$\beta$–$\nu$ correlation measurements in nuclear decays with LPCTrap

E. Liénard

LPC Caen, University of Caen
Development of LPCTrap: context in 1997

- **Exotic couplings in weak interaction: situation of "a" measurements**
  - GT: $^6$He (Johnson *et al.* PRC 1963) → $a_{GT} = -0.3308 (30)$
  - F: $^{32}$Ar (project Adelberger *et al.*) → $a_F = 0.9989 (65)$ published in 1999
    - $^{38m}$K (project Gorelov *et al.*) → $a_F = 0.9981 (48)$ published in 2005
- **SPIRAL project @ GANIL**
  - Light n-rich beams (noble gases): $^6$He, $^8$He, $^{18}$Ne, $^{19}$Ne, $^{32}$Ar, $^{35}$Ar, ...
    - with high intensities
  - First beam in 2001

_Aim of LPCTrap: improvement of $a_{GT}$ precision using up-to-date technologies_
The LPCTrap setup

• Decay source confined in a transparent Paul trap

- β - recoil ion detection in coincidence
- α deduced from recoil time-of-flight distribution

beam

recoil

- Decay source confined in a transparent Paul trap

• 6He: good candidate

- Pure GT transition
- 100% G.S. to G.S.
- Reasonable \( T_{1/2} = 806.7 \text{ ms} \)
- High \( Q_\beta = 3.51 \text{ MeV} \), \( T_{\text{max}} = 1.4 \text{ keV} \)
- High production rate: \( 2 \times 10^8 \text{ ions/s} \)

Simulation for \(^6\text{He}^+\) decay

\[ a_{\beta^-} = -\frac{1}{3} \quad a_{\beta^+} = +\frac{1}{3} \]
LPCTrap @ GANIL

Beams characteristics:
- 10-30 keV, 80 $\pi$ mm mrad
- rate: $10^7 - 10^8$ ions/s

SPIRAL beam:
- 10-30 keV
- $\Delta E \sim 20$ eV

Paul trap:
- Effective potential: 2-3 V
LPCTrap @ LIRAT

Beam from LIRAT

RFQ (Cooling & bunching)

- $KE_{ion}$: 10 keV
- $\Delta KE$: ~20 eV
- 100 eV - <1 eV
- ~1 eV

Pulsed cavity
- 1 keV
- 100 eV
- 0 eV
- ~0.1 eV

Paul Trap

Buffer-gas: $H_2$ (He for heavier nuclei)
- accumulation: 200ms (cycle)

Total efficiency: ~10$^{-3}$

~1.5 $10^8$ $^6$He$^+$ /s
LPCTrap: the detection setup

- \(< 2010\)

**Trigger:** $\beta$ scintillator

**Parameters:**
- $\beta$ energy
- $\beta$ position
- recoil ion ToF
- recoil ion position
- + timestamp in cycle 
  & trap RF phase

- \(\geq 2010\)

**Time of flight of RI**

**BG suppression**

**Control of systematic effects**

**Control of results consistency**

\[E. \text{ Liénard et al., NIMA551(2005)}\]
First experiment in 2006

- $a_{\beta v} = -0.3335 \pm 0.075$ (73) stat (75) syst


- Best precision on $a_{GT}$ using coincidence technique ($\Delta a/a = 3\%$)
- Good control of experimental & simulation parameters

