THE MORA PROJECT

Matter's Origin from Radioactivity of trapped ions

GANIL COLLOQUE 2026

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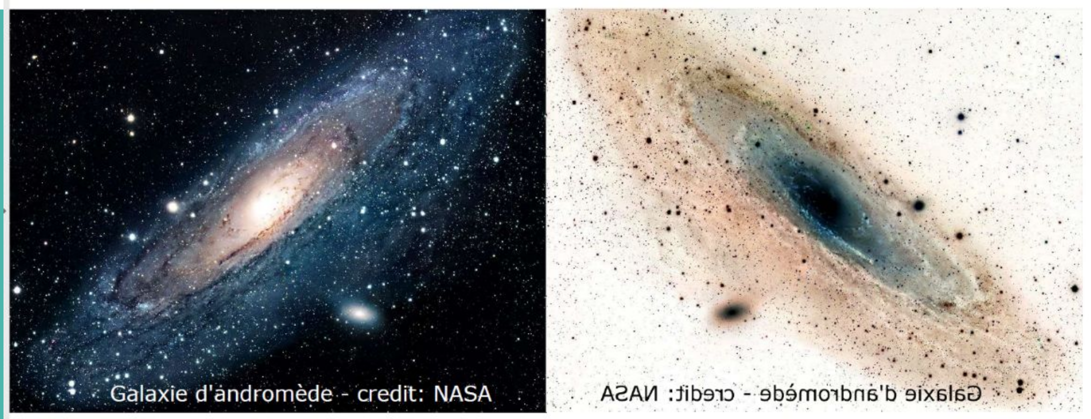
- Small introduction
- MORA setup, IGISOL
- Experimental developments: Mg and Ca
- Future of MORA in IGISOL
- Outlook and conclusions

Small introduction: D correlation and setup



β decay D-Correlation

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

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

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

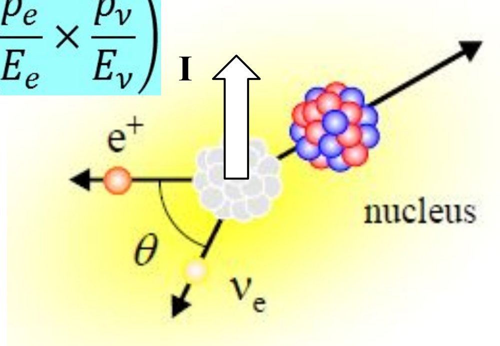
$$\left.\frac{\langle\mathbf{J}\rangle}{J}\cdot\left[A\frac{\mathbf{p}_e}{E_e} + B\frac{\mathbf{p}_\nu}{E_\nu} + D\frac{\mathbf{p}_e\times\mathbf{p}_\nu}{E_e E_\nu}\right]\right\}$$

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

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

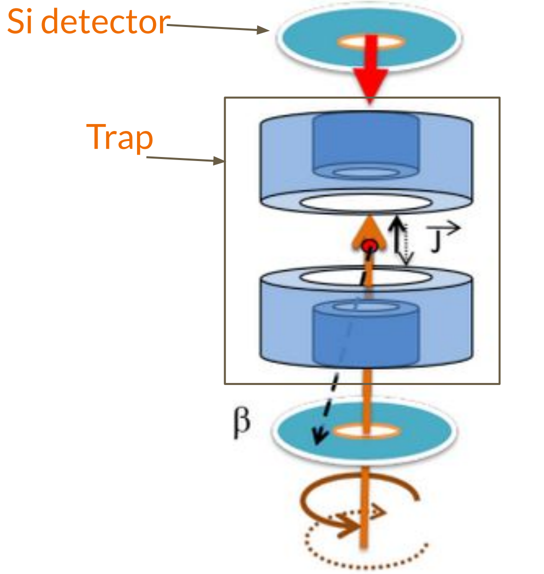


A precise measurement of **D** would allow to:

- 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

MORA Setup

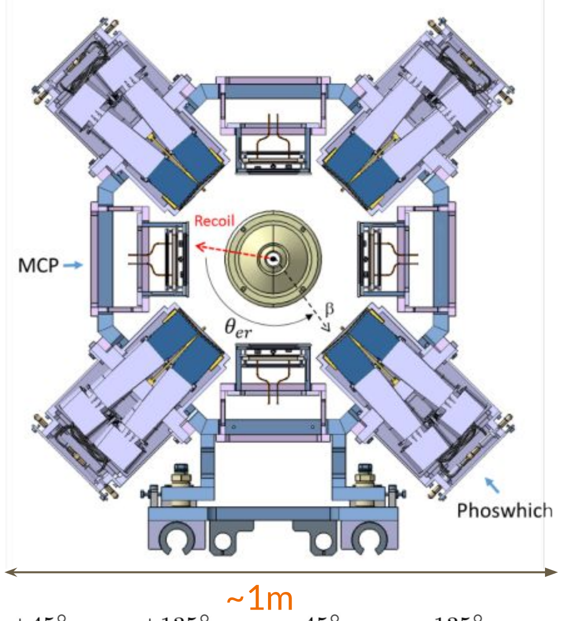
Polarization measurement



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

- **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 90º 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

