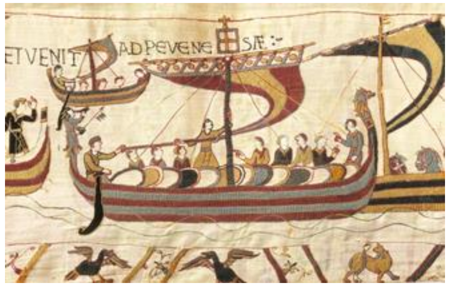


La MORA
Bayeux tapestry

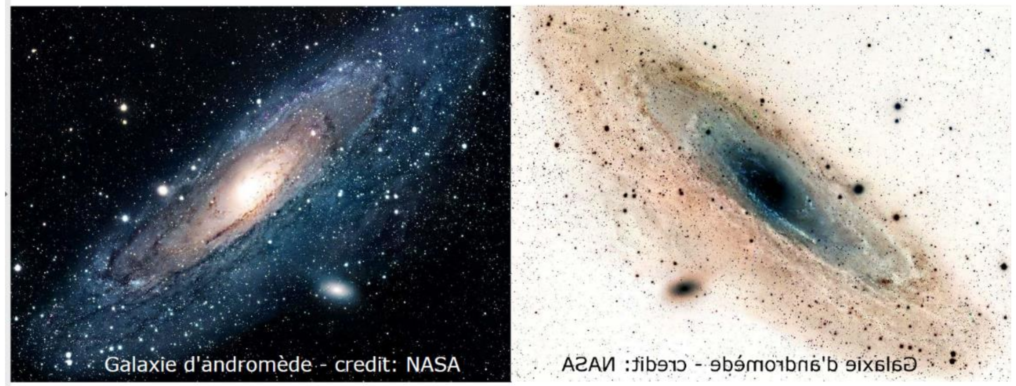
The Matter's Origin from RadioActivity experiment

Pierre Delahaye, GANIL

THE MORA EXPERIMENT

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 !

CP violation probes

- CPT theorem: CP violation equivalent to T violation

T-odd probes!

Electric dipole moments of particles and nuclei: $\boldsymbol{d} \cdot \vec{\boldsymbol{\sigma}}$

Correlations in nuclear β - decay

Sensitive probes to larger CP violations than predicted by the Standard Model, by 5 to 10 orders of magnitude

P. Herczeg, Prog. Part. Nucl. Phys. 46 (2001) 413.

New physics beyond the TeV scale

Learn more from presentations at the International MORA Workshop at JYFL (past event 2nd to 5th of May) https://indico.in2p3.fr/event/25986/

THE MORA EXPERIMENT

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

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

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
- Specific New Physics models
  - 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**

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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
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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**

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*

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

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

$D_{^{19}Ne} = (1 \pm 6) \cdot 10^{-4}$ — *Calaprice, Hyp. Int. 22(1985)83*

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

Search for New Physics

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Callan and Treiman, Phys. Rev. 162(1967)1494.

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

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

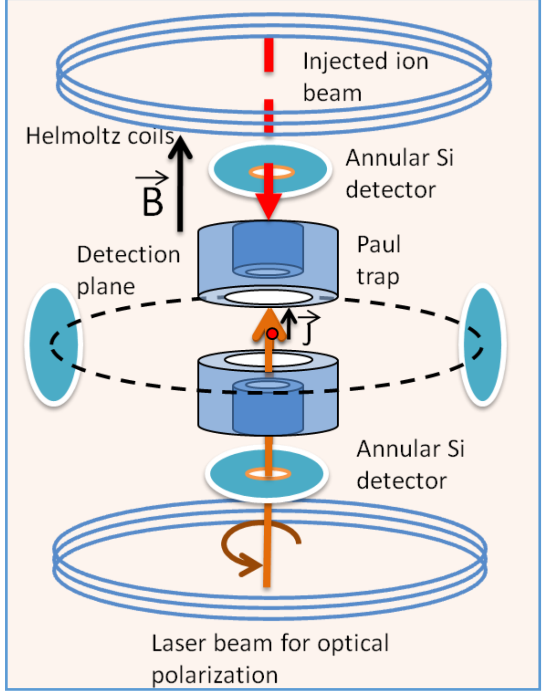
- **Ion cooling and trapping originally developped for**