Systematic error budget

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
<th>$\Delta a_{\beta v} (\times 10^{-3})$</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cloud temperature</td>
<td>6.5%</td>
<td>6.8</td>
<td>off-line measurement</td>
</tr>
<tr>
<td>$\theta_{x,MCPSD}$</td>
<td>0.003 rad</td>
<td>0.1</td>
<td>present data</td>
</tr>
<tr>
<td>$\theta_{y,MCPSD}$</td>
<td>0.003 rad</td>
<td>0.1</td>
<td>present data</td>
</tr>
<tr>
<td>MCPPS offset (x,y)</td>
<td>0.145 mm</td>
<td>0.3</td>
<td>present data</td>
</tr>
<tr>
<td>MCPPS calibration</td>
<td>0.5%</td>
<td>1.3</td>
<td>present data</td>
</tr>
<tr>
<td>$d_{DSSD}$</td>
<td>0.2 mm</td>
<td>0.3</td>
<td>present data</td>
</tr>
<tr>
<td>$E_{\text{scint}}$</td>
<td></td>
<td>0.8</td>
<td>present data</td>
</tr>
<tr>
<td>$E_{\text{scint}}$</td>
<td>10%</td>
<td>0.8</td>
<td>GEANT4</td>
</tr>
<tr>
<td>Background</td>
<td></td>
<td>0.9</td>
<td>present data</td>
</tr>
<tr>
<td>$\beta$ Scattering</td>
<td>10%</td>
<td>1.9</td>
<td>GEANT4</td>
</tr>
<tr>
<td>Shake off</td>
<td>0 - 0.05</td>
<td>0.6</td>
<td>theoretical calculation</td>
</tr>
<tr>
<td>$V_{\text{RF}}$</td>
<td>2.5%</td>
<td>1.7</td>
<td>off-line measurement</td>
</tr>
<tr>
<td>total</td>
<td></td>
<td>7.5</td>
<td></td>
</tr>
</tbody>
</table>

First need : data on $\beta$ scattering ! possible @ Bordeaux electron spectrometer ($^{90}$Sr source)
\( ^6\text{He} : \text{first results} \)

- **Last experiment in 2010**

- Analysis performed to extract \( P_{\text{shake-off}} \) (complete simulation @ low statistics : \( \sim 4 \times 10^5 \))
  \[
P_{\text{shake-off}} = 0.02339(35)_{\text{stat}}(07)_{\text{syst}}
  \]
  - High precision : \( \Delta P_{\text{shake-off}} = 3.6 \times 10^{-4} \)
  - Excellent agreement : theoretical value 0.02322
  
  *Couratin et al., PRL108 (2012)*

- **About \( a_{GT} \)**:
  - \( (\Delta a_{GT} / a_{GT})_{\text{expected}} \sim 0.63 \% \)
  - difficulties to properly reproduce different experimental distributions \( \rightarrow \) bad Chisquare!

\( 1.2 \times 10^6 \) good events recorded

- Improvement of ion cloud modelling including gas cooling & space charge effects (GPU's, CUDA) \( \rightarrow \) Xavier Fabian

**Second need** : extraction of "\( a \)" requires dedicated simulations including systematic parameters under perfect control...
Measurements in the mirror decays of $^{35}\text{Ar}$ & $^{19}\text{Ne}$

- **Mirror decays = source of data to determine $V_{ud}$**

$$V_{ud}^2 = \frac{K'}{\left( f_V T_{1/2} / BR \right)( 1 + C \rho^2 )}$$

- **Status for some decays**

$\rho = GT/F$:
- the least or even not known quantity!
- precisely determined from correlation measurements

$$a_m = \frac{1-\rho^2}{3}$$
$$A_m = \rho^2-2\rho\sqrt{J(J+1)}\left( 1+\rho^2 \right)(J+1)$$
$$B_m = -\rho^2+2\rho\sqrt{J(J+1)}\left( 1+\rho^2 \right)(J+1)$$

adapted from Severijns et al PRC78(2008)

Naviliat et al., PRL102(2009)
Update of data in 2014: $M$, $T_{1/2}$, $BR$

**2009**
Naviliat et al., PRL102(2009)

**2014**

Q($^{23}$Mg): AME2012 $\rightarrow$ gain of a factor 1.9

Q($^{21}$Na): Mukherjee et al EPJA35(2008) $\rightarrow$ gain of a factor 3.3

$T_{1/2}$($^{19}$Ne): Triambak et al PRL101(2012) $\rightarrow$ gain of a factor 8.5

Broussard et al PRL112(2014)

$V_{ud}$ (2009) = 0.9719 (17)

should change $V_{ud}$ "mirror" value....
Update of data in 2014: $M, T_{1/2}, BR$

**2009**

Naviliat et al., PRL102(2009)

**2014**

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should change $V_{ud}$ "mirror" value….

