Matter's Origin from the RadioActivity of trapped and laser oriented ions

Pierre Delahaye for the MORA collaboration
β-decay as a laboratory for weak interaction
O. Naviliat, *Rare isotopes as laboratories for fundamental-interactions studies*, this conference

- Probing intrinsic symmetries

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

Parity violation in $^{60}$Co decay

- Polarized nuclei

\[
A_\beta \frac{\langle \vec{J} \rangle \cdot \vec{p}_e}{J \cdot E_e} = A \left( C_A^2, C_V C_A \right)
\]

P odd
**β-decay as a laboratory for weak interaction**

O. Naviliat, *Rare isotopes as laboratories for fundamental-interactions studies*, this conference

### Unpolarized nuclei

- Recoil detection
- \( β - \text{recoil coincidences} \)

\[ a_{βν} \frac{p_e}{E_e} \cdot \frac{p_ν}{E_ν} \]

*LPCTrap@GANIL*

- Pure GT: \( a_{GT} (C_T^2, C_A^2) = -1/3 \) (SM)
- Pure F: \( a_F (C_S^2, C_V^2) = +1 \) (SM)

### Polarized nuclei

- \( β - \text{recoil coincidences} \)
- Fixed \( J \)

\[ D \frac{⟨J⟩}{J} \cdot \left( \frac{p_e}{E_e} \times \frac{p_ν}{E_ν} \right) \]

*The MORA project!*

- \( D \propto \text{Im} (C_V C_A^*) \)
- \( D = 0 \) (SM)

- P, T even
- Search for exotic currents
- T odd
- Search for new sources of CP violation

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P. Delahaye, INPC2019, Glasgow
LPCTrap: a Paul trap based precision experiment

- Transparent Paul trap, UHV
- Ions confined in the middle of the device, nearly at rest
- In coincidence detection of the electron and the recoil ion

\[ a_{\beta,\gamma} \frac{p_e}{E_e} \cdot \frac{p_\gamma}{E_\gamma} \]

\( E_\beta, t_{\text{start}} \) \( \beta \) particle \( \theta_{er} \) Recoil ion \( t_{\text{stop}} \)

- Beta telescope
- Silicone stripped detector + Scintillator
- MCP
- Delay lines anode

In coincidence measurement of:
- the time of flight of the recoil ion \( t_R \)
- the beta particle energy \( E_\beta \)
- the angle between these two particles \( \theta_{er} \)

Trap and detection setup


- **MCP**
  - Active Ø80 mm
  - \( \sigma_T \sim 200\text{ps} \)

- **Delay lines**
  - \( \sigma_x, \sigma_y \sim 200\mu \text{m} \)
  - E. Liénard et al. NIMA 551(2005)

- **DSS Si Detector**
  - 60 x 60mm x 300µm
  - 1 mm resolution
  - Plastic scintillator
  - \( \sigma_E \) 10% at 1 MeV
  - \( \sigma_T \sim 200\text{ps} \)

- **Trap**
  - Effective trapping radius 5mm

Results of LPCTrap

- $\alpha_{\beta V}$ measurement for different nuclei
  - Analysis ongoing within « THESMOG »

- New constraints on $|C_T|/|C_A|$ from $^6$He decay
- Improvements on $\sigma(V_{ud}) / V_{ud}$ from mirror decays of $^{35}$Ar and $^{19}$Ne

- Shake–off probabilities and precise tests of atomic physics models

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Date</th>
<th>$\alpha$</th>
<th>$\sigma_{\text{stat}}$</th>
<th>$\sigma_{\text{syst}}$</th>
<th>Published results</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^6$He</td>
<td>2006</td>
<td>-0.3335</td>
<td>0.0073</td>
<td>0.0075</td>
<td>$\sigma_a /a \sim 3%$ Fléchard et al. JPG38 (2011)</td>
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<tr>
<td></td>
<td>2010</td>
<td>-1/3 (SM)</td>
<td>0.0015</td>
<td>?</td>
<td>Shakeoff Couratin et al. PRL108 (2012)</td>
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<tr>
<td>$^{35}$Ar</td>
<td>2011</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>Shakeoff Couratin et al. PRA88 (2013)</td>
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<tr>
<td></td>
<td>2012</td>
<td>0.9004 (SM)</td>
<td>0.0013</td>
<td>?</td>
<td></td>
</tr>
<tr>
<td>$^{19}$Ne</td>
<td>2013</td>
<td>0.0438 (SM)</td>
<td>0.0046</td>
<td>?</td>
<td>Shakeoff Fabian et al. PRA97(2018)</td>
</tr>
</tbody>
</table>
Precision measurement of the triple correlation $D$

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

- CP violation observed in the K and B-meson decays is not enough to account for the large matter–antimatter asymmetry
- T-odd correlations in beta decay ($D$ and $R$) and n-EDM searches are sensitives to larger CP violations by 5 to 10 orders of magnitude

Below $10^{-4}$, Final State Interactions mimic a non zero correlation

$D$ correlation measurement to the $10^{-5}$ level with some beam, laser and trapping R&D

- Best measurement so far $d_n < 2 \times 10^{-4}$
- Complementary probe to search for New Physics with nEDM and LHC searches
- First approach / probe of $D_{FSI}$

See P. Herczeg, Prog. Part. Nucl. Phys. 46 (2001) 413.
Sensitivity to NP

• $D$ correlation measurements in neutrons and nuclei
  – Best limits on T-violating phase $\text{Im}(C_V/C_A)$
    • neutron decay, $D_n = (-0.94 \pm 1.89 \pm 0.97) \times 10^{-4} \Rightarrow \text{Im}(C_V/C_A) < (1.6 \pm 6.3) \times 10^{-4}$
      *emiT collaboration, PRL 107, 102301 (2011),

