The Matter’s Origin from RadioActivity experiment

Pierre 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 asymmetry 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.


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
  \[ T\text{-odd probes!} \]

Electric dipole moments of particles and nuclei: \( d \cdot \vec{\sigma} \)

Correlations in nuclear \( \beta \)-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 2\textsuperscript{nd} to 5\textsuperscript{th} of May) [https://indico.in2p3.fr/event/25986/](https://indico.in2p3.fr/event/25986/)
Search for new physics via the $D$ correlation measurement

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

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

T reversal odd

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

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

$\varphi_{AV} = 180.013^\circ \pm 0.028^\circ$ (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:
  - via the LQ model
    - Thorough investigation undertaken at IJClab by Adam Falkowski and Antonio Rodriguez-Sanchez
      - Presentation at MORA workshop [https://indico.in2p3.fr/event/25986/](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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emiT collaboration, PRL 107, 102301 (2011),  
Calaprice, Hyp. Int. 22(1985)83

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- Direct constraints on CP-violating Wilson coefficients in the nucleon-level EFT
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Below $10^{-4}$, measurement of Final State Interactions

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

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

Never accessed by a direct measurement in $D$
Search for new physics via the $D$ correlation measurement

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


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

*State of the art techniques from ISOL facilities*

- **Ion cooling and trapping originally developed for**
  - LPCTrap
  - New trap and new detection setup: off-line commissioning at JYFL and completed in autumn 2021
  - Theoretical studies with state-of-the-art EFTs

- **Innovative laser polarisation techniques at**
  - JYFL installation at JYFL/IGISOL (completed!)
  - Proof of principle of polarization
    - First $D$ measurement
    - Started in Feb 2022

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

$D$ correlation measurement in $^{23}\text{Mg}$, $^{39}\text{Ca}$ decays to the $10^{-5}$ level with some beam, laser and trapping R&D
MORA: Best candidates for $D$ measurement

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

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

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<thead>
<tr>
<th></th>
<th>n</th>
<th>$^{19}$Ne</th>
<th>$^{23}$Mg</th>
<th>$^{35}$Ar</th>
<th>$^{39}$Ca</th>
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<tr>
<td>Sensitivity $F(X)$</td>
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<td>-0,52</td>
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<td>$D_1 \times 10^{-4}$</td>
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<td>-0,489</td>
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<td>-0,024</td>
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$D_{n} = (-0.94 \pm 1.89 \pm 0.97) \times 10^{-4}$

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

Best measurement so far, statistics limited

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

\[ D \equiv \sin(\varphi_{AV}) \cdot \frac{2\rho}{1+\rho^2} \cdot \left( \frac{J}{J+1} \right)^{1/2} \]

**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
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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

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\[ D_n = (-0.94 \pm 1.89 \pm 0.97) \times 10^{-4} \quad D_{^{19}\text{Ne}} = (1 \pm 6) \times 10^{-4} \]

Best measurement so far, *statistics limited*

\[ D_{FSI}(p_e) = \left( \frac{D_1 \cdot p_e}{P_{\text{emax}}} + \frac{D_2 \cdot P_{\text{emax}}}{p_e} \right) \times 10^{-4} \]

MORA: in-trap laser polarization

- The nuclear spin $I$ interacts with the atomic one $J \rightarrow F=I+J$
- $\sigma+$ or $\sigma-$ light to scan the hyperfine structure forces ions in the $m_F=\pm F$ state

Transitions excited using trippled Ti:Sa laser pulses $\lambda \sim 280$nm $\sigma+$ polarization, $\sim 4$GHz width

Doppler shift/broadening due to ion motion $\sim 1.6$GHz

Collisions with He atoms (no spin) do not depolarize

Polarization monitoring thanks to $\beta$ asymmetry: $A_\beta$

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

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

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

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

In trap optical polarization

\[ \frac{N_{+45^\circ} + N_{+135^\circ} - N_{-45^\circ} - N_{-135^\circ}}{N_{+45^\circ} + N_{+135^\circ} + N_{-45^\circ} + N_{-135^\circ}} = \delta \cdot D \cdot P \]

