Polarization of trapped ions in MORA at IGISOL

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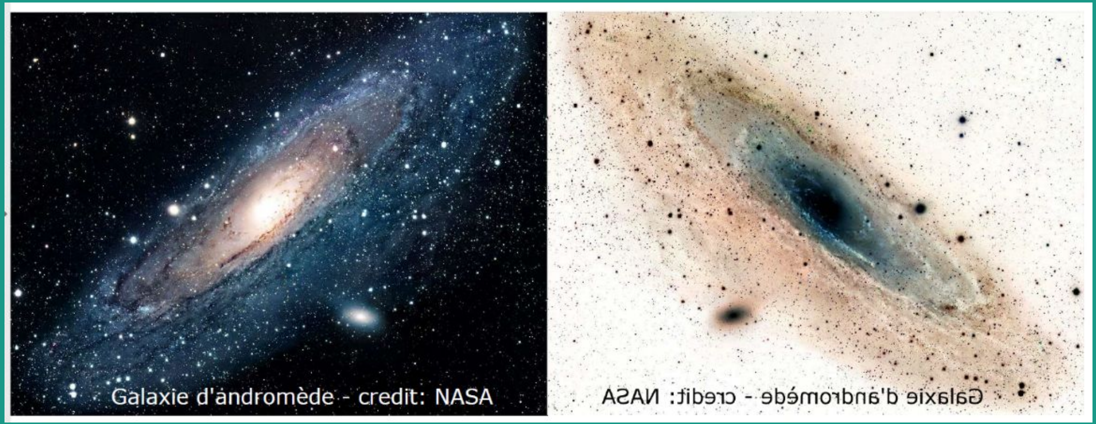
RÉGION NORMANDIE

Contents

- CP Violation and D correlation, the search for baryogenesis
- MORA Setup, IGISOL
- Latest experimental developments
- Outlook and conclusions

CP Violation and D correlation, baryogenesis



In search of CP Violation

- **Matter** and **antimatter** should have been created in **equal** amounts
- Why do we **only** see **baryonic matter**?
- Sakharov **conditions** for **baryogenesis**
  - Baryon number violation
  - CPV
  - Process out of equilibrium

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

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- **CPV** known in the **SM**
- Seen in decay of **K, B** and **D** mesons
- **Not enough** to explain baryogenesis

- **Where to find CPV**
  - **In** the **SM:** complex phase **CKM matrix**
  - **Outside SM**: D-correlation of beta decay

β decay D-Correlation

In a **GT-F** mixed **β**-decay the energy phase space can be written as *

$$\omega\left(\langle J\rangle|E_e,\ \Omega_e,\ \Omega_\nu\right) dE_e d\Omega_e d\Omega_\nu = \frac{F(\pm Z, E_e)}{(2\pi)^5} p_e E_e (E^0 - E_e)^2 dE_e d\Omega_e d\Omega_\nu$$

$$\times\, \xi \left\{ 1 + a\frac{\mathbf{p}_e \cdot \mathbf{p}_\nu}{E_e E_\nu} + b\frac{m}{E_e} + c\left[\frac{\mathbf{p}_e \cdot \mathbf{p}_\nu}{3E_e E_\nu} - \frac{(\mathbf{p}_e \cdot \mathbf{j})(\mathbf{p}_\nu \cdot \mathbf{j})}{E_e E_\nu}\right]\left[\frac{J(J+1) - 3\langle(\mathbf{J}\cdot j)^2\rangle}{J(2J-1)}\right]\right.$$

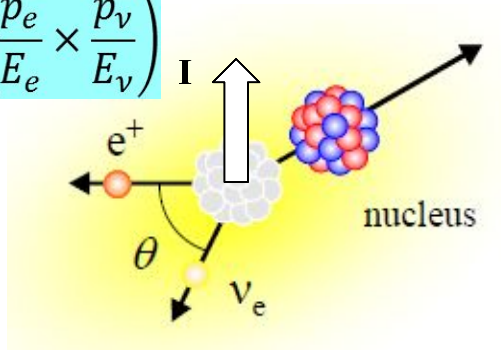
$$\left. \frac{\langle \mathbf{J}\rangle}{J} \cdot \left[A\frac{\mathbf{p}_e}{E_e} + B\frac{\mathbf{p}_\nu}{E_\nu} + D\frac{\mathbf{p}_e \times \mathbf{p}_\nu}{E_e E_\nu}\right] \right\}$$

β asymmetry	*β-ν* correlation	Fierz interference	D correlation

D is **non-zero** for **T** reversal violation

* Jackson, J. D.; Treiman, S. B.; Wyld, H. W. (1957) Phy Rev 106(3), 517−521

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



A precise measurement of **D** would allow to:

- Give **direct constraints** on CP-violating **Wilson coefficients** in the nucleon-level EFT
- **Probe** specific **BSM Models**, like **L-R** symmetric model and **Leptoquark** model
- Measure **Final State Interactions**, predicted by the SM

Determination of the D-Correlation

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

We need to maximize F(X) and the polarization degree of ions to get the highest sensitivity for CPV

Proportional to GT-F mixture degree (ρ) and axial vector-vector phase

Final state interactions (**FSI**), never measured using D-correlation

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)

$$D_{FSI} \sim Z\alpha \frac{E_e}{M} \cdot A(\mu_f - \mu_i)$$

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

Selection of nuclei for D-Correlation

Maximal **sensitivity to F(X)**

Maximal spin **polarization**

Two cases to **separate** new physics from **FSI**

Well produced in GANIL, easy to polarize, short half-life, GT-F decay

Shorter half-life, opposite sign for FSI, good candidate for IGISOL

	neutron	^{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

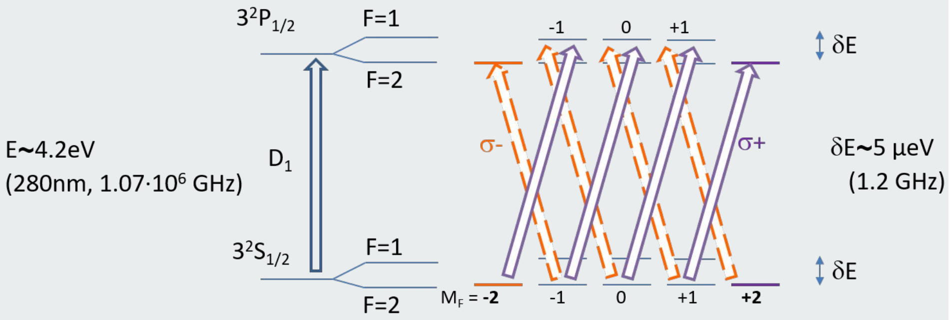
$D_{neutron} = (-0.94 \pm 1.89 \pm 0.97)\cdot 10^{-4}$ $D_{19Ne} = (1 \pm 6)\cdot 10^{-4}$