• $^{19}$Ne decay, $D = 0.0001 \pm 0.0006$, limited by statistics
  Calaprice et al, Hyp. Int. 22 (1985) 83

– Sensitivities depends on the transition $D_X = F(X) \times \text{Im}(C_V/C_A)$

– Final State Interactions as well
  J. C. Brodine Phys Rev D1(1970)1

<table>
<thead>
<tr>
<th></th>
<th>n</th>
<th>$^{19}$Ne</th>
<th>$^{23}$Mg</th>
<th>$^{39}$Ca</th>
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<tbody>
<tr>
<td>$F(X)$</td>
<td>-0.55</td>
<td>0.66</td>
<td>0.82</td>
<td>-0.90</td>
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<tr>
<td>$D_{FSI}$</td>
<td>$1.2 \times 10^{-5}$</td>
<td>$1.5 \times 10^{-4}$</td>
<td>$1.2 \times 10^{-4}$</td>
<td>$-3 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

$^{23}$Mg and $^{39}$Ca can be laser polarized as ions
$^{23}$Mg best produced and laser polarized $\Rightarrow$ first candidate
**D correlation measurement setup**


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**In trap optical polarization**

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

Where \( \delta \) is depending on the phase space coverage.
Experimental challenges


• In trap polarization:
  – Novel method not yet tested
  – Simulations with 10kHz pulsed lasers → >99% polarization in ~1ms

• Trapping capacity and trapping half life
  – Presently 5\cdot10^5 ions/bunch, aiming at 5\cdot10^6/bunch
  – Presently 500ms, aiming at several s (^{23}\text{Mg}: T_{1/2}=11s)

Optimized trap geometry M. Benali and G. Quemener

Trapping radius
From: 4.5\text{mm} (LPCTrap + environment)
To: 11\text{mm} (MORA + environment)
  ➢ Negligible evaporation losses
  ➢ pseudo-potential depth x 5

• Systematic effects \approx 10^{-5}
  – $D_n$ measurement, dominated by statistics, give hints
  – Tests and simulations of the detection setup are just starting
    • GEANT 4 simulations for electrons
    • Home made simulations for dynamics of trapped ion and recoil ion trajectories
Phoswich detector: combination of two plastic scintillators:
- thin scintillator (0.5 mm, \(\tau=1.8\) ns)
- thick scintillator (5 cm, \(\tau=285\) ns)
(+ Mylar + Téflon)

\[ Q_{\text{fast}} + Q_{\text{slow}} = Q_{\text{tot}} \]

=> beta, gamma discrimination
Phoswich detectors tests

- Detectors calibration using $^{207}\text{Bi}$ ($\beta, \gamma$) and $^{137}\text{Cs}$ ($\beta$)
  - Done

- Study of the magnetic field effect on PMs
  - Done
  - (effect of magnetic field on signal resolution and PMs gain)

- Detector test in a secondary vacuum
  - Done

- GEANT 4 simulations
  - in progress

Stable resolution by varying the magnetic field

M. Benali
JYFL: $\sim 10^5 \, ^{23}\text{Mg/s}$
Laser setup readily available

1) Polarization degree measurement $\sim \%$ level
2) $D$ correlation measurement $\sim 5 \cdot 10^{-4}$ level
Highest sensitivity measurements

SPIRAL 2 LINAC

High intensity p, d, He beams
(1-5 mA) 30-40 MeV
High intensity heavy ion beams
(1-10 pµA) 14.5 AMeV

S3 NEUTRON FOR SCIENCE EXPERIMENTAL AREA
Up to 30 MeV n

Experimental hall for very low energy beams (keV)

NFS DESIR

GANIL

Super Separator Spectrometer
RIBs from fusion reactions

SPIRAL 1: >10^8 \(^{23}\)Mg/s
?? S3-LEB: >10^6 39Ca/s

D correlation < 5 \times 10^{-5} level

Experimental areas and cyclotrons: heavy ions (pµA) up to 95 AMeV

SPIRAL 1 facility: RIBs from fragmentation
Summary/Perspectives

- **New perspectives with polarized beams with MORA at JYFL**
  - **Proof of principle of the polarization to be done at JYFL**
    - Adapted IGISOL – 4 Laser setup
      - Pulsed (TiSa) or CW (Dye) laser schemes are being investigated
    - Adapted trapping setup from LPCTrap
    - Adapted detection setup carried out by GANIL and LPC Caen

  - **First measurement of D at JYFL**
    - Best sensitivity for nuclear beta decay is probably possible
      - LoI for $^{23}\text{Mg}$ beam characterization

  - **Theoretical efforts**
    - for defining what NP one is probing with D measurements to the $10^{-5}$ level
    - For reviewing $D_{FSI}$ calculations

- **$D$ correlation measurement with unprecedented accuracy in SPIRAL 2**
  - 1 week of beam time:
    - same accuracy as for the neutron with existing techniques
    - Better sensitivity to NP: type of transition and selection of detection plane
  - Can go down to the $10^{-5}$ level with some beam, laser and trapping R&D
    - improvement by 1 order of magnitude on the sensitivity to NP $Im(C_V/C_A)$
    - First approach/probe of $D_{FSI}$ for $^{23}\text{Mg}$
  - Great physics with great challenges!

- **Project has officially started in April 2018**

- **ANR funds for PhD and postdoc positions as of 2020**

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P. Delahaye, INPC2019, Glasgow
Thanks a lot for your attention

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