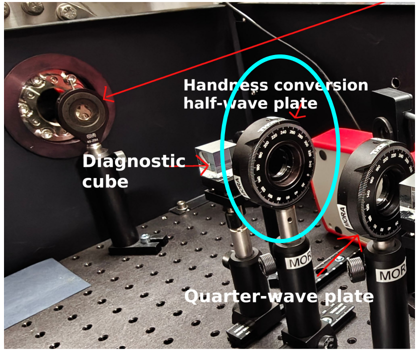


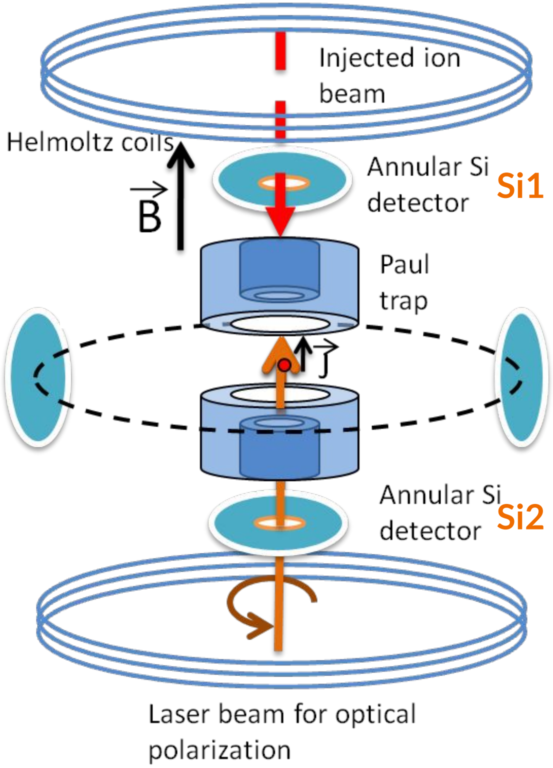
$$\frac{N^{+45^\circ}_{coinc} + N^{+135^\circ}_{coinc} - N^{-45^\circ}_{coinc} - N^{-135^\circ}_{coinc}}{N^{+45^\circ}_{coinc} + N^{+135^\circ}_{coinc} + N^{-45^\circ}_{coinc} + N^{-135^\circ}_{coinc}} = \delta \cdot D \cdot P$$

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 $\mathbf{A_{\beta}}$, **the beta asymmetry** and **P is the polarization degree**
- **Needed ~10² ions per trap cycle to measure P**
- **We need at least ~10⁴ ions per trap cycle to attempt to measure D**

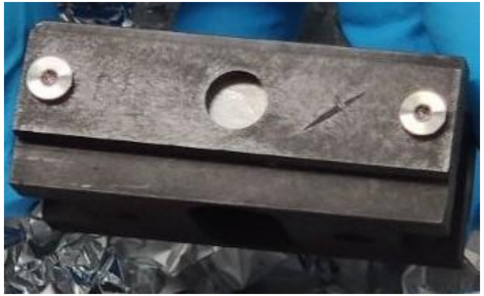
$$A = \frac{N^{\uparrow}_{\beta+} - N^{\downarrow}_{\beta+}}{N^{\uparrow}_{\beta+} + N^{\downarrow}_{\beta+}} \propto A_{\beta} \cdot P$$

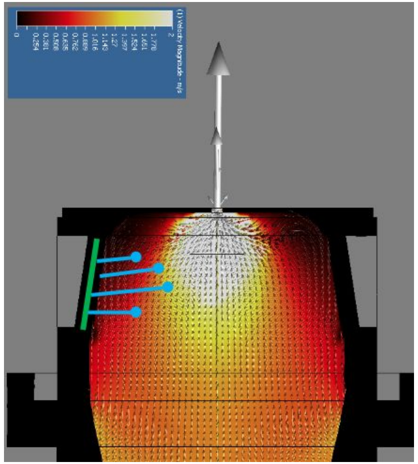


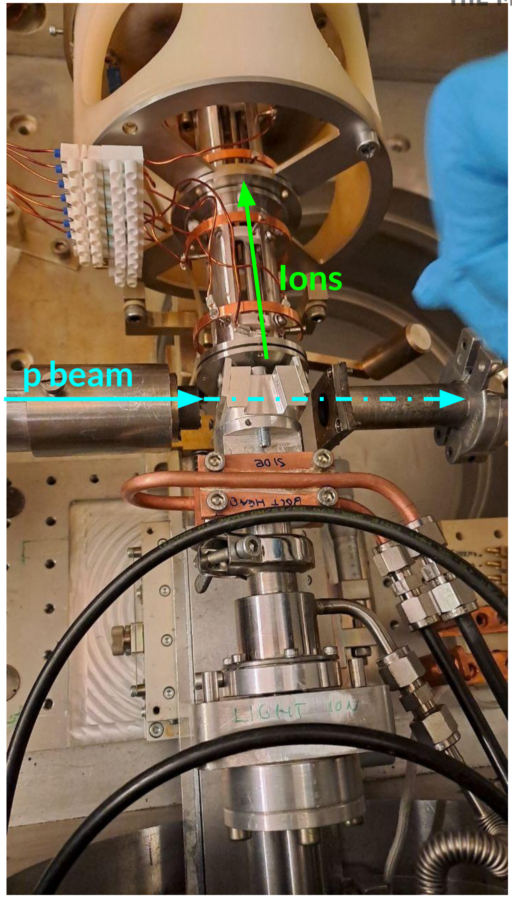


Ion Production at IGISOL

- 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





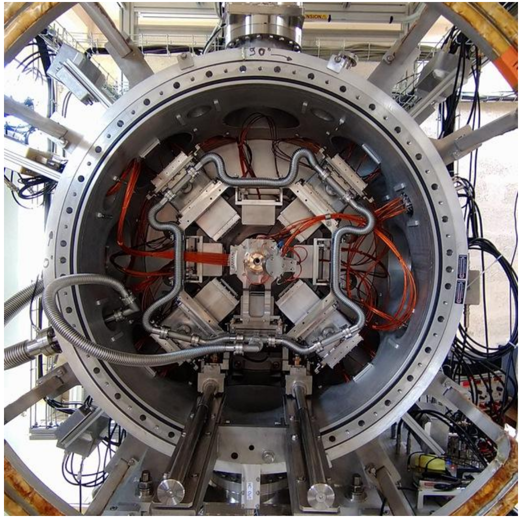


Experimental developments, Mg and Ca

Typical 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 (~2·10^5 ions)** 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