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

Best measurement so far, *statistics limited*, but not enough for CPV

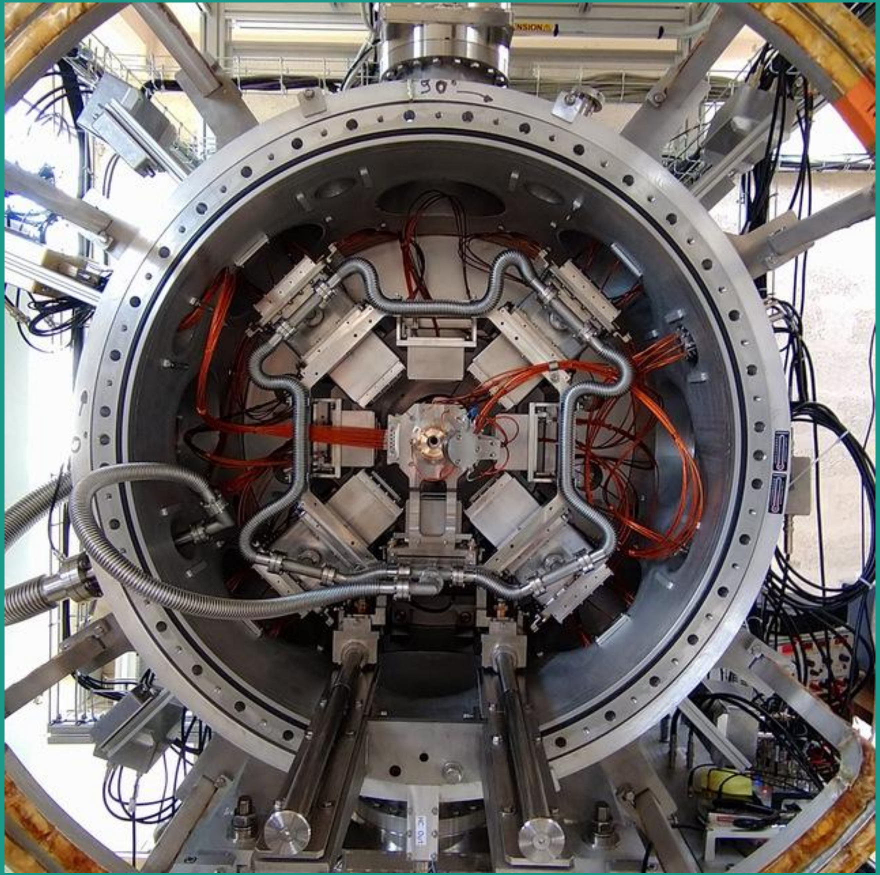
Callan and Treiman, Phys. Rev. 162(1967)1494.
Chen, Phys. Rev. 185(1969)2003.

Laser polarization of ^{23}Mg



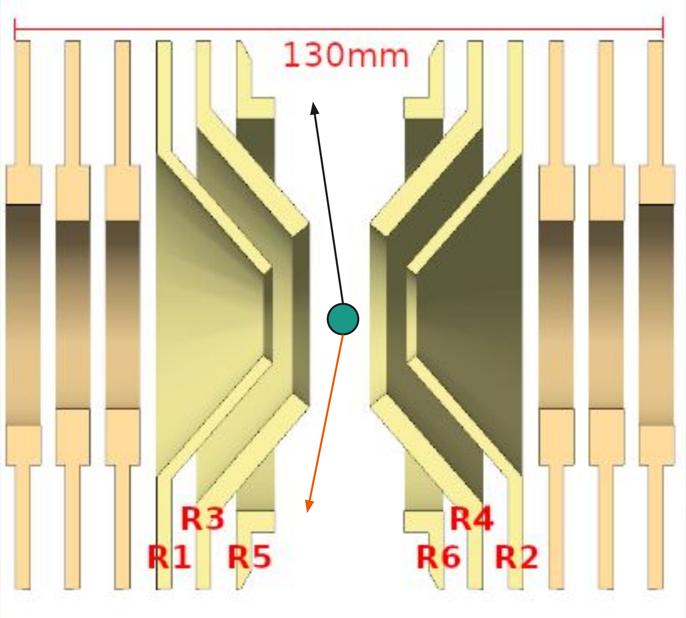
- **Pump** the **ions** to **M_F = ± 2** for **spin J polarization**
- We use a **dipole** excitation with a **circular polarized laser** to **increase**(**decrease**) the **projection** number **M_F**
- ^{39}**Ca** has a more complex structure to polarize than ^{23}**Mg** (2 lasers vs 1 laser)
- **^{23}Mg is the best candidate for the first experiments at IGISOL**
  - **First candidate for DESIR**
  - **Easy to produce and polarize**
  - **High sensitivity to FSI and new physics**

MORA Setup, IGISOL



MORA Trap

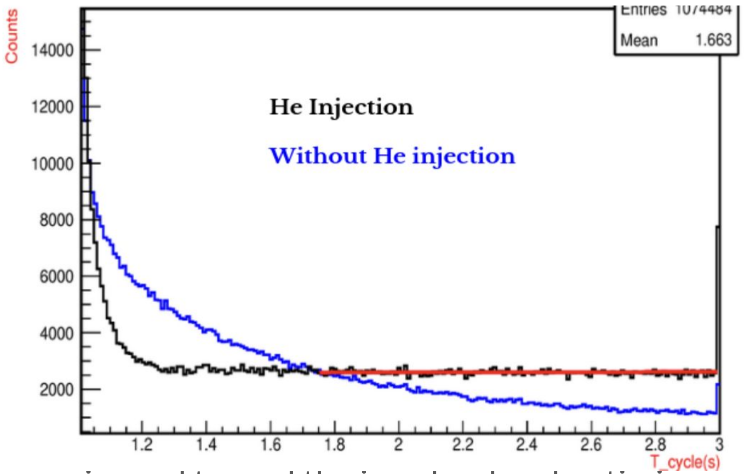
Open Paul Trap developed in **LPC Caen**



Paul Trap consisting on 3 pairs of **electrodes** (R1-R6) and 2 **Einzel lenses**

The electrodes (R1-R6) trap the ions

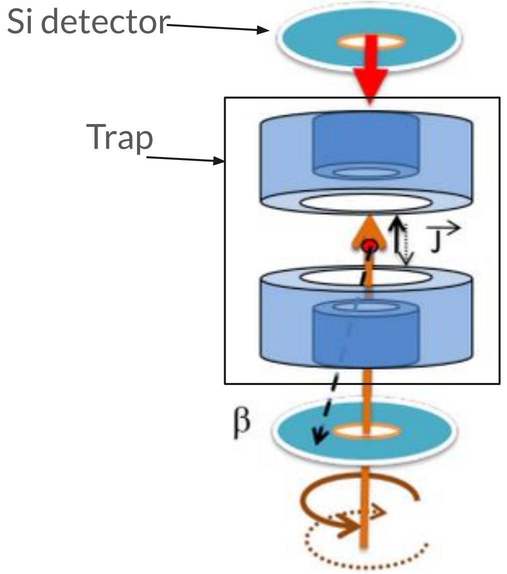
Einzel lenses focus the beam



He gas is used to cool the ion cloud and optimize trapping efficiency

MORA Setup

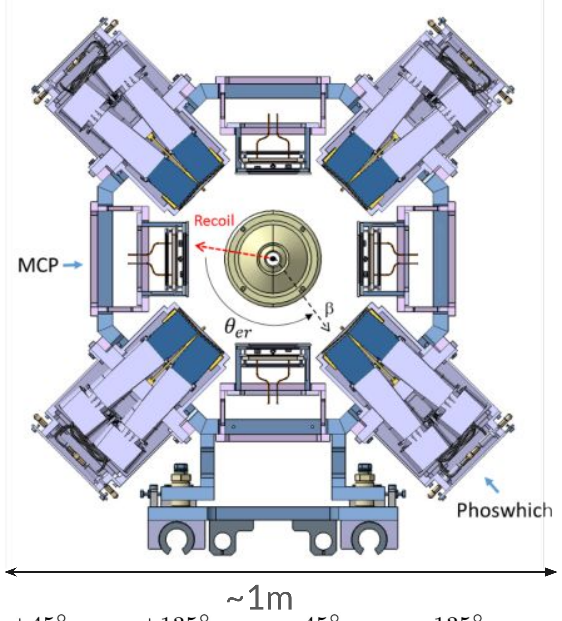
Polarization measurement



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

- **Paul Trap** in the middle of the detection system
- 2 annular **Si detectors** in the line axis
  - For continuous polarization measurement by betas
- 4 **MCP detectors**, each 90° apart from each other
  - For recoil ion detection
- 4 **phoswich detectors**, between the MCP detectors
  - For beta detection
- Laser setup for polarization