LPCTrap

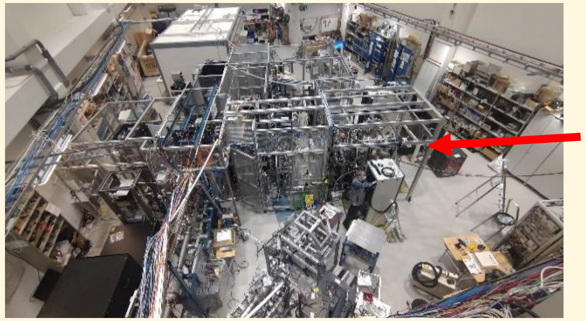
New trap and new detection setup:
off-line commissioning at LPC Caen and GANIL

Completed in automn 2021

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



- **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), The University of Manchester

Back to GANIL /DESIR, making use of the intense and purified ISOL beams from SPIRAL 1/ S3-LEB: **2027**

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**
- 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 (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

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

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

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- 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})	0,108	2,326	1,904	0,386	-0,489
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10^7 pps requested

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Best measurement so far, *statistics limited*

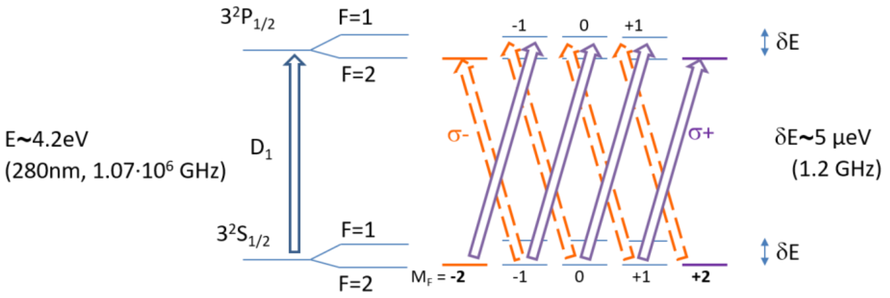
$$D_{FSI}(p_e) = \left(D_1 \cdot \frac{p_e}{p_{emax}} + D_2 \cdot \frac{p_{emax}}{p_e}\right) \times 10^{-4}$$

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

MORA: in-trap laser polarization

- 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   F= I+J

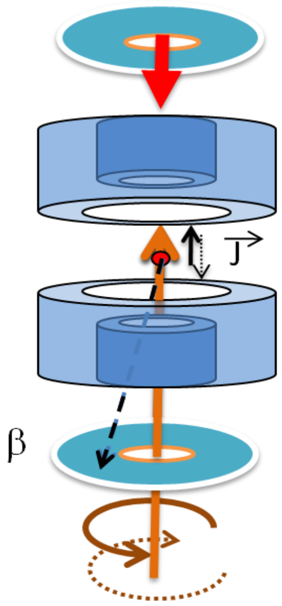


Transitions excited using trippled Ti:Sa laser pulses
λ~280nm σ+ polarization, ~4GHz width