In search of Na contamination's origin

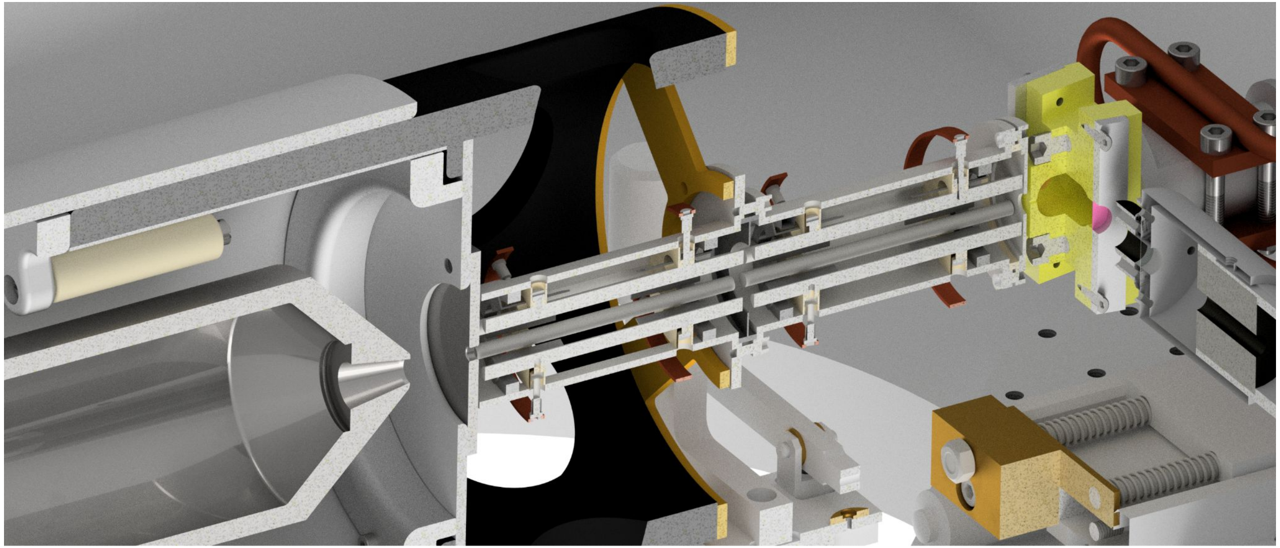
Origin: Sputtering in the SPIG

Coherent with all past observation

- Gas purity
- Gas pressure
- SPIG tuning

Cleaned with deionized water in March 2025

Changed rods for Nb in June 2025



Previous experimental developments

Mg:

- Achieved **40k ions** per cycle in the entrance of **MORA**
- Achieved **~40% trap efficiency**
- **Measured polarisation** degree
- **Mg** and **Na separated** with **MRToF** for measurement and **injection** into **MORA**
- **Na:Mg** ratio reduced down to ~**2:1**

Ca:

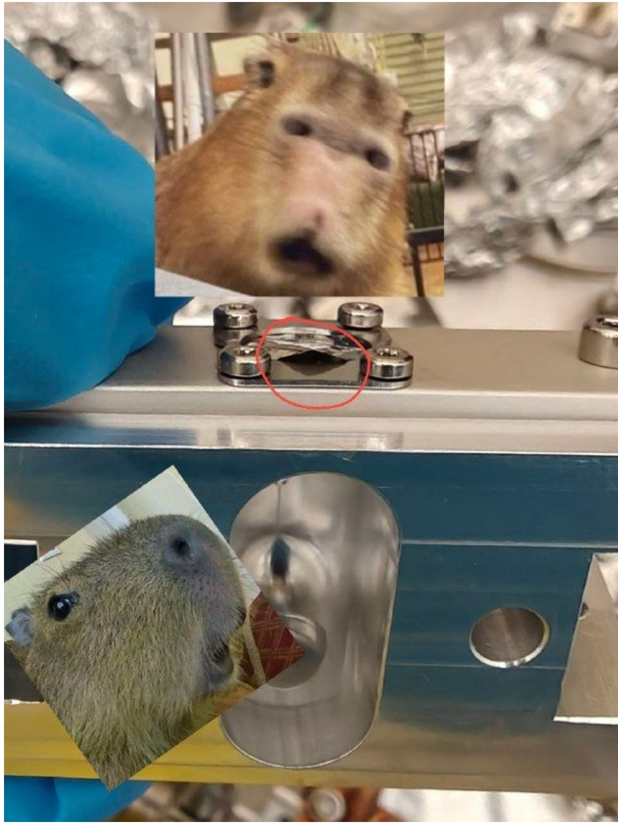
- **Short test** in October2025
- ~**1200 ips** before cooler at **low power** (1uA)
- Contamination ratio not measured, but **comparable amounts** of **K**. Down to ~3pA.
- **Laser** production **not ready yet**, but getting prepared
- Quick **estimates** are **optimistic** to achieve **at least** the **same** activity as **Mg**

MORA in 2026

April 2026

- Even with a **gas leak**, ratio controlled under **10:1**, with a satisfactory **~90k Mg ions/s** produced and extracted after the Dipole Magnet separator
- 40k Mg ions per bunch found in the MORA Si with a ~40% trap efficiency simultaneously
- **5k Mg** ions per cycle were trapped (new record!) which suggests a 13% trap eff vs the ~40% that was observed from the MCPs

Why do we lose Mg ions? What can we do to improve it?



September 2026 - *More ions are more ions*

- Modifications on SPIG and extractor electrodes to maximise transport
- Fixes to stability and border effects of extractor and a bender electrode
- **ABZURD**


LIVE
BREAKING
NEWS

September 2026 - Abzurdly good!

- **Abzurd** (Abzu-R&D) is a new femtoamp-meter developed in Jyvaskyla by Jan Saren and Risto Kronholm
- First prototype used at IGISOL for this MORA beamtime
- It was possible to measure down to **~10 fA** currents, which depending of the cycle lengths it can measure 100s/bunch or 1000s/bunch of ions reliably.
- It allowed:
    - Improve the transmission to MORA, up to **2 million ions/bunch**, never achieved due to the limits of precision of the MCP
    - Calibrate MCP2 after trap extraction to measure ions/bunch, allowing for precise and fast tuning of the setup

September 2026 - Results

- The beamtime objective was to produce more Mg

- If given enough time, a short injection to MORA would be attempted, to give constraints on trapped Mg ions

- Study losses and trap efficiency

September 2026 - Results

- The beamtime objective was to produce more Mg
- **At least 300k Mg ions/s extracted, probably more due to saturation of the detector**
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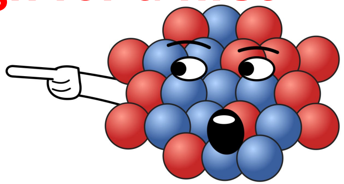
September 2026 - Results