$V_{ud}$ (2009) = 0.9719 (17) $\rightarrow$ $V_{ud}$ (2014) = 0.9717 (17) !!

**Third need:** for $V_{ud}$ determination, $\rho$ improvements are necessary...
• \( \rho \) precisely determined from correlation measurements

\[
a_m = \frac{(1 - \rho^2/3)}{(1 + \rho^2)} \quad A_m = \frac{\rho^2 - 2 \rho \sqrt{J(J+1)}}{(1 + \rho^2)(J+1)}
\]

Severijns & Naviliat PST152(2013)

\( a \) or \( A @ 0.5\% \)?

"A" more sensitive than "a" in a few cases and it is more difficult to measure precisely...

A part of job could be achieved with LPCTrap....
Update of data in 2014-2015: $\rho$?

LPCTrap @ GANIL (LIRAT)

- Measurements of $\alpha_{\beta\nu}$ and shakeoff probabilities in decay of $^{35}\text{Ar}^{1+}$ & $^{19}\text{Ne}^{1+}$

2011-2012: $^{35}\text{Ar}$

Ban et al., ADP525 (2013)

$^{19}\text{Ne}$

2013: $^{19}\text{Ne}$

Analysis of data in progress (development of new simulation tools...)

Shakeoff: Couratin et al., PRA (2013)
Update of data in 2014-2015: $\rho$?

LPCTrap @ GANIL (LIRAT)

- Measurements of $\alpha_{\beta\nu}$ and shakeoff probabilities in decay of $^{35}\text{Ar}^{1+}$ & $^{19}\text{Ne}^{1+}$

2011-2012: $^{35}\text{Ar}$

2013: $^{19}\text{Ne}$

Shakeoff: Couratin et al., PRA (2013)

Analysis of data in progress (development of new simulation tools...)

- Expected results $(\Delta a / a)$: ~0.25 %
- Factor gained on $\Delta \rho / \rho$: ~4.5
- $V_{ud}$ (2009) = 0.9719 (17)
- $V_{ud}$ (expected) = 0.9734 (10) !!
Future @ GANIL ?

• Development of new beams @ SPIRAL

<table>
<thead>
<tr>
<th>Ion</th>
<th>$T_{1/2}$ (s)</th>
<th>Expected rate (pps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{21}$Na</td>
<td>22.49</td>
<td>1.8E+08</td>
</tr>
<tr>
<td>$^{23}$Mg</td>
<td>11.32</td>
<td>4.3E+07</td>
</tr>
<tr>
<td>$^{33}$Cl</td>
<td>2.51</td>
<td>1.8E+07</td>
</tr>
<tr>
<td>$^{37}$K</td>
<td>1.22</td>
<td>1.1E+07</td>
</tr>
</tbody>
</table>

- Contact: Pierre Delahaye
- Available in 2016?

• DESIR @ SPIRAL2 $\phi 1+$ (Lol 2011, 2014)

- In 2018?
DESIR layout (draft version)

- α measurements
- $T_{1/2}$, BR measurements
- M measurements
What can we expect from α measurements?

- Ion with rate > 1E+07 pps

<table>
<thead>
<tr>
<th>Ion</th>
<th>T_{1/2} (s)</th>
<th>Expected rate (pps)</th>
<th>Expected nb of coinc.</th>
<th>Estimated α ± σ_α</th>
<th>New ρ ± σ_ρ</th>
<th>Gain factor</th>
</tr>
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<tbody>
<tr>
<td>^{21}Na</td>
<td>22.49</td>
<td>1.8E+08</td>
<td>1.7E+06</td>
<td>0.5587(18)</td>
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</tr>
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<td>0.5426(30)</td>
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<td>1.5E+06</td>
<td>0.8848(19)</td>
<td>0.3075(27)</td>
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<tr>
<td>^{37}K</td>
<td>1.22</td>
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**Estimation of coinc. (1 week):**
- Based on ^{35}Ar experiment
- T_{1/2} taken into account
- LPCTrap → LPCTrap2

- phoswich for β detection
- detectors number X 2
- FASTER DAQ system

Gain in stat: factor of ~ 4
What can we expect from $\alpha$ measurements?

