A UV laser system for the Hg co-magnetometer in the nEDM experiment at PSI

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Outline

1. Short introduction to nEDM experiment
2. The Hg co-magnetometer and the new UV laser: first results
3. New possibilities opened up by the UV laser system
The strong CP problem: 1 CP violating dimension 4 operator in QCD

\[ H_0 = - \left( -d \frac{\bar{\sigma}}{|\bar{\sigma}|} \cdot \vec{E} + \mu \frac{\bar{\sigma}}{|\bar{\sigma}|} \cdot \vec{B} \right) \quad H_T = - \left( -d \frac{(-\bar{\sigma})}{|(-\bar{\sigma})|} \cdot \vec{E} + \mu \frac{(-\bar{\sigma})}{|(-\bar{\sigma})|} \cdot (-\vec{B}) \right) \neq H_0 \]

T violation, assuming CPT conservation, also CP violation.
(Purcell and Ramsey, Phys. Rev. 78, 807 (1950))

The strong CP problem: 1 CP violating dimension 4 operator in QCD

\[ \mathcal{L}_{\text{QCD}}^{\dim=4} = \frac{g_s^2}{32\pi^2} \bar{\theta} G_{\mu\nu}^a \tilde{G}^{\mu\nu,a} \]

\[ d_n \approx \bar{\theta}_{\text{QCD}} \times 10^{-16} \text{e} \cdot \text{cm} \]

But: \( d_n \leq 2.9 \times 10^{-26} \text{e} \cdot \text{cm} \) (90\% CL) \( \rightarrow \bar{\theta}_{\text{QCD}} \approx 10^{-10} \)
History of nEDM

Neutron EDM Upper Limit [e\cdot cm]

- ORNL, Harvard
- MIT, BNL
- LNPI
- Sussex, RAL, ILL
- Expected Sensitivity at PSI

Not excluded supersymmetry predictions

Standard model predictions

5 x 10^{-27} e\cdot cm (95% CL)

5 x 10^{-28} e\cdot cm (95% CL)
Goal: detect $\Delta \omega_L$ correlated to the relative B and E field direction

$\omega_L$ major source of systematic effects

extract nEDM from:

$$d_n = \frac{\hbar \Delta \omega - \mu_n (B_{\uparrow\uparrow} - B_{\uparrow\downarrow})}{2 (E_{\uparrow\uparrow} + E_{\uparrow\downarrow})}$$

$B_0 \approx 1 \mu T \implies \omega_{L,n} \approx 2\pi \times 30 \text{ Hz}$

$E \approx 12 \text{ kV/cm}, d_n \leq 3 \times 10^{-26} \text{ e \cdot cm} \implies \Delta \omega_{L,n} \approx 2\pi \times 9 \text{ nHz}$
nEDM apparatus

- Four-layer Mu-metal shield
- Vacuum chamber
- Precession chamber where neutron precession is induced and measured
- Photomultiplier tube to detect the intensity modulation of the mercury light
- Mercury polarizing cell where the mercury is polarized
- Mercury lamp to polarize the mercury ultraviolet (253.7 nm)
- High voltage lead
- Cesium magnetometer
- Electrode (upper)
- UV light from discharge lamp or laser system to detect spin precession
- Magnetic field coils
- Switch
- Spin analyzer
- Neutron detector

surrounding field compensation
nEDM