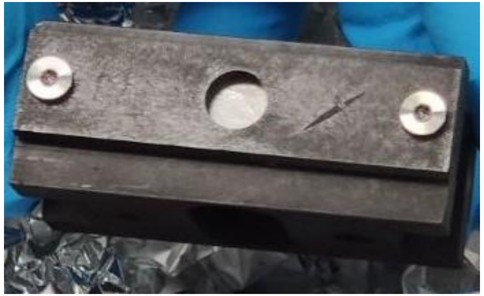
D correlation measurement

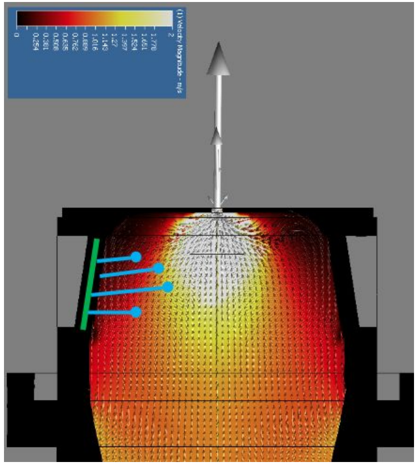


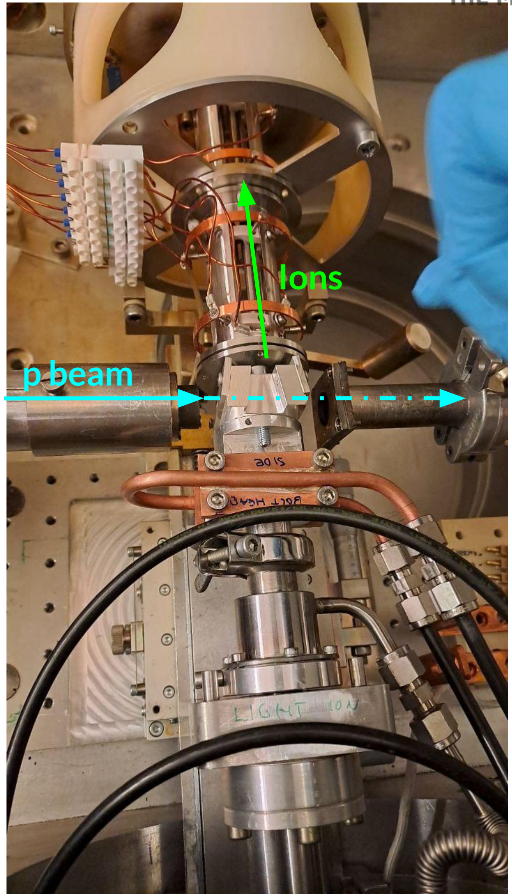
$$\frac{N^{+45^\circ}_{coinc} + N^{+135^\circ}_{coinc} - N^{-45^\circ}_{coinc} - N^{-135^\circ}_{coinc}}{N^{+45^\circ}_{coinc} + N^{+135^\circ}_{coinc} + N^{-45^\circ}_{coinc} + N^{-135^\circ}_{coinc}} = \delta \cdot D \cdot P$$

Ion Production at IGISOL

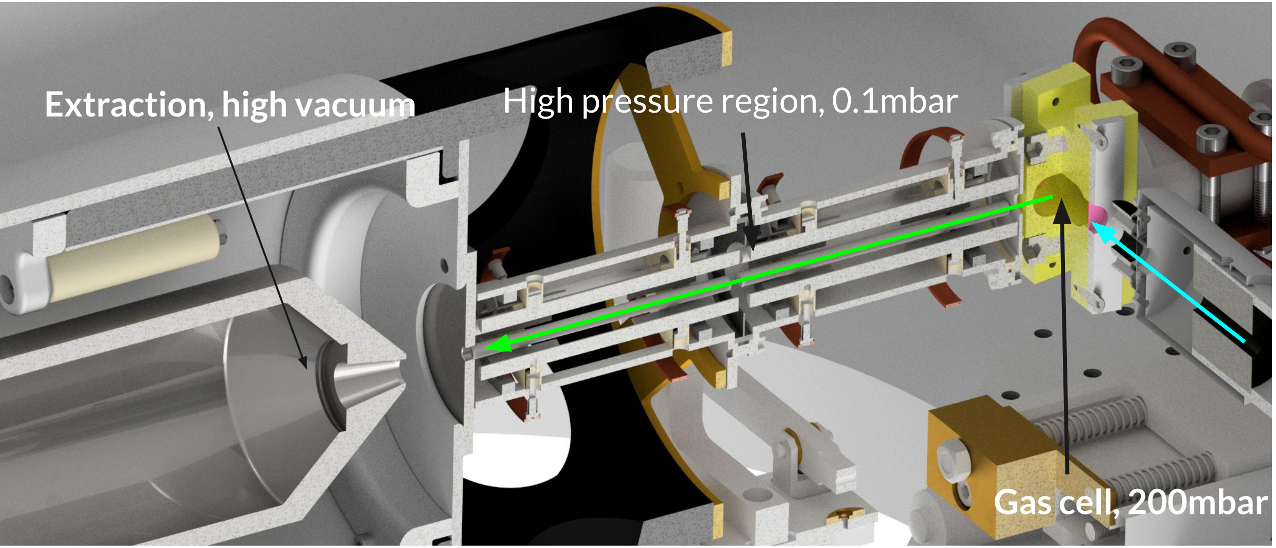
- Radioactive ions produced by the **IGISOL** method. Collision of a **primary beam** (**proton**, 3He...) with a **target** in a **gas cell** .
- Transfer reactions, ^{24}Mg(p,d) or ^{40}Ca(p,d)
- Ions transported within **purified He gas** into the **Sextupole Ion Guide (SPIG)**, later accelerated at **30keV** towards the **Dipole Magnet** mass separator