Where \( \delta \) is depending on the phase space coverage
In trap optical polarization

\[ \bar{\theta}_{er} \sim 135^\circ \]

\[ \bar{\theta}_{er} \sim -135^\circ \]

\[ \bar{\theta}_{er} \sim 45^\circ \]

\[ \bar{\theta}_{er} \sim -45^\circ \]

\[ \delta = 0.775(1) \text{ for } ^{23}\text{Mg}, \text{ compared to } \delta \sim 0.3 \text{ for the neutron} \]

Where \( \delta \) is depending on the phase space coverage.
MORA: sensitivity challenges

\[ D \equiv \left( \delta \cdot P \cdot \sqrt{N_{\text{coinc}}^{+45^\circ} + N_{\text{coinc}}^{+135^\circ} + N_{\text{coinc}}^{-45^\circ} + N_{\text{coinc}}^{-135^\circ}} \right)^{-1} \]

<table>
<thead>
<tr>
<th>Place and type of measurement</th>
<th>Trapped ions /cycle</th>
<th>Decays/s</th>
<th>Meas. time (days)</th>
<th>Detected coincidences (P)</th>
<th>( \sigma_p ) stat (%)</th>
<th>Detected coincidences (D)</th>
<th>( \sigma_D )</th>
</tr>
</thead>
<tbody>
<tr>
<td>JYFL: P - 23Mg</td>
<td>2,00E+04</td>
<td>1,23E+03</td>
<td>8</td>
<td>1,7E+05</td>
<td>1,9E+00</td>
<td>1,5E+06</td>
<td>1,0E-03</td>
</tr>
<tr>
<td>JYFL: D - 23Mg</td>
<td>2,00E+04</td>
<td>1,23E+03</td>
<td>32</td>
<td>6,7E+05</td>
<td>9,4E-01</td>
<td>6,1E+06</td>
<td>5,2E-04</td>
</tr>
<tr>
<td>JYFL: D - 39Ca</td>
<td>2,00E+04</td>
<td>1,61E+04</td>
<td>32</td>
<td>9,2E+06</td>
<td>2,0E-02</td>
<td>8,1E+07</td>
<td>1,4E-04</td>
</tr>
<tr>
<td>DESIR: D - 23Mg</td>
<td>5,00E+06</td>
<td>3,07E+05</td>
<td>24</td>
<td>1,3E+08</td>
<td>6,9E-02</td>
<td>1,2E+05</td>
<td>3,8E-05</td>
</tr>
<tr>
<td>DESIR: D - 39Ca</td>
<td>5,00E+06</td>
<td>4,03E+06</td>
<td>24</td>
<td>1,7E+09</td>
<td>1,5E-03</td>
<td>1,5E+14</td>
<td>1,0E-05</td>
</tr>
</tbody>
</table>

So far statistical uncertainties have dominated, over systematic uncertainties

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


Provided that

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

\( \rightarrow \) Below \( 5.10^{-5} \) is feasible
MORA: sensitivity challenges

Down to a few $10^{-5}$ sensitivity

- The emiT experiment gives a few hints

$$Dn = (-0.94 \pm 1.89 \pm 0.97) \times 10^{-4}$$

Systematic effects

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

<table>
<thead>
<tr>
<th>Source</th>
<th>Correction</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background additive</td>
<td>-0.07</td>
<td>0.07</td>
</tr>
<tr>
<td>Multiplicative$^a$</td>
<td>0.03</td>
<td>0.09</td>
</tr>
<tr>
<td>Electron backscattering additive</td>
<td>0.09</td>
<td>0.07</td>
</tr>
<tr>
<td>Multiplicative</td>
<td>0.11</td>
<td>0.03</td>
</tr>
<tr>
<td>Proton backscattering</td>
<td>0</td>
<td>0.03</td>
</tr>
<tr>
<td>Electron threshold nonuniformity</td>
<td>0.04</td>
<td>0.10</td>
</tr>
<tr>
<td>Proton-threshold effect</td>
<td>-0.29</td>
<td>0.41</td>
</tr>
<tr>
<td>Beam expansion</td>
<td>-1.50</td>
<td>0.40</td>
</tr>
<tr>
<td>Polarization nonuniformity</td>
<td>0</td>
<td>0.10</td>
</tr>
<tr>
<td>ATP misalignment</td>
<td>-0.07</td>
<td>0.72</td>
</tr>
<tr>
<td>ATP-total</td>
<td>0</td>
<td>0.24</td>
</tr>
<tr>
<td>Spin-correlated flux</td>
<td>0</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Spin-correlated polarization</td>
<td>0</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Polarization</td>
<td>0</td>
<td>0.04$^b$</td>
</tr>
<tr>
<td>$K_B$</td>
<td>0.04$^c$</td>
<td></td>
</tr>
<tr>
<td>Total corrections</td>
<td>-1.66</td>
<td>0.97</td>
</tr>
</tbody>
</table>