- Ion with rate $> 1E+07$ pps

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- **Estimation of coinc. (1 week):**
  - Based on $^{35}$Ar experiment
  - $T_{1/2}$ taken into account
  - LPCTrap $\rightarrow$ LPCTrap2
    - phoswich for $\beta$ detection
    - detectors number $\times 2$
    - FASTER DAQ system

- **Error estimation on $\alpha$:**
  - Based on $^6$He experiment
  - $\sigma_{\text{stat}} = \sigma_{\text{syst}}$

$$\rho^2 = (1-a)/(a+1/3)$$

+ combination with existing results

Gain in stat: factor of $\sim 4$
What can we expect from $\alpha$ measurements?

**2009**

**LPCTrap2 @ GANIL**

Naviliat et al PRL102(2009)

$Ft_0 = F(1+C\rho_2)$

Test of CVC @ $3.6 \times 10^{-3}$ level

Test of CVC @ $1.3 \times 10^{-3}$ level
What can we expect from $\alpha$ measurements?

Naviliat et al PRL102(2009)

$Ft_0 = Ft(1+C\rho^2)$

Test of CVC @ $3.6 \times 10^{-3}$ level

$V_{ud} = 0.9719 (17)$

• Gain: factor of 2.5
• To be compared to $V_{ud} = 0.97425 (22)$ from pure Fermi

LPCTrap2 @ GANIL

$Ft_0 = 6148 \pm 8$ s

$V_{ud} = 0.97391 (68)$
What can we expect from \( a, T_{1/2}, BR \) & \( M \) measurements?

**LPCTrap2 @ GANIL**

+ \( T_{1/2}, BR \) & \( M \) improvements

\[ \begin{align*}
\text{• } ^{21}\text{Na, expected gain: } & 10 \ (T_{1/2}) \quad \text{Finlay et al @ TRIUMF 2014} \\
\text{• } ^{23}\text{Mg, expected gain: } & 3.7 \ (BR) \quad \text{Blank et al @ JYFLTRAP (performed)} \\
\text{• } ^{33}\text{Cl, expected gain: } & 2.2 \ (T_{1/2}), 2 \ (BR) \quad \text{Kurtukian et al @ SPIRAL1 ?} \\
\text{• } ^{35}\text{Ar, expected gain: } & 2.8 \ (T_{1/2}), 6.6 \ (BR), 4.7 \ (M) \quad \text{Finlay et al @ TRIUMF 2015 ?} \\
\text{• } ^{37}\text{K, expected gain: } & 6.1 \ (T_{1/2}), 14 \ (BR) \quad \text{Kurtukian et al @ ISOLDE 2015 ?}
\end{align*} \]
What can we expect from $a$, $T_{1/2}$, BR & M measurements?

LPCTrap2 @ GANIL

$V_{ud} = 0.97391 \ (68)$

+ $T_{1/2}$, BR & M improvements

$V_{ud} = 0.97423 \ (49)$

- Gain of a factor 1.4
- To be compared to $V_{ud} = 0.97425 \ (22)$ from pure Fermi
- Best cases: $^{35}{\text{Ar}}$, $^{33}{\text{Cl}}$ and $^{37}{\text{K}}$
What can we expect from $a$, $T_{1/2}$, $BR$ & $M$ measurements?

\[ \mathcal{F}t_0 = 6144 \pm 6 \text{ s} \]

- Gain of a factor 1.4
- To be compared to $V_{ud} = 0.97425 (22)$ from pure Fermi
- Best cases: $^{35}\text{Ar}$, $^{33}\text{Cl}$ and $^{37}\text{K}$

**LPCTrap2 @ GANIL**

$V_{ud} = 0.97391 (68)$

**+ $T_{1/2}$, BR & M improvements**

$V_{ud} = 0.97423 (49)$

$^{33}\text{Cl}$, $^{37}\text{K}$: good candidates for first experiments

with only these 3 cases: $V_{ud} = 0.97402 (55)$
Further development: cloud polarization