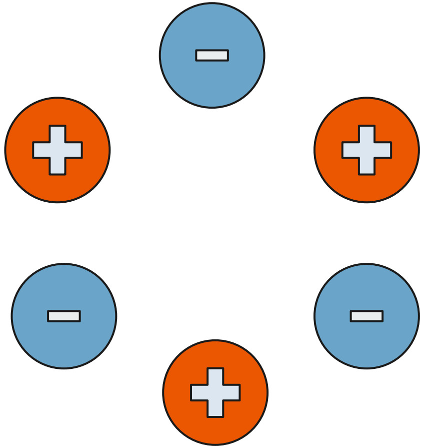






Sextupole Ion Guide



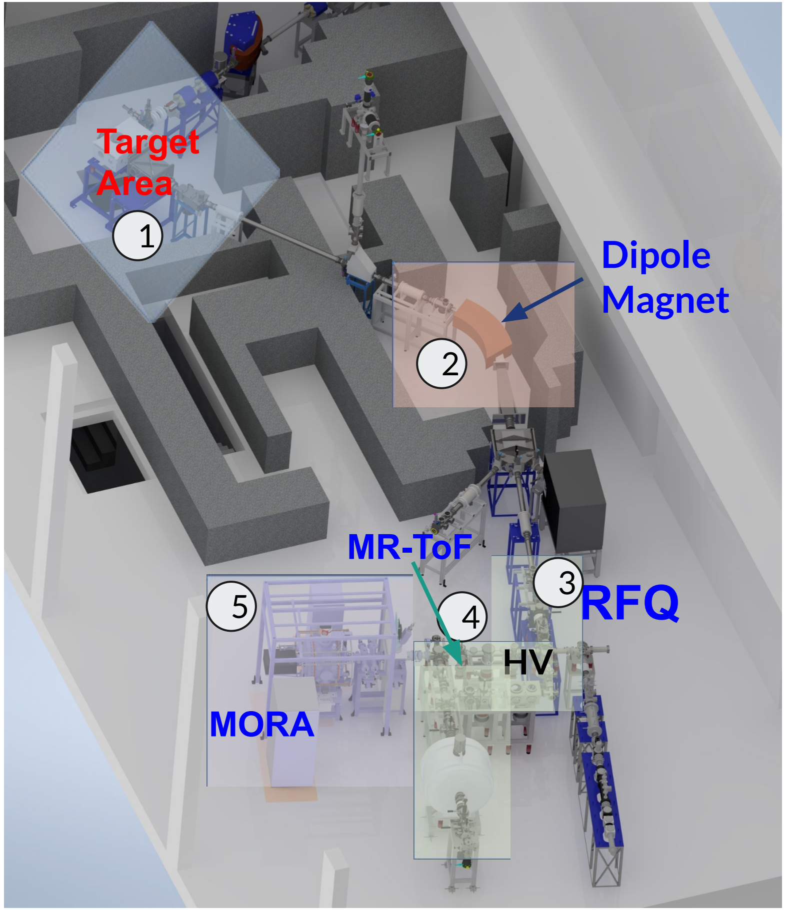


RF sextupole ion guide, 3-5MHz , ~1kV V_{pp}

Transports ions from **high pressure** (~0.1 mbar) section into **high vacuum**

IGISOL Beamline

1. Ion production
2. Isobar (A/q) separation
3. Ions enter the HV cage, at 30kV -> slowed down <100eV
   a. Ions get cooled and bunched in the RFQ Cooler Buncher
   b. When exiting, they get accelerated to 2keV
4. Ions travel through the MRToF, where mass separation can be done
5. Arrival to MORA, at ground potential
   a. Pulsed Drift Tube (PDT) to slow down and bring to ground potential the ions
   b. Second PDT to further slow down the ions
   c. MORA Trap and detection setup
   d. The ions get ejected from the trap



Latest developments

Laser polarization proof-of-principle
Beam purification efforts

First conditions of MORA, Nov 2022

Typical conditions at IGISOL

- He gas purified by zeolite cold trap and getter purified
- ~200mbar of He gas inside of gas cell
- Ti windows on the gas cell, nat Mg target facing the beam
- 5MHz SPIG RF, usual extraction voltages
- Usual Al ion guide

- Too **high contamination**, getting **only ~10 ^{23}Mg ions per trap cycle**, even with high production (>10k ions/s)
- **Impossible to do polarization proof-of-principle**
- The culprit: **^{23}Na contamination**

- The **RFQ Cooler Buncher** has a limited charge space, that gets **saturated by too much $^{23}Na^{+}$**
- Since the ions are limited by the Cooler, **we cannot make use of the MRToF for cleaning the beam**
- Need to tackle contamination on the **production**

In search of contamination's origin

Possible origin: Target

- Traces of Na
- Nuclear reaction
- Surface ionization
- Sputtering

Various **target tests** done, **coatings** to prevent ionization and different **target material** (Al)

No improvement

Possible origin: Gas cell

- Surface ionization / sputtering from the gas cell

Changed usual **Al to graphite** gas cell **baked** at **high temperature** (**1300°C**) for long period of time to **evaporate traces**

No improvement

Possible origin: Gas

- Stopping He purification showed improvement
- Traces of Na coming from Zeolite
- Forming molecules with Na that could improve yield

Various **gas tests done**, different traces of gases over purified He and different **getter** and **cold trap configurations**

No improvement

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In search of contamination's origin

