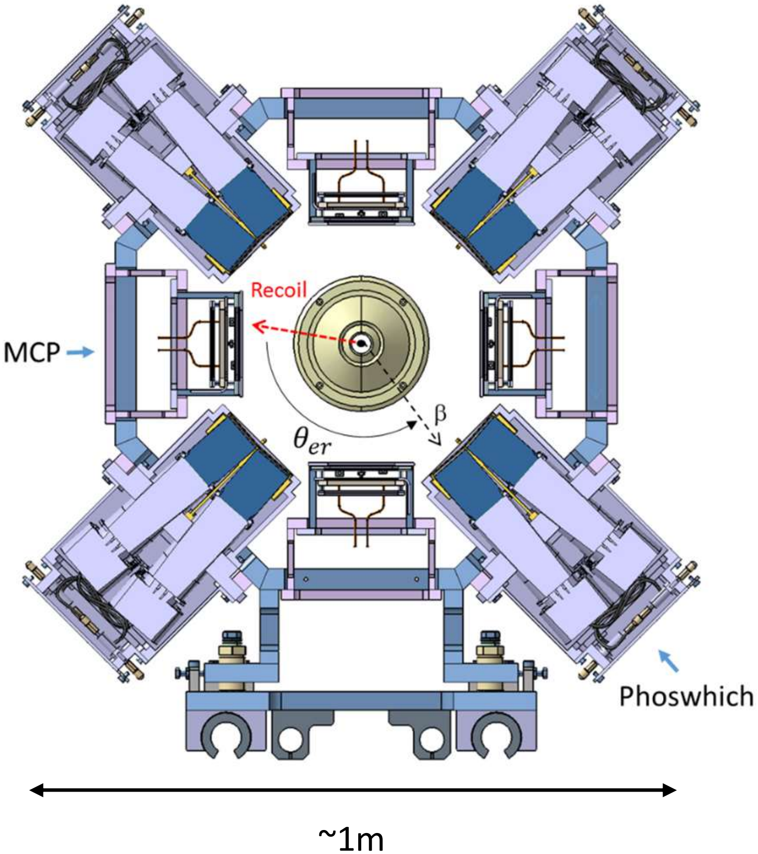


Premières coincidences

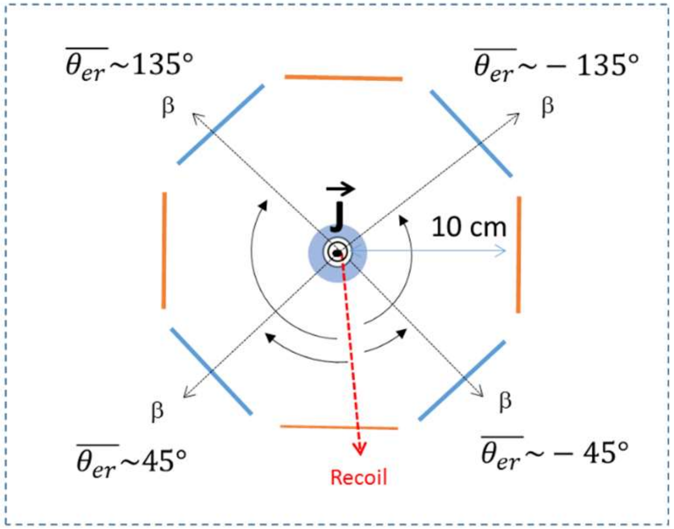
Indication de polarisation

MORA: measurement principle

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



In trap optical polarization

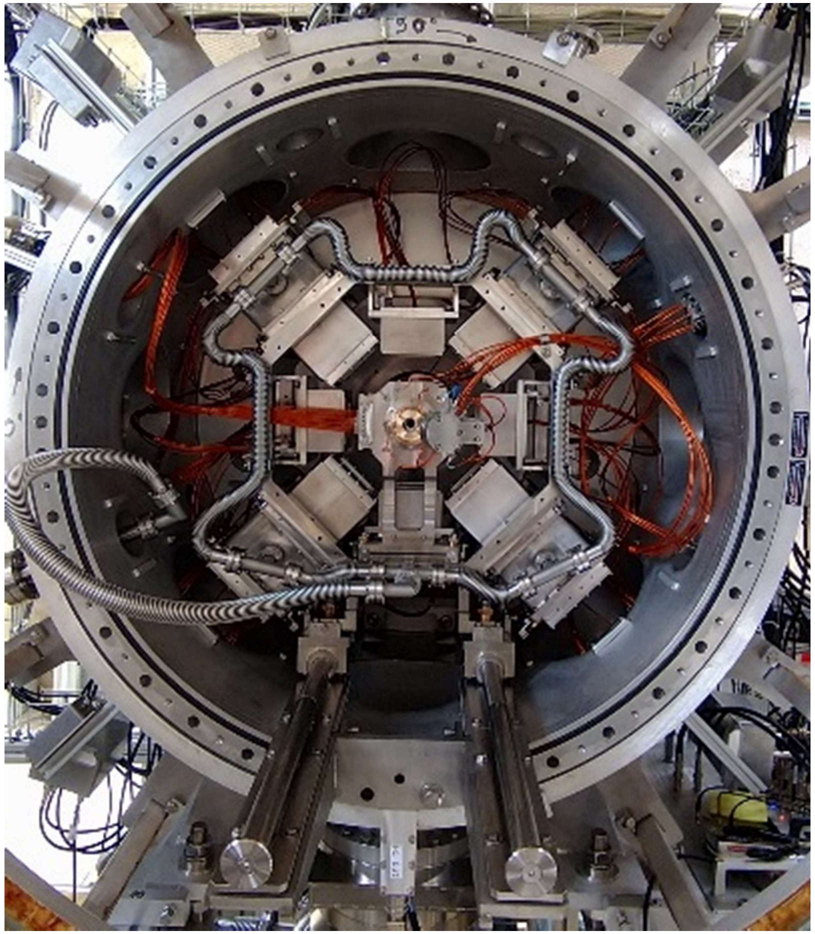


$$\frac{N_{coinc}^{+45°}+N_{coinc}^{+135°}-N_{coinc}^{-45°}-N_{coinc}^{-135°}}{N_{coinc}^{+45°}+N_{coinc}^{+135°}+N_{coinc}^{-45°}+N_{coinc}^{-135°}}=\delta\cdot D\cdot P$$