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

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

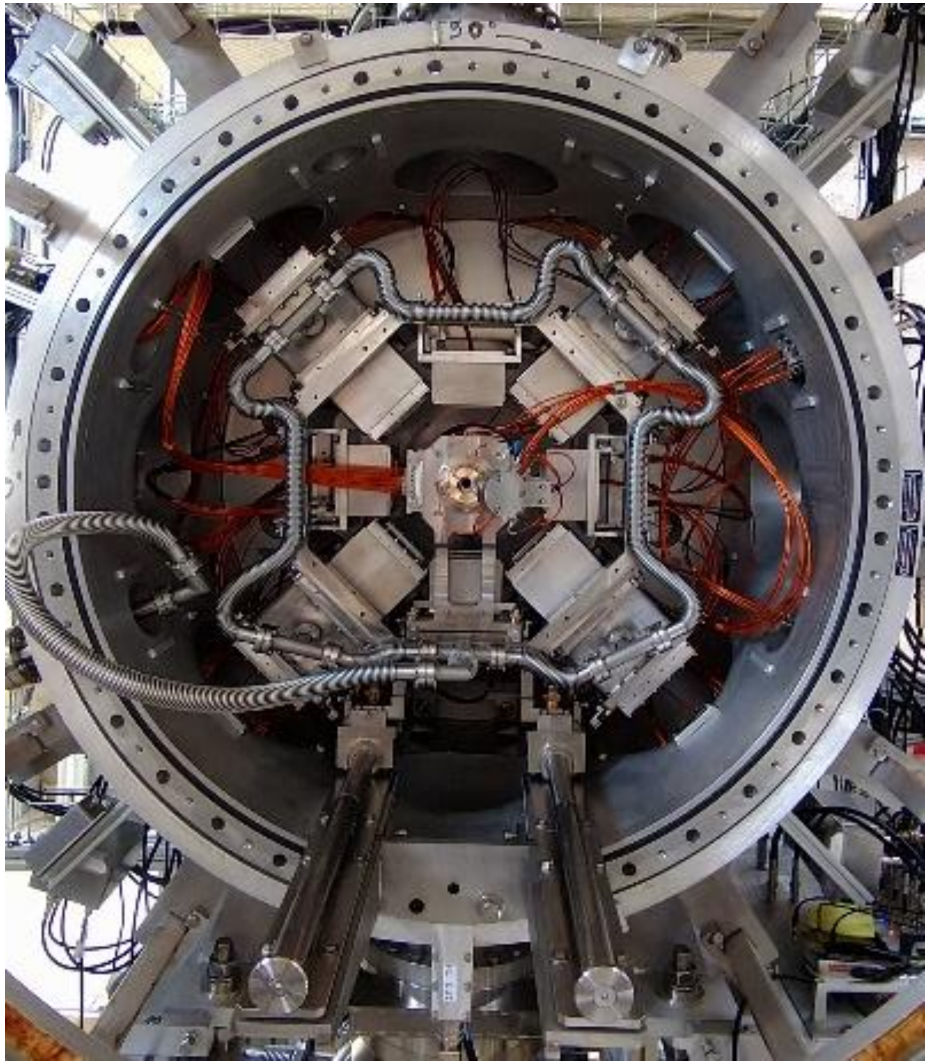
$$\frac{N_{\beta^+}^{\uparrow} - N_{\beta^+}^{\downarrow}}{N_{\beta^+}^{\uparrow} + N_{\beta^+}^{\downarrow}} \propto A_\beta \cdot P$$

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

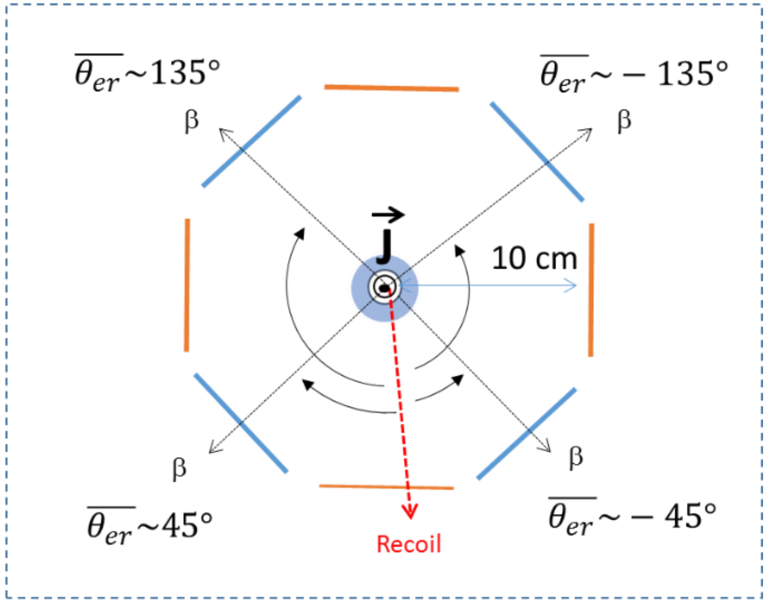
Transition probabilities: numerical simulations
R. de Groote, X. Fléchard and W. Gins