- New chamber, lasers & detectors

Upgrade of the detector setup:

→ arrangement of maximum 6 detector modules
depending on the experiment performed
Example: measurement of $D$ in the decay of $^{23}$Mg

© P. Delahaye 2014

$^{23}$Mg = "good" candidate:

- Expected yield @ SPIRAL: $4.3 \times 10^7$ pps
- Can be laser polarized as ions: optical pumping $\rightarrow$ 80%
- Trapping: $5 \times 10^4$ ions / cycle
- Optimized solid angle of detection

$\sigma_D < 5 \times 10^{-4}$ (assuming $\sigma_{syst} = \sigma_{stat}$)

is accessible in 1 week of beam time

Final aim $\rightarrow \sigma_D < 1 \times 10^{-4}$

Current best results in nuclear decays:

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

n decay $\rightarrow D= (-0.94 \pm 1.89 \pm 0.97) \times 10^{-4}$ Mumm et al., PRL 107 (2011), Chupp et al., PRC 86 (2012)
• **LPCTrap**

- Transparent Paul trap for $\beta-\nu$ correlation measurements
- Measurements performed in $^6\text{He}$, $^{35}\text{Ar}$, $^{19}\text{Ne}$
  - charge state distributions: unique in 1+ ions decay
  - $\beta-\nu$ correlation coefficient:
    - development of new dedicated simulation tools (CUDA & GPU's)
    - need for data on $\beta$ scattering (e$^-\text{ spectrometer in Bordeaux}$)
    - $^6\text{He}$ pure GT decay $\rightarrow (\Delta a_{GT}/a_{GT})_{\text{expected}} \sim 0.6 \%$
    - $^{35}\text{Ar}$ mirror decay $\rightarrow (\Delta a_{m}/a_{m})_{\text{expected}} \sim 0.25 \%$

**Perspectives**

- "Short"- range plan: measurements of "$a$" in mirror decays at LIRAT & DESIR with LPCTrap2 using the new beams provided by SPIRAL ($^{21}\text{Na}$, $^{23}\text{Mg}$, $^{33}\text{Cl}$, $^{37}\text{K}$)
  - required to improve $\rho$ & $V_{ud}$ deduced from mirror transitions
  - with M, T & BR improvements $\rightarrow$ "only" a factor 2.2 worse than "pure" Fermi
  - $^{33}\text{Cl}$ & $^{37}\text{K}$: good candidates for first experiments

- "Mid"- range plan: measurement of the triple correlation $D$ in $^{23}\text{Mg}$ decay
  - cloud polarization with laser in LPCTrap of second generation
  - final aim: $\sigma_D < 1 \times 10^{-4}$
Thank you ...

LPC Caen: Gilles Ban
Dominique Durand
Xavier Fabian
Xavier Fléchard
Etienne Liénard
François Mauger
Gilles Quéméner

GANIL: Pierre Delahaye
Jean-Charles Thomas

CIMAP: Alain Méry

CELIA: Bernard Pons
Baptiste Fabre

NSCL MSU: Oscar Naviliat-Cuncic

IKS KUL: Claire Couratin
Paul Finlay
Tomica Porobic
Nathal Severijns
Philippe Velten

and the LPC & GANIL technical staffs ....
LPCTrap2 = minimal upgrade of LPCTrap

In the current chamber

β phoswich:

• association of 2 plastic scintillators (thin & thick) with ≠ decay constants and read by a single PM → β-γ discrimination

• thick plastic = scintillating fibers and PM sensitive to position → β location

First tests will start soon …
Further tests: with scintillating fibers

- $\Delta E$: > 5.5 MeV
- $\Delta E$: slow plastic ($\tau = 285$ ns)
- $\Delta E$: fast fibers ($\tau = 3.2$ ns)
- $3 \text{ cm}$
- $1 \text{ mm}$
- $\varnothing = 6 \text{ cm}$

- $\varnothing = 6 \text{ cm}$
- Square section of 0.5 cm side
- Direct light
- No glue $\rightarrow$ system assembly?