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

Measurements needed

- $< 10^{-6}$
  - Under scrutiny, disturbance of recoil tof by RF look small
  - $< 10^{-6}$
  - $\sim 1 \times 10^{-6}$
  - $< 10^{-6}$
MORA first steps in pictures: from Caen to Jyväskylä

Off-line commissioning in LPC Caen
September 2021

Installation in JYFL
November 2021 – injection line

Commissioning in JYFL
Mid February – off-line

Shipping incident – trap chamber to be repaired - October 2021

Installation in JYFL
January 2021 – trap and detectors

23Na trapped ions from cooler buncher

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

23Na trapped ions from alkali source

Large involvement of LPC Caen technical resources

First $^{23}\text{Mg}$ β activity is recorded
First results

• 2 short beam times with $^{23}\text{Mg}$ (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 $\sim 5 - 10\%$, to be verified and optimized in November
      • Long trapping half life $>500\text{ms}$, to be measured in November
  • Large production of $^{23}\text{Mg}$, $10^5$ pps/uA, while 10 uA are possible
    • natMg(p,d)$^{23}\text{Mg}$ 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 $^{23}\text{Na}$ contamination from IGISOL yields a ratio $^{23}\text{Na}:^{23}\text{Mg} \geq 500$

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

Goal: $10^4$ trapped ions/cycle

R&D on production and minibuncher RF ongoing

PhD Nishu Goyal
PhD Sacha Daumas-Tschopp
**Next steps**

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

May 2022: asymmetry measured **during 43min**, $\sigma^+$ polarized light

- **Si2**
  - $N_1=97$ counts
  - on 6 sectors (2 are noisy)
  - **Background is unknown**

- **Si1**
  - $N_2=48$ counts
  - on 5 sectors (3 are noisy)
  - **Background is unknown**

Background unknown on single events → **no possible conclusions on $P$**
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Hypothesis:
- asymmetry is due to $P \rightarrow 1$
- Background is isotropic - let’s call it $N_0$

$$\alpha P = \frac{(N_1 - N_2)}{(N_1 + N_2 - 2N_0)}$$

$$\alpha \sim 0.5$$

$N_0=30$, **17 trapped ions on average**

Background unknown on single events $\rightarrow$ no possible conclusions on $P$
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May 2022: assymetry measured during 43min, $\sigma^+$ polarized light

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$\alpha \sim 0.5$

$N_0 = 30$, 17 trapped ions on average

Prospects for 8h spin up, 8h spin down, 8h background

$N_0 = 335$ (Background)

$N_1 = 657$ $N_2 = 1330$ ($\sigma^+$)

$N_2 = 1330$ $N_1 = 657$ ($\sigma^-$)

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

A 10% measurement of $P$ is possible if $P \rightarrow 1$

---

Background unknown on single events $\rightarrow$ no possible conclusions on $P$
Next steps

• Prospects for short beam time with $^{\text{nat}}\text{Mg}(p,d)^{23}\text{Mg}$ (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 $^{12}\text{C}+^{12}\text{C}\rightarrow^{23}\text{Mg}+n$ @5MeV/u, 10mbarn
      • $^{24}\text{Mg}$ implantation from cyclotron
      • Laser ionisation scheme development/ ionisation efficiency measurement
      • Measure of $^{24}\text{Mg}$ release time
      • Evolution of $^{23}\text{Na}$ vs $^{24}\text{Mg}$ 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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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

Remind SPIRAL 1 beam session
MORA collaboration

Thanks a lot for your attention!

In blue PhD students and postdocs hired for MORA