➡ Probable limitation: laser light polarization

MORA: measurement principle



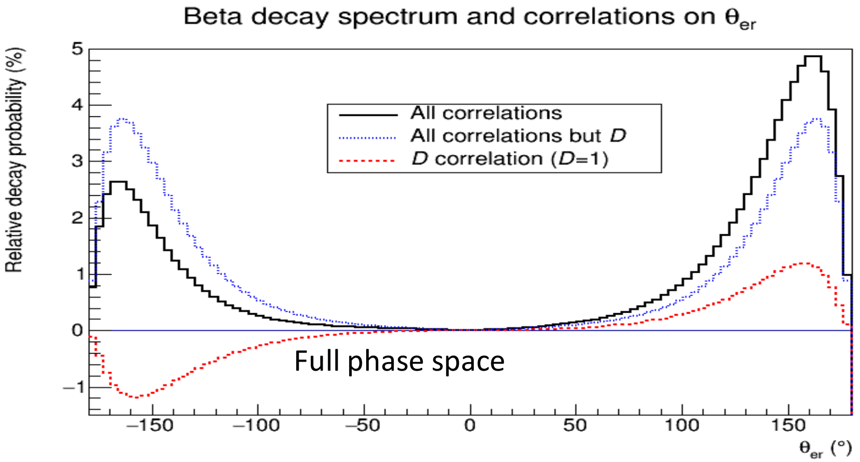
In trap optical polarization

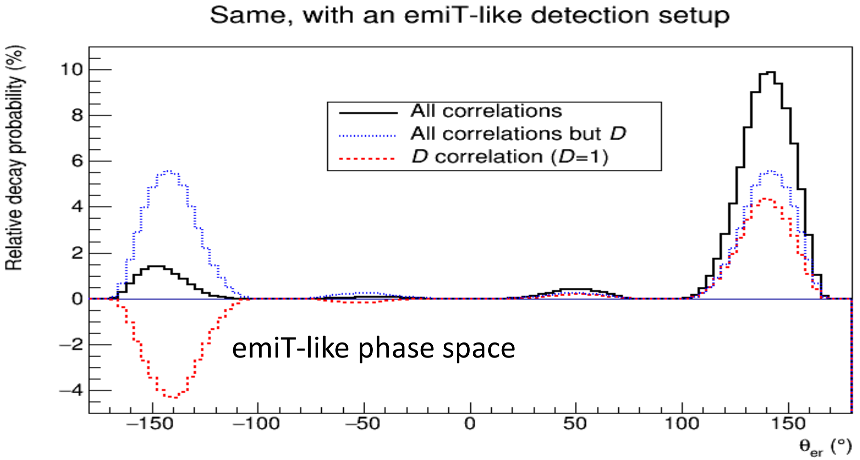


$$\frac{N_{coinc}^{+45°} + N_{coinc}^{+135°} - N_{coinc}^{-45°} - N_{coinc}^{-135°}}{N_{coinc}^{+45°} + N_{coinc}^{+135°} + N_{coinc}^{-45°} + N_{coinc}^{-135°}} = \delta \cdot D \cdot P$$