- $200 \text{ keV}$
- $3 \text{ cm}$
- $1 \text{ mm}$

- Active area of the PM

- 88 fibers
- 100 fibers

- Position sensitive PM
- $E$: fast fibers
- $\Delta E$: slow plastic

- $15 \text{ cm}$
• Which beam for a day-1 experiment?

- SPIRAL2
  - $I \sim 2 \times 10^8$ pps
- SPIRAL1
  - $I \sim 4 \times 10^7$ pps

or

- $^{31}\text{S}$
- $^{39}\text{Ca}$

$M(f_V), T_{1/2}, a(\rho)$ measurements

Bunches sent alternatively in the 3 setups

Optimization of the beam time:

- (7+5+3) days ~ 12 days!

3 experiments in 1 shot!! without "lost" beam period

Final request ~ 12 days

LoI 8: Status in 2011
Test of the Time reversal symmetry in the beta decay of $^{23}\text{Mg}$ and $^{39}\text{Ca}$ using an in-trap polarization method at DESIR


GANIL – LPC Caen – IPN Orsay – IKS Leuven collaboration
Precision measurements 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
Precision measurements 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 assymetry
  – 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

• $D$ correlation measurements
  – Best values
    • neutron decay, $D_n= (-0.94 \pm 1.89 \pm 0.97) \times 10^{-4}$, emiT collaboration, PRL 107, 102301 (2011), Phys. Rev. C 86 (2012) 035505
    • $^{19}$Ne decay, $D=0.0001 \pm 0.0006$ Calaprice et al, Hyp. Int. 22 (1985) 83, limited by statistics

• Aim of the experiments: $\sigma_D \leq 10^{-4}$

Making use of intense RIBs at SPIRAL, polarized by LUMIERE, and of a specific arrangement of LPCtrap!
Possible candidates

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Yield SPIRAL (pps)</th>
<th>$D_{FSI}$</th>
</tr>
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<tr>
<td>$^{21}$Na</td>
<td>$&gt;1e8$pps</td>
<td>$6.7 \times 10^{-5}$</td>
</tr>
<tr>
<td>$^{23}$Mg</td>
<td>$&gt;1e8$ pps</td>
<td>$-1.3 \times 10^{-4}$</td>
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<tr>
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<td>$&gt;1e8$ pps</td>
<td>$-1.9 \times 10^{-4}$</td>
</tr>
<tr>
<td>$^{39}$Ca</td>
<td>$5.7e5$pps (estimated!)</td>
<td>$4.7 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

Can be laser polarized as ions!
Experimental setup

In trap optical polarization of $^{23}\text{Mg}^+$ and $^{39}\text{Ca}^+$

$$a_{\beta\nu} \frac{\bar{p}_e \bar{p}_v}{E_e E_v} \quad D \frac{\langle \vec{J} \rangle}{J} \cdot \left( \frac{\bar{p}_e}{E_e} \times \frac{\bar{p}_v}{E_v} \right)$$
Possible upgrades of the LPCtrap detector and trapping setup

Upgrade of the detector setup
3 telescopes instead of 1
from 5‰ to 1‰ precision on $\alpha_{\beta
\nu}$

Simpler beta and recoil ion detectors may be used
Statistical considerations

• 5.10^4 ions trapped / 200ms
  – Ok for ^{23}\text{Mg}^+
  – Some R&D for ^{39}\text{Ca}^+
• 80% polarization
• Upgraded / suitable detector setup
  – 8 detectors instead of 2 → 16x higher solid angle coverage

• Sensitivity on $D$: $\sigma_D \approx \frac{4}{\sqrt{2N}}$ with $N$ the number of coincidences
• 30% time for interruptions

1 week of beam time:

$\sigma_D \approx 4.310^{-4}$ $^{23}\text{Mg}$  
$\sigma_D \approx 1.310^{-4}$ $^{39}\text{Ca}$