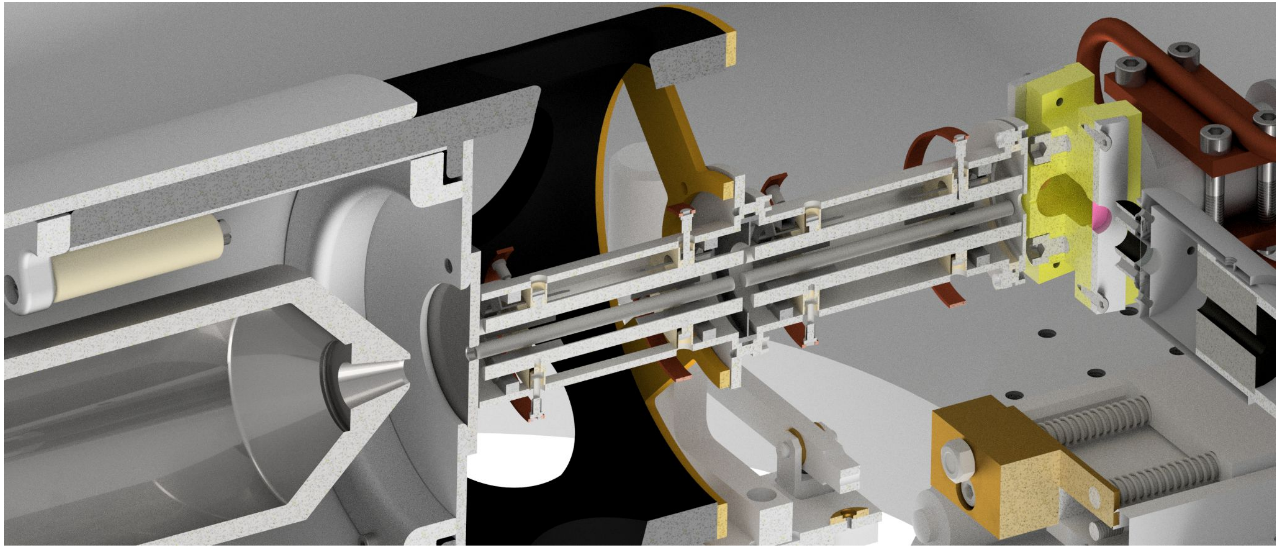
Origin: Sputtering in the SPIG

Coherent with all past observation

- Gas purity
- Gas pressure
- SPIG tuning

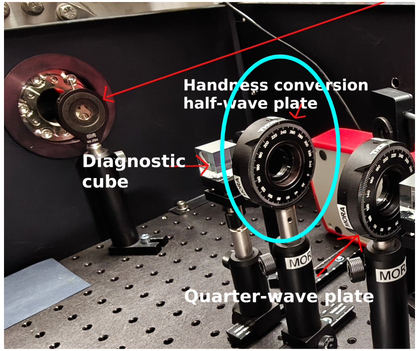
Cleaned with deionized water in March

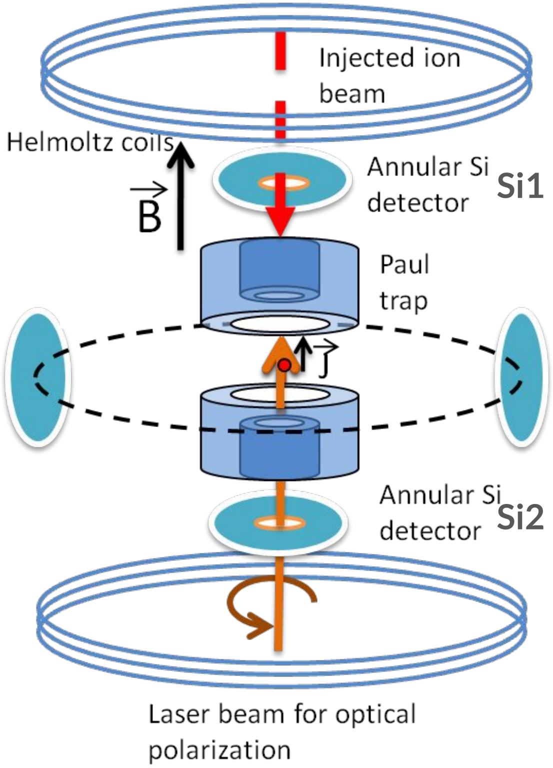
Changed rods for Nb in June



Polarization proof-of-principle

- Using **detections** ($N_{\beta+}$) **on the Si detectors** (Si1 and Si2) **in each polarization** (σ_+ or σ_-, ↑or ↓) **to measure the asymmetry** (A)
- A = $\alpha \cdot$ P, where $\boldsymbol{\alpha}$ **is a sensitivity factor** estimated from simulations, which includes A_β, **the beta asymmetry** and **P is the polarization degree**
- **Needed ~10^2 ions per trap cycle to measure P**
- **We need at least ~10^4 ions per trap cycle to attempt to measure D**





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

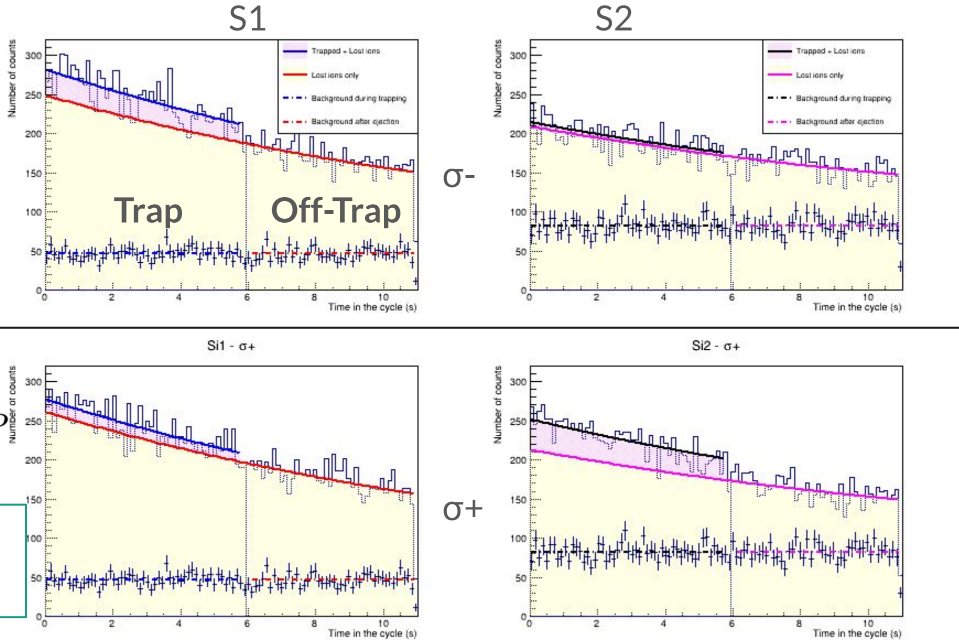
March 2025, Results

Asymmetry Polarization σ- : 0.72±0.25
Asymmetry Polarization σ+ : -0.42±0.16
Asymmetry with full polarization of the cloud (from simulations): =0.51±0.01

A = 0.51±0.14

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

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



Trapped ions/cycle

90±9 from Si detectors

145±55 from coincidences

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

June/July 2025

- Objectives:
  - **Reduce contamination from Na** as much as possible
  - Use **MRToF** to **measure contamination** and **clean beam from Na**
  - Achieve **10^4 Mg ions in trap per cycle**.
  - Measure the **P degree and D correlation**
- **Achievements:**
  - **Contamination reduced (~2:1 Na:Mg)**
  - **MRToF used for measurement and separation**
  - **40k Mg ions in the entrance of MORA**
  - **P degree measurement (under analysis)**

- **To solve:**
  - **Low trap efficiency**, due to bad steering due to the MRToF
  - **Peak coalescence** observed from the MRToF, possibly due to higher energy dispersion from the RFQ cooler buncher and ion-ion interactions inside the MRToF (10^5 ions per bunch)
  - **D correlation not measured**
- **All the pieces are on the table for the measurement**

Outlook

- **Proof of principle achieved with ^{23}Mg, D correlation measurement close to be reached**
    - Short beamtime **next week**, aiming to **achieve 10^4 Mg ions trapped**
- **^{39}Ca to be started soon, both for polarization and D correlation**
    - **Laser scheme more complex**, **unknown contamination** from **^{39}K**, and many other possible challenges, also to be **tested next week**
- This has been possible thanks to the efforts on **improving the contamination**
- We are also able to **improve trap efficiency** thanks to tackling other **less conspicuous effects, e.g. increase of energy dispersion of the bunches by desynchronization of the MORA RF with the cooler**
- After the test next week we will have a **short** beamtime for **^{39}Ca** and a **long** one for **^{23}Mg** measurements

Thank you for your attention!