Where δ is depending on the phase space coverage

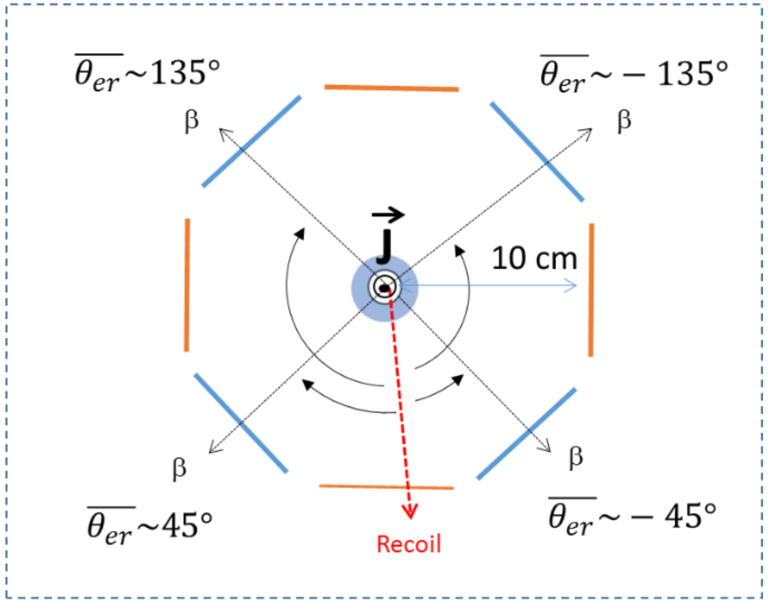
MORA: measurement principle





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

In trap optical polarization



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

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

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**

MORA: sensitivity challenges

Down to a few 10^{-5} sensitivity

- The emiT experiment gives a few hints

H. P. Mumm et al, Rev. Sci. Instrum. 75, 5343 (2004)
H. P. Mumm et al, PRL 107, 102301 (2011)

Dn= (−0.94 ±1.89±0.97) 10^{-4}

Systematic effects

Source	Correction	Uncertainty
Background additive	−0.07	0.07
Multiplicative[a]	0.03	0.09
Electron backscattering additive	0.09	0.07
Multiplicative	0.11	0.03
Proton backscattering	0	0.03
Electron threshold nonuniformity	0.04	0.10
Proton-threshold effect	−0.29	0.41
Beam expansion	−1.50	0.40
Polarization nonuniformity	0	0.10
ATP-misalignment	−0.07	0.72
ATP-twist	0	0.24
Spin-correlated flux	0	<0.01
Spin-correlated polarization	0	<0.01
Polarization	[b]	0.04[c]
K_D	[b]	0.04
Total corrections	−1.66	0.97

[a]In Ref. [11] this entry had a typographical error.
[b]Polarization and K_D are included in the definition of $\bar{D}$.
[c]Assumes polarization uncertainty of 0.05.

- Investigations of systematic effects is ongoing
  - Postdoc **Abhilasha Singh,** PhD **Luis Miguel Motilla**
- Dominant effects highly reduced **by the trap confinement**

Measurements needed

< 10^{-6}

Under scrutiny, disturbance of recoil tof by RF look small

< 10^{-6}

~ 1×10^{-6}

< 10^{-6}

MORA first steps in pictures: from Caen to Jyväskylä

THE MORA PROJECT
MATTER'S ORIGIN FROM RADIOACTIVITY

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

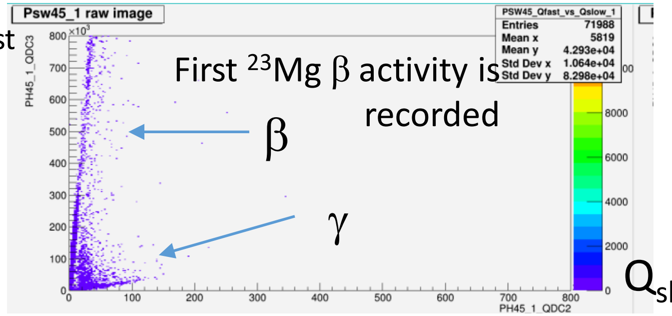
Installation in JYFL
January 2021 – trap and detectors