Where δ is depending on the phase space coverage

MORA: measurement principle

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



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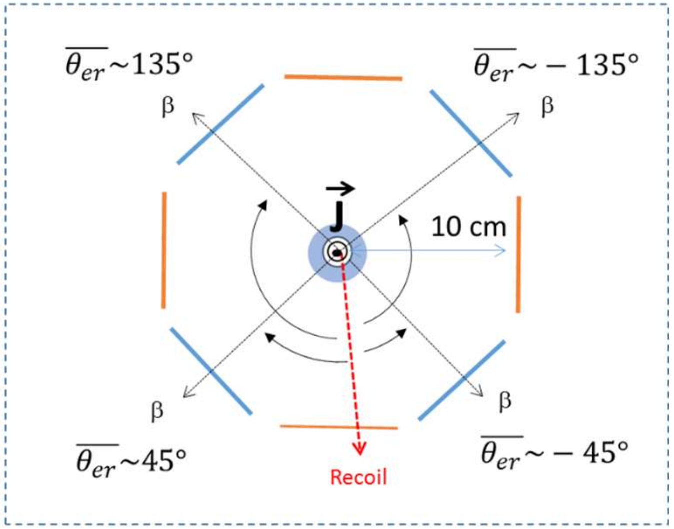

$$\frac{N_{coinc}^{+45°} + N_{coinc}^{+135°} - N_{coinc}^{-45°} - N_{coinc}^{-135°}}{N_{coinc}^{+45°} + N_{coinc}^{+135°} + N_{coinc}^{-45°} + N_{coinc}^{-135°}} = \delta \cdot D \cdot P$$