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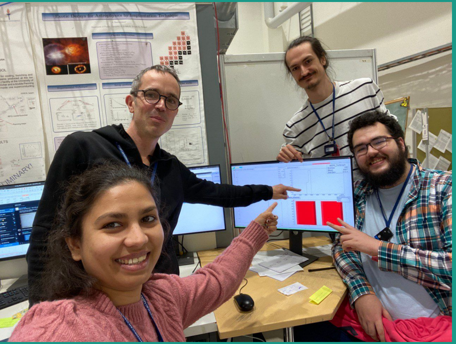

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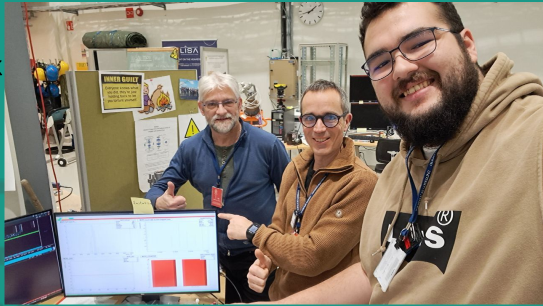
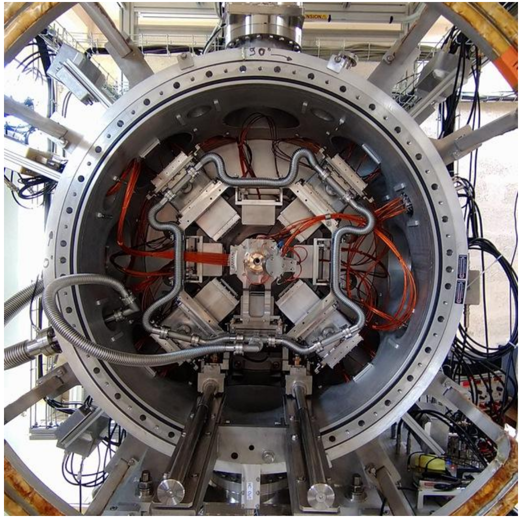


Extra slides

MORA Experiment at IGISOL

- **Proton beam @30MeV** hits the target, ^{24}**Mg(p,d)**^{23}**Mg** reaction.
- **Ions cool** down and **charge** exchange **to 1+**, travel through **SPIG** and go to **dipole magnet**
- Choose **Isobar** (**A/q=23**) and send beam to **RFQ Cooler buncher**
- **Beam** gets **cooled** and gets **bunched** for ~2.7ms. Sending **one bunch** to MORA **every 11s**.
- Bunched beam arrives to **MORA PDT**, where it gets **pulsed down to -1kV** to send to ground, **ions at ~1keV**
- Bunched **ions arrive to second PDT**, where they get further **deaccelerated to ~100eV**
- **Ions get trapped for 6s**
- After trap, the **ions get ejected**
- **5s of "off-trap" measurement** for active background
- **Measurement repeated** for **two different** circular **polarizations**, changing every hour



Source: ~~target?~~ gas cell? gas?

Data Acquisition: June2024

Installation of **baked C gas cell** trying to evaporate all Na → No immediate improvement.

Second gas injection attempt, trying to find the gas that makes Na disappear

Gases planned to be used: **CO_2, N_2, He+CF_4, SF_6, He+Kr, He+Ne**

Gases used: **CO_2, He+CF_4, He+Kr**

Mass flow controller allows for precise measurement of gas flow we are introducing into the chamber

Source: ~~target?~~ ~~gas cell?~~ gas?

Data Acquisition: July2024

- **First polarization evidence** (1.53σ) measured
- The improvement was achieved mainly by having a **full dewar of LN** and **fine tuning the SPIG** voltages
- If the Na was produced at a lower energy/other mechanism, it is safe to assume that the extraction would be much different
- Further **gas injection test did not prove useful**, but it might be coming from the zeolite in the purification system
- PDT stability issues and how to fix them

Ringing from the PDT after pulsing down

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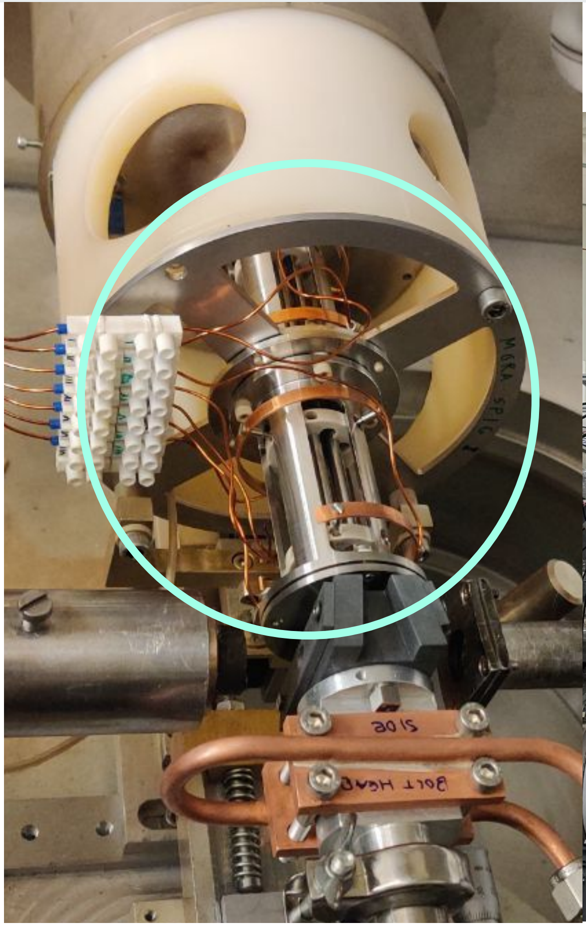
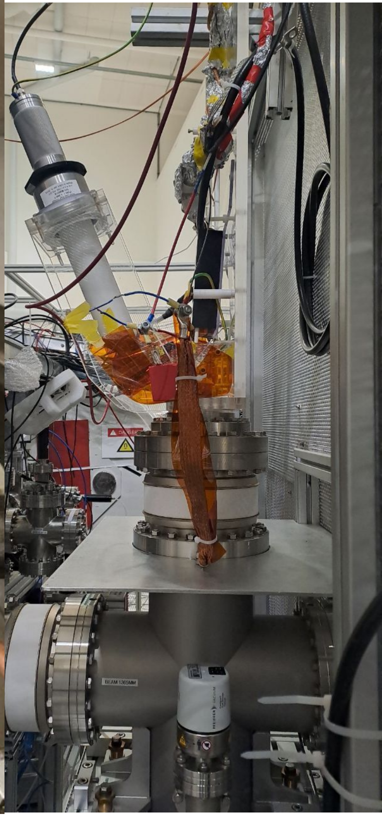
Source: ~~target?~~ ~~gas cell?~~ gas?

Data Acquisition: Dec2024

- We used **charcoal and SiO2** based **cold trap** to avoid any zeolite, and new **filters inside of LN** to simulate the events in July (full dewar)
- Immediately we saw **no improvement** in the yield Na:Mg
- **The only suspect left was the SPIG**
- The SPIG is coherent with all other observations:
    - Effects of gas purity/pressure
    - The Na+ can be trapped in the SPIG
    - Na+ only appears with beam on
- Fixed PDT!