Large involvement of LPC Caen technical resources

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



First results

- 2 short beam times with ^{23}Mg (18-20 Feb. & 27-31 May 2022)
  - MORA apparatus is working **with close to nominal performances**
    - **All detectors up and running**, data acquisition running
      - Original noise on detectors due to RF amplifier has been suppressed
    - **Trapping efficiency** ~5 – **10%**, to be verified and optimized in November
      - Long trapping half life >500ms, to be measured in November
  - **Large production of ^{23}Mg, 10^5 pps/uA**, while 10 uA are possible
    - ^{nat}Mg(p,d)^{23}Mg with 30 MeV p, 100 mbarn
  - **280nm circularly polarized laser light** produced at required intensity: 90mW
  - But **beam purity and related space charge issues** are a major concern
    - Minibuncher @ IGISOL: presently space charge limited to **10^5** ions/bunch
    - Stable ^{23}Na contamination from IGISOL yields a ratio ^{23}Na:^{23}Mg $\gtrsim$ **500**

$$\text{Number of trapped } ^{23}\text{Mg ions: } 0.1 \ \text{x} \ 10^5/500 = \mathbf{20}$$

Goal: 10^4 trapped ions/cycle

PhD **Nishu Goyal**

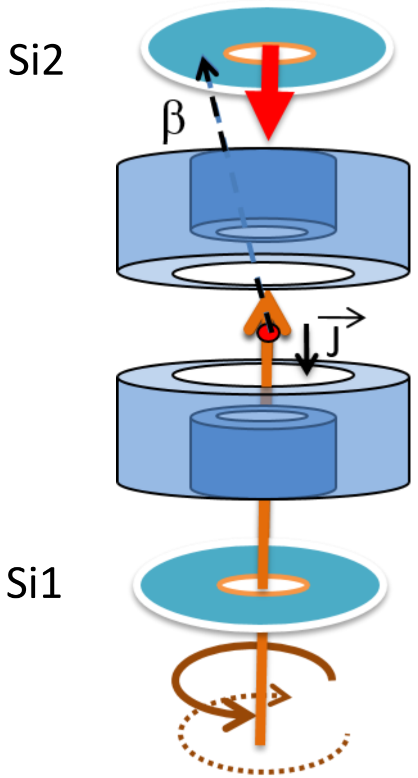
PhD **Sacha Daumas-Tschopp**

R&D on production and minibuncher RF ongoing

Next steps

- Prospects for short beam time with ^{nat}Mg(p,d)^{23}Mg (10-13 Nov.)

May 2022: assymetry measured **during 43min**, σ+ polarized light



N1=97 counts
on 6 sectors (2 are noisy)
Background is unknown

N2=48 counts
on 5 sectors (3 are noisy)
Background is unknown

Background unknown on single events → no possible conclusions on P

Next steps

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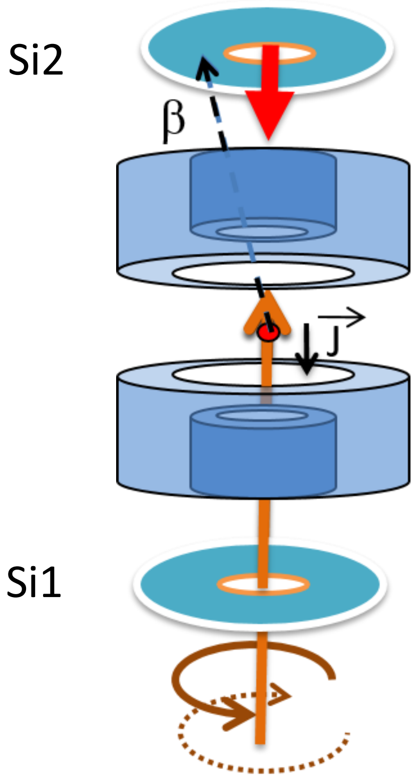
May 2022: assymetry measured **during 43min**, σ+ polarized light



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Background is unknown

Hypothesis:

- assymetry is due to P→1
- **Background is isotropic - let's call it N0**

$$\alpha P = (N1 - N2)/(N1 + N2 - 2N0)$$

$$\alpha \sim 0.5$$

➡ N0=30, **17 trapped ions on average**

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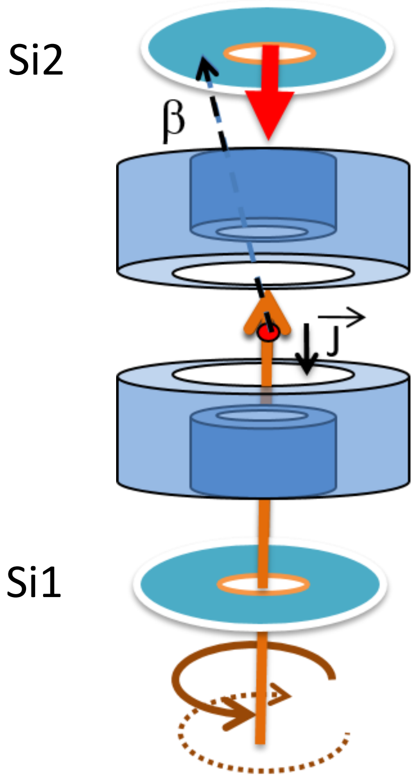

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→ N0=30, **17 trapped ions on average**

Prospects for **8h spin up, 8h spin down, 8h background**
N0 = 335 (Background)
N1 = 657 N2 = 1330 (σ+)
N2 = 1330 N1 = 657 (σ-)

$$\frac{\sigma_P}{P} = 0.07$$

A 10% measurement of P is possible if P → 1

Background unknown on single events → no possible conclusions on P

Next steps

- Prospects for short beam time with $^{nat}Mg(p,d)^{23}Mg$ (10-13 Nov.)
  - Efficiencies before cooler and entrance of MORA verified with Si detectors
  - Better RF for minibuncher (up to 1kVpp 3MHz): higher number of ions in the trap
  - **Polarization degree measurement with 10% accuracy**
  - Measuring Mg^{2+} yields before cooler for possible beam purification
- Early 2023
  - **Testing hot cavity for contaminant reduction**
    - Hot cavity: stable, natural ^{23}Na is outgased with time
    - Studying prospects for $^{12}C+^{12}C \rightarrow ^{23}Mg+n$ @5MeV/u, 10mbarn
      - ^{24}Mg implantation from cyclotron
        - Laser ionisation scheme development/ ionisation efficiency measurement
        - Measure of ^{24}Mg release time
      - Evolution of ^{23}Na vs ^{24}Mg as a function of time

Wish list for a performant facility for fundamental interactions

- **Beam manipulation techniques**
  - DESIR will feature from the start many valuable instruments
    - **HRS with R>10,000**
    - General purpose buncher
    - PIPERADE
    - MR – TOF – MS
    - Laser barracks
- **Beam intensities > 10^7 pps for correlation experiments**
  - 10^7 ~ capacity of present traps
  - Nuclei close to stability: low energy reactions with high cross sections are possible
    - An interesting aspect for difficult ISOL beams (ex: ^{39}Ca)
      - Tailored production system, with thin targets + gas cell or catchers
        - ^{39}Ca in TULIP system?
- **Beam time availability+regular access is a significant advantage**
  - Precision experiments need time to collect statistics
  - And time for investigating systematics

Slide from ISOL@MYRRHA workshop

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  - 10^7 ~ capacity of present traps
  - Nuclei close to stability: low energy reactions with high cross sections are possible
    - An interesting aspect for difficult ISOL beams (ex: ^{39}Ca)
      - Tailored production system, with thin targets + gas cell or catchers
        - ^{39}Ca in TULIP system?

Remind SPIRAL 1 beam session

The ultimate sensitivity of MORA to New Physics technically depends on:

- **Statistics**
- **Control of systematic effects**

Taking example of successful measurements carried out with neutron decay, and EDM

A regular access to online run with possible long data accumulation periods* is highly desired

*** 3 to 4 weeks typically**

Thanks a lot for your attention!

MORA collaboration

THE MORA EXPERIMENT

anr® RÉGION NORMANDIE

lpc caen

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