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MORA: measurement principle

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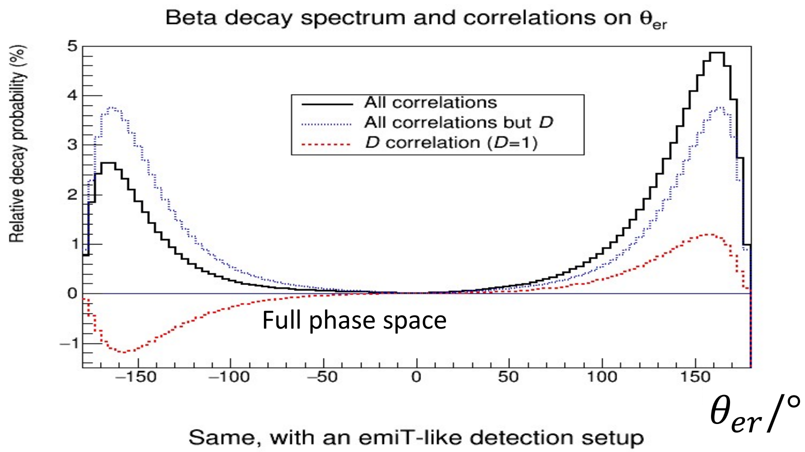
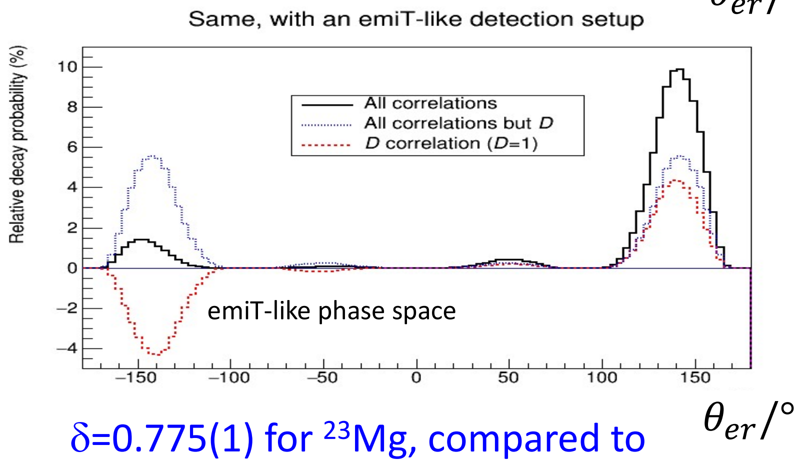
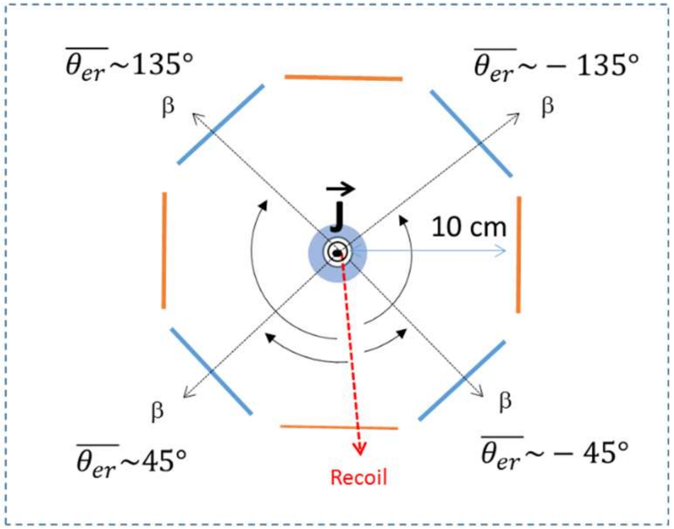




δ=0.775(1) for ^{23}Mg, compared to δ~0.3 for the neutron

In trap optical polarization



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

Where δ is depending on the phase space coverage

MORA: sensitivity challenges

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

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	**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	**1,0E-05**

So far statistical uncertainties have dominated, over systematic uncertainties

See for ex.: **D_n= (–0.94 ±1.89±0.97)·10^{-4}**

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

Provided that

- Trapping capacity is attained
- Efficient laser polarization is demonstrated
- Systematic effects are kept under control

→ Below 5.10^{-5} is feasible

Search for new physics via the *D* correlation measurement

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

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

T reversal odd

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

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

$D_{^{19}Ne}$=(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 » , arXiv:2207.02161
      - 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**

MORA: Best candidates for *D* measurement

THE MORA PROJECT
MATTER'S ORIGIN FROM RADIOACTIVITY
anr

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

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

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})	0,108	2,326	1,904	0,386	-0,489
D_2 (x10^{-4})	0,023	0,169	0,099	0,010	-0,024

10^7 pps requested

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

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.