In search of contamination's origin

July 2024 beamtime

- Observed **improvement** on **ratio** Na:Mg by completely **filling the cold trap**, getting the **filter submerged in LN**
- Instead of maximizing ^{23}Mg yield, we tried to **minimize the contamination from ^{23}Na** with the SPIG
- **Trace gas** injection did **not provide useful** for the Mg beam
- With this, we managed to get a **first measurement of polarization inversion** with **1.53σ** precision

December 2024 beamtime

- Tried to replicate July condition, by using new cold traps with **activated charcoal** and **SiO_2**
- **No improvement on contamination**, but the **PDT** was finally **fixed**
- After discarding other suspects, the only possibility left was the **SPIG as a source of Na.**

Polarization proof-of-principle

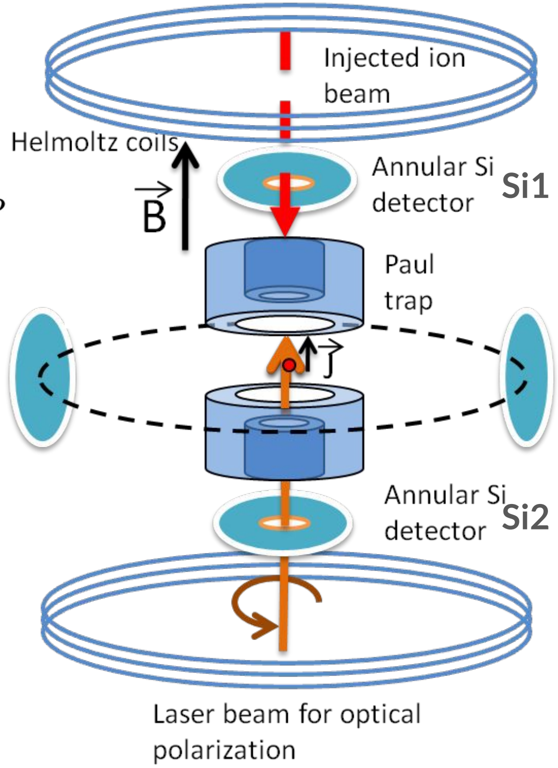
- Using **detections** ($N_{\beta+}$) **on the Si detectors** (Si1 and Si2) **in each polarization** (+ or -, ↑or ↓) **to measure the asymmetry** (A)

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

- A = $\alpha \cdot A_{\beta} \cdot$ P, where $\boldsymbol{\alpha}$ **is a sensitivity factor** estimated from simulations, $\mathbf{A_{\beta}}$ **is the beta asymmetry** and **P the polarization degree**

- **Needed ~10^2 ions per trap cycle to measure P**
- **We need at least ~10^4 ions per trap cycle to attempt to measure D**

- Using **coincidences** between Si and MCP to improve **signal to noise ratio**
- Then we need to use $\mathbf{B_{\nu}}$, **the neutrino asymmetry**

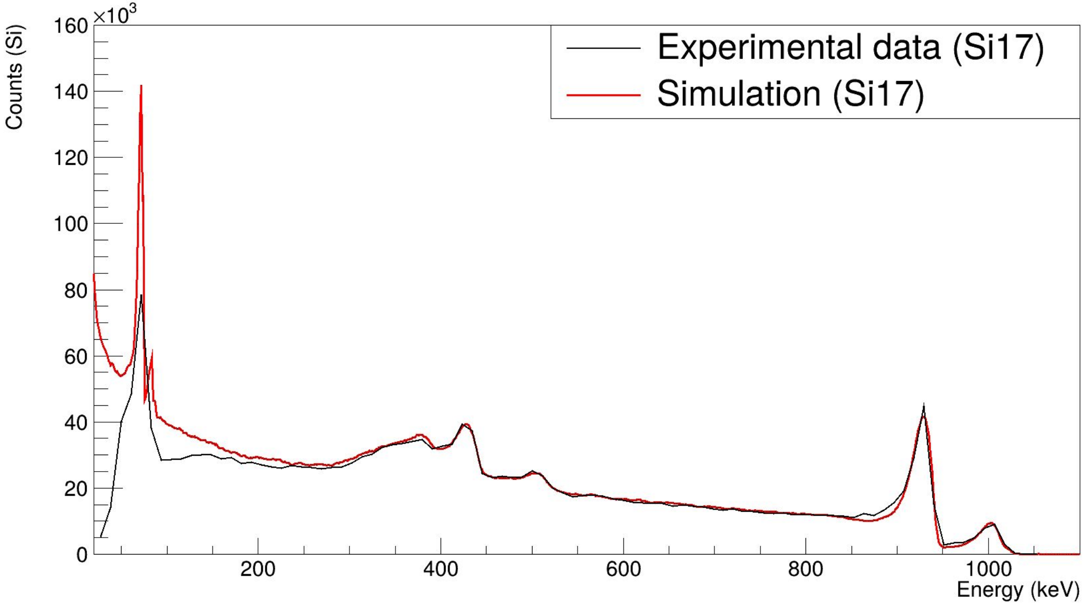


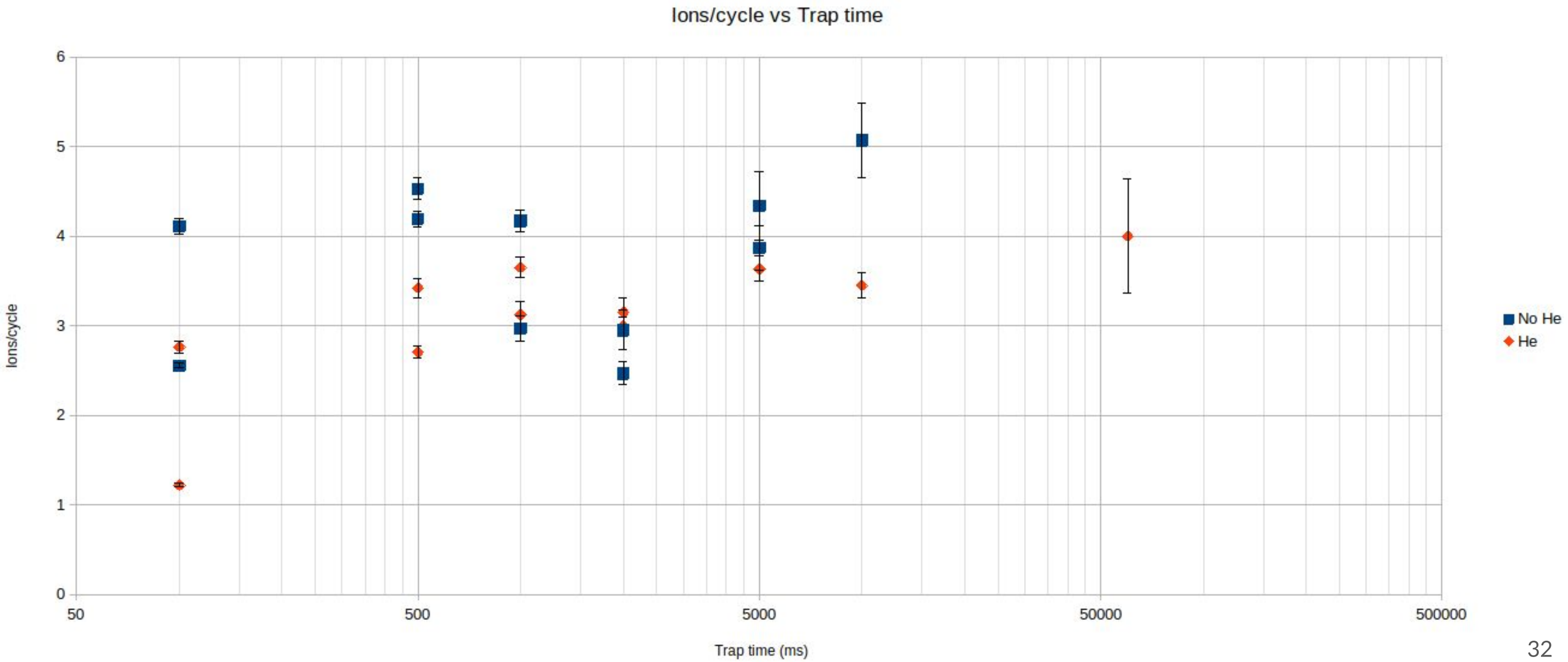
Data Analysis: Calibration

The calibration fit is done with a PENELOPE simulation

Bi^{207} source for the Si detectors and 3 alpha sources for the RIDE detectors

Si calibration using 3 parameters and resolution




Ions/cycle vs Trap time
6
5
4
3
2
1
0
Ions/cycle
50
500
5000
50000
500000
Trap time (ms)
No He
He

MORA Timeline

Biggest challenge: Na contamination for trap efficiency

2022

MORA installation in IGISOL

First polarization measurement in November

2023- early 2024

Origin of contamination: gas, gas cell, target tests

We observe PDT instabilities

July2024

Third polarization attempt

First success!