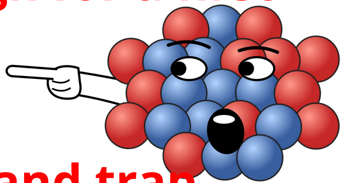
- The beamtime objective was to produce more Mg
- **At least 300k Mg ions/s extracted, probably more due to saturation of the detector**
- If given enough time, a short injection to MORA would be attempted, to give constraints on trapped Mg ions
- **20k Mg ions/bunch consistently trapped in MORA, enough for a first measurement attempt on D correlation**
- Study losses and trap efficiency



^{23}Mg

September 2026 - Results

- The beamtime objective was to produce more Mg
- **At least 300k Mg ions/s extracted, probably more due to saturation of the detector**
- If given enough time, a short injection to MORA would be attempted, to give constraints on trapped Mg ions
- **20k Mg ions/bunch consistently trapped in MORA, enough for a first measurement attempt on D correlation**
- Study losses and trap efficiency
- **Found that at large beam currents, transport efficiency and trap efficiency decreases, new clear objective to improve**



^{23}Mg

Future for MORA at IGISOL

The future - challenges

Some challenges are still present:

- Losses at injection/trapping/extraction
- Control over laser polarisation
- Trapped Mg, where does it go?
- Stability issues from frontend
- Ca production and polarisation

Plenty of work for Marah, Ville and Jonathan!

Outlook and conclusions

- **A first D correlation measurement can be attempted with confidence**
- Even with remaining challenges, MORA has progressed a lot from its first stages
- Ca could offer a huge improvement over Mg if the contamination is controlled as well
- Abzurd and MCP calibrations give a precise measurement of high ion rates, better for tuning
- New developments in the RFQ cooler buncher, MRToF-MS, and beam transmission improvements will allow for higher number of trapped Mg
- Polarimeter and laser developments for greater control over polarisation

Thank you for your attention!

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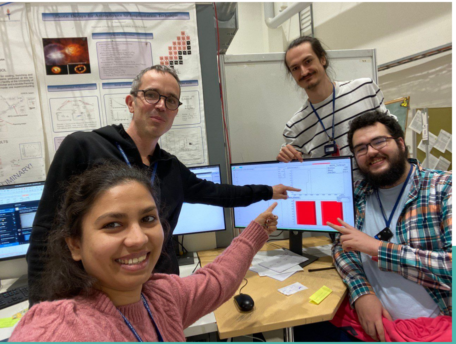

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A. Kankainen
S. Kujanpää
M. Stryjczyk
S. Rinta-Antila
Z. Ge

M. Kowalska

For more information: Thesis defense 23rd of October at Maison d’hôtes, GANIL, 17:00

Simulations:
Si calibrations and polarisation sensitivity

Polarisation sensitivity α

Asymmetry = α * P

- α is needed to estimate **P**, and any **systematics** affecting it will be **carried over to P**.
- There are **two different (analogous)** ways of **calculating** the **asymmetry**:

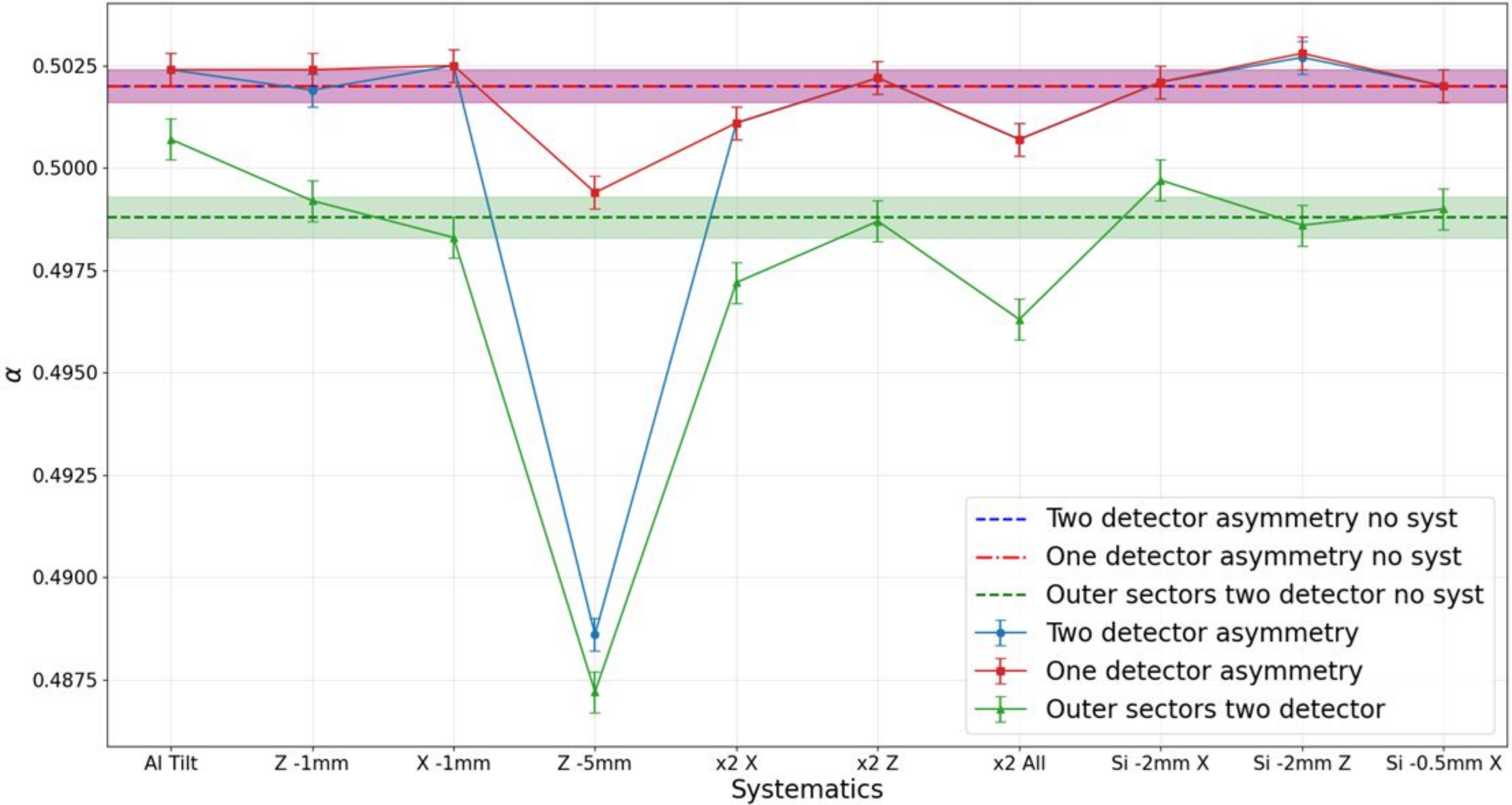
$$A_i = \frac{N_i^+ - N_i^-}{N_i^+ + N_i^-} = \alpha P,$$

$$\tilde{A}_j = \frac{N_1^j - N_2^j}{N_1^j + N_2^j} = \tilde{\alpha} P,$$

Averaged for detectors (i=1,2) or polarisations (j=+,-)

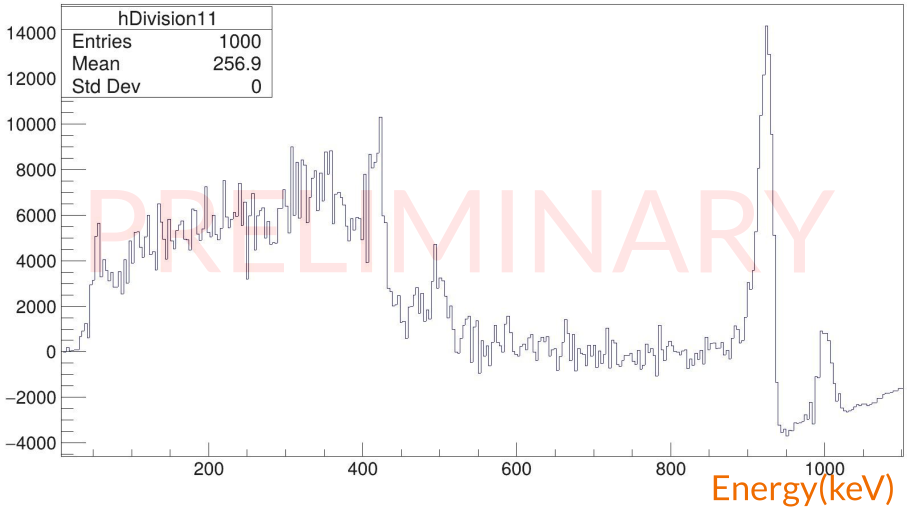
- The **possible sources** of **systematics** for α are:
  - **Energy threshold** choice
  - Energy **calibration**
  - **Misalignment** of the **detectors**/trap **electrodes/ion cloud**
  - **Magnetic field**
  - **Ion cloud size**
  - Protective **Al foil** tilt
- These effects have been **measured**:
  α = 0.5024 ± 0.0003 [stat] ± **0.004** [**syst**] with the **biggest possible** sources being a **larger ion cloud** than expected, a **non-centered ion cloud** and the **tilt of the Al foil**. (**Published** to EPJ Web of Conferences)

Polarisation sensitivity

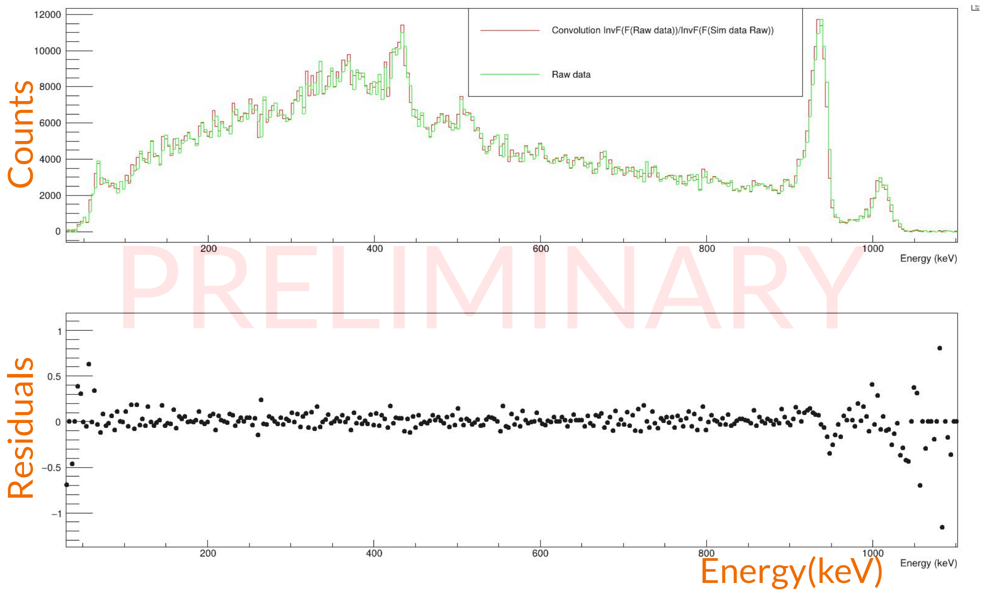


Fourier calibration discussion

Detector calibration, Fourier



Response Function H



Green: Experimental data Red: Simulated data convoluted with response function H

Extra slides

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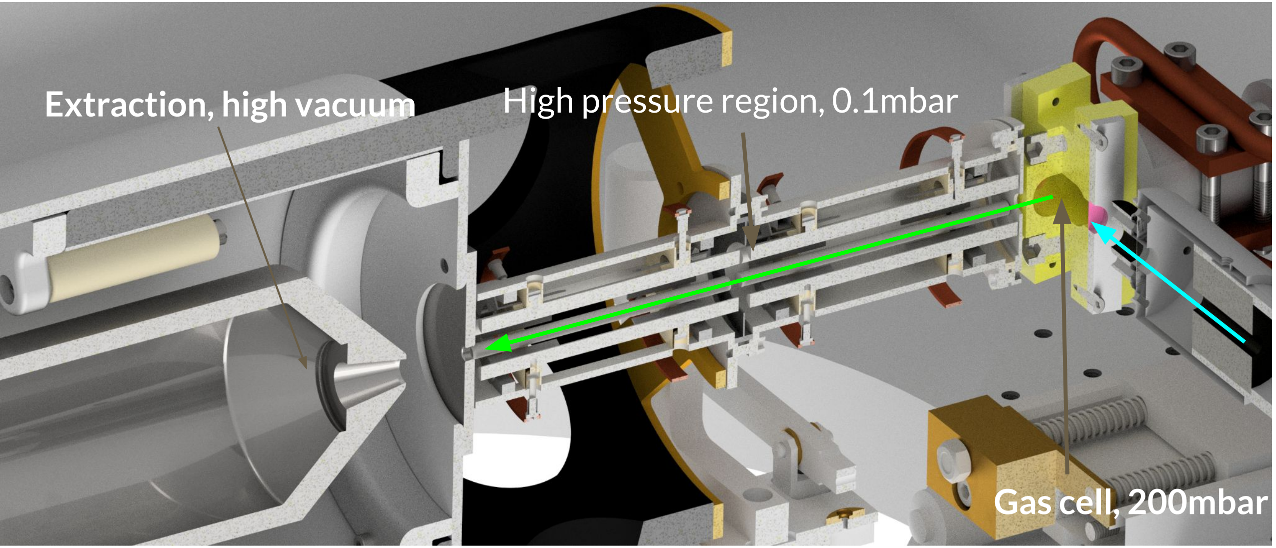
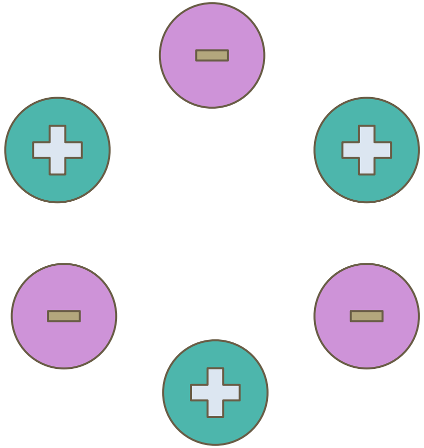
Sextupole Ion Guide



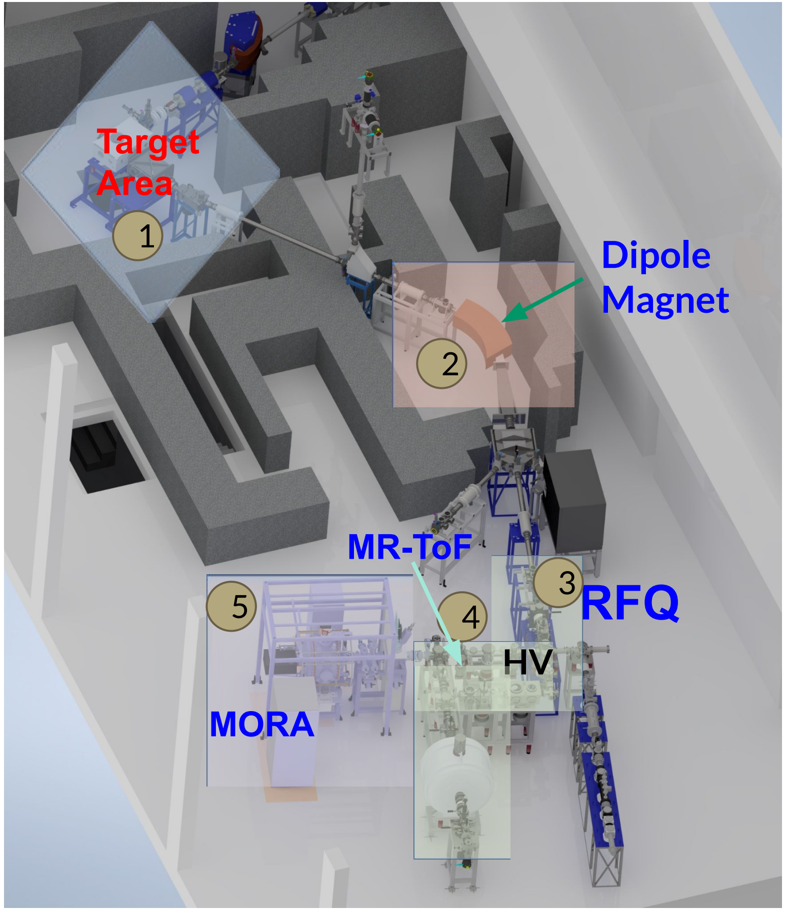


RF sextupole ion guide, 3-5MHz , ~1kV V_{pp}

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



Detector calibration

Green: Experimental data

Red: Simulated data convoluted with response function H

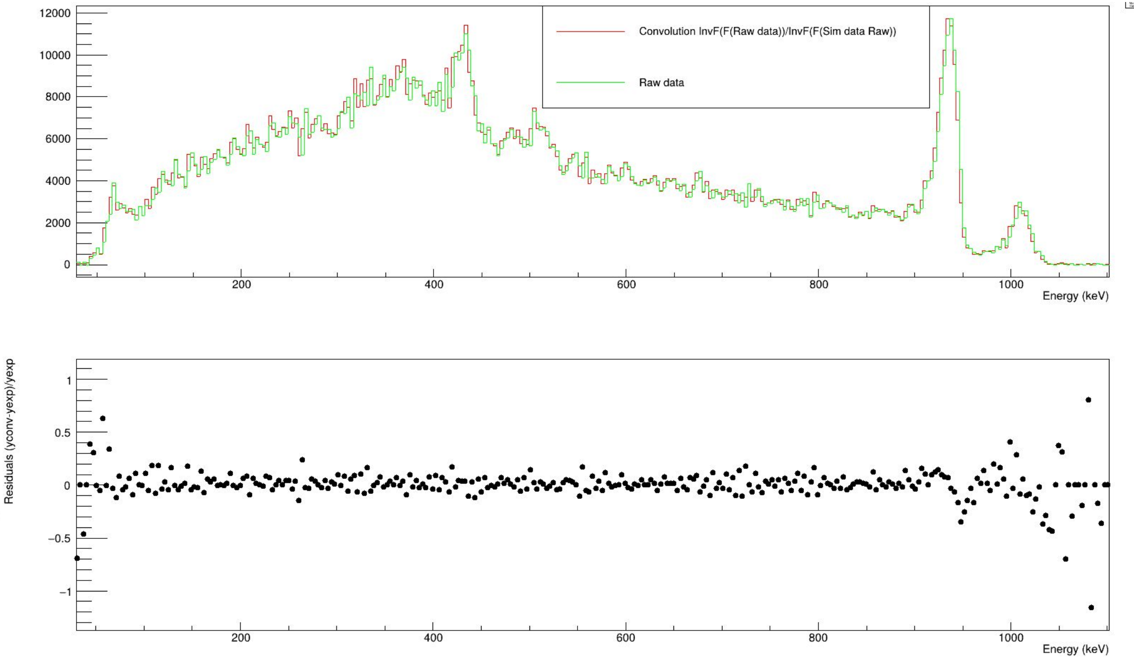
H is the response function extracted by:

$\mathcal{F}^{-1}(\mathcal{F}(\text{Experimental})/\mathcal{F}(\text{Simulation})) = H$

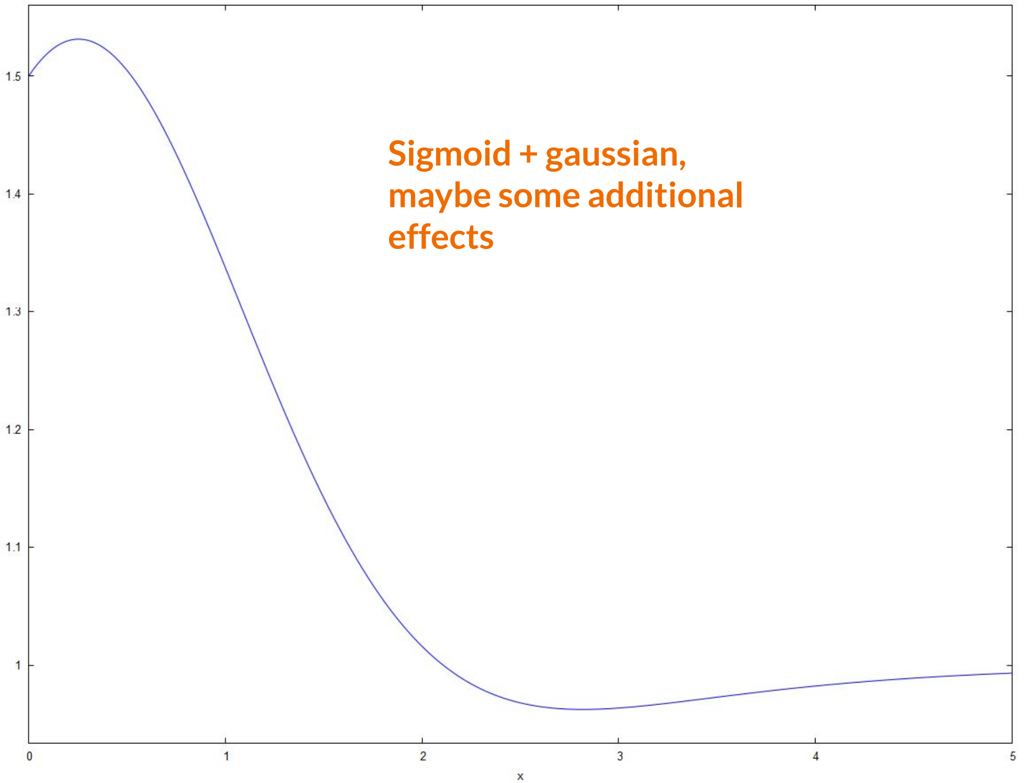
(Convolution theore

$$\{u * v\}(x) = \mathcal{F}^{-1}\{U \cdot V\}.$$

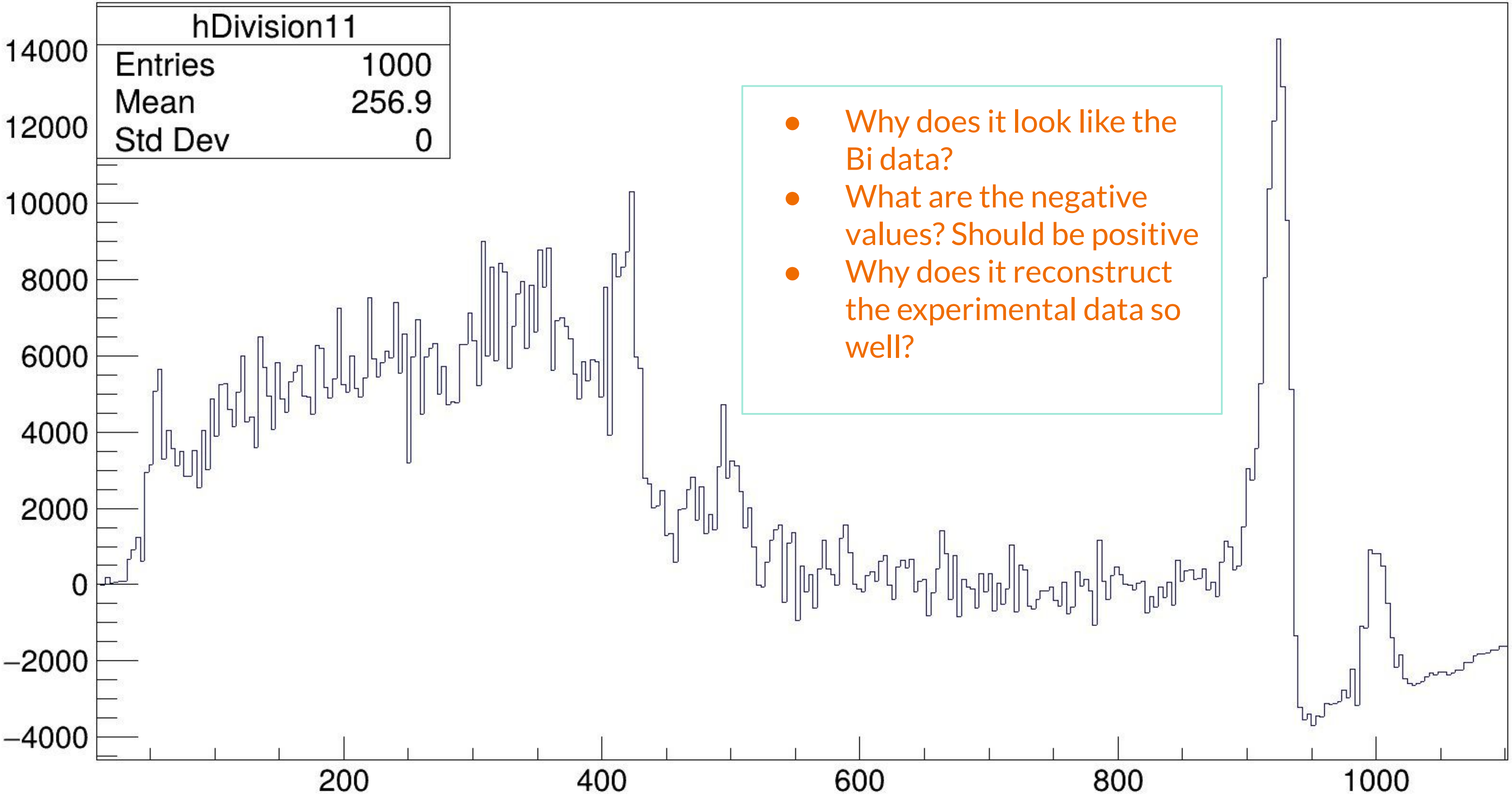
Problem?: It creates the function H needed to transform Simulation -> Experimental, regardless of physical meaning



Expectations for H (arbitrary units)



Response Function H



- Why does it look like the Bi data?
- What are the negative values? Should be positive
- Why does it reconstruct the experimental data so well?

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**

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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

March 2025, Results

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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.

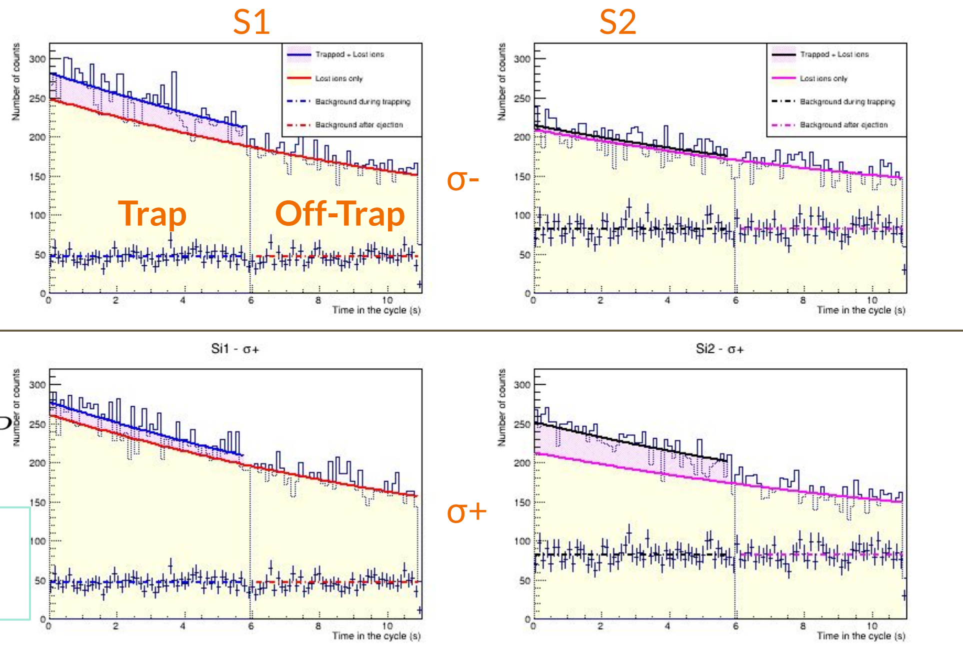
$$A = \frac{N^{\uparrow}_{\beta+} - N^{\downarrow}_{\beta+}}{N^{\uparrow}_{\beta+} + N^{\downarrow}_{\beta+}} \propto A_{\beta} \cdot P$$

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**

Determination of the D-Correlation

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

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

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.

Selection of nuclei for D-Correlation

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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.

Polarization proof-of-principle

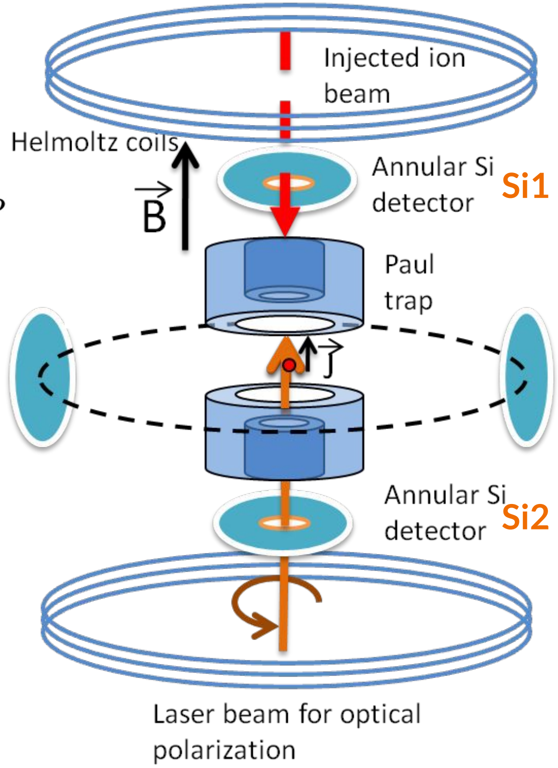
- Using **detections** ($N_{\beta+}$) **on the Si detector**s (Si1 and Si2) **in each polarization** (+ or -, ↑or ↓) **to measure the asymmetry** (A)

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

- 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 **B_ν, the neutrino asymmetry**



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