Dec2024

Fourth polarization attempt

Fixed PDT

Not as good as July, why?

March2025

Fifth polarization attempt, clean SPIG

Second success!

June/July2025

MRToF assisted contamination analysis and long measurement

Present day!

In search of contamination’s origin

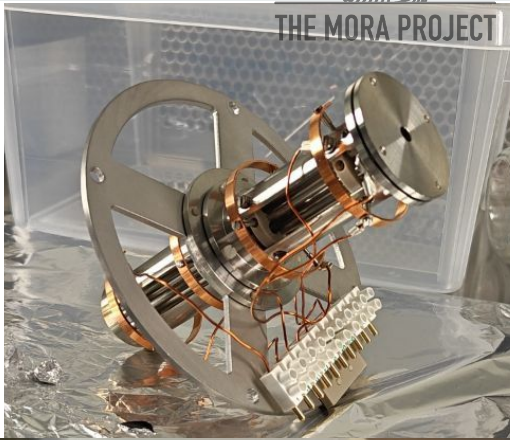
Second half 2024

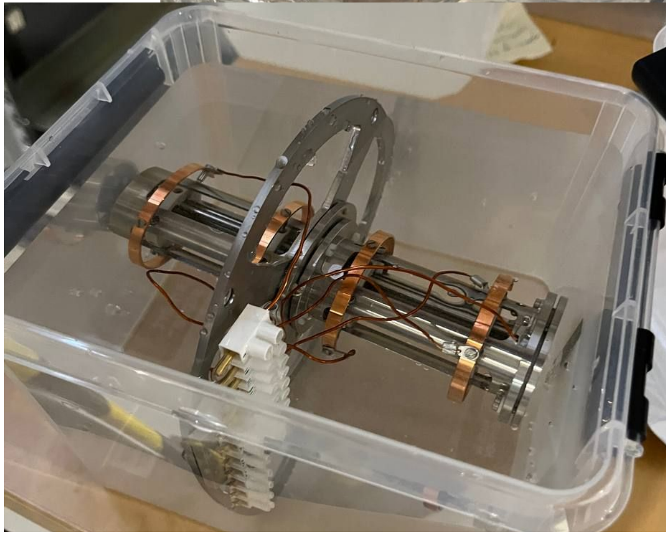
- **Progress** made for **polarization measurement**
  - Managed to get a **first measurement of polarization inversion** with **1.53σ** precision
- **Fixed PDT** instabilities
- Better understanding of the **source** of **contamination**
- **Only the SPIG** can explain what we see
  - Sputtering inside of the SPIG, affected by gas purity
  - Voltages greatly affect the contamination
  - Na only appears with beam on

March 2025, Clean SPIG measurement

- Next step was **removal of Na from all SPIG surfaces**
- **Used ACCLAB cooling loop water**, conductivity of ~0.23uS/cm
- **SPIG disassembled**, **cleaned** and **reassembled** carefully to not spread contamination
- **Minimal ratio of Na:Mg yet**
- **Best results to this date!**

- The **rods** are the most **critical part**, cleaned with special care
- **New Nb rods** commissioned **baked** at **high temperature** for **evaporating Na**



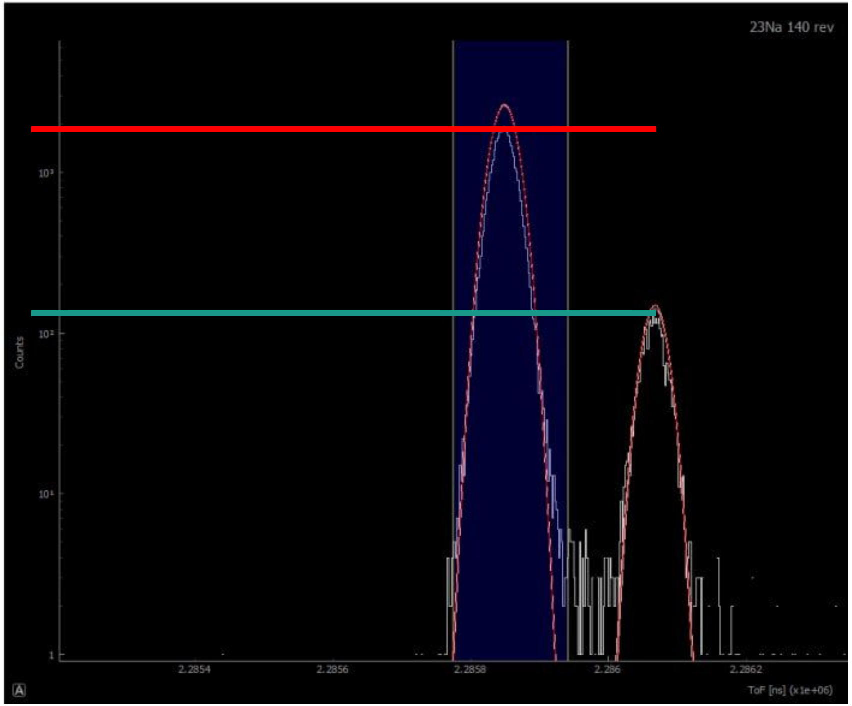


June beamtime, beam purity

New **Nb rods for the SPIG, baked at high temperature**

Different settings and tests to get the **best yield and ratio of Na:Mg**

With the latest measurement:
Integral of Na Gaussian peak: 80283.1
Integral of Mg Gaussian peak: 5268.93
Ratio Na/Mg: 15.2371



July 2025

- Objectives:
  - **Reduce contamination from Na** as much as possible
  - Use **MRToF** to **measure contamination** and **clean beam from Na**
  - Achieve **10^4 Mg ions in trap per cycle**.
  - Measure the **P degree and D correlation**
- **Achievements:**
  - **Contamination reduced**
  - **MRToF used**
  - **40k Mg ions in the entrance of MORA**
  - **P degree measurement (under analysis)**
- **To solve:**
  - **Low trap efficiency**, due to bad steering due to the MRToF
  - **Peak coalescence** observed from the MRToF, possibly due to higher energy dispersion from the RFQ cooler buncher and ion-ion interactions inside the MRToF (10^5 ions per bunch)
  - **D correlation not measured**
- **All the pieces are on the table for the measurement**

Determination of the D-Correlation

As previously said: we need a **GT-F** mixed decay and **polarization of the ions** → **We need to maximize F(X) and the polarization degree of ions to get the highest sensitivity for CPV**

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

→ Proportional to mixture degree and axial vector-vector phase

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)

Final state interactions (**FSI**), never measured using D-correlation

$$D_{FSI} \sim Z\alpha \frac{E_e}{M} \cdot A(\mu_f - \mu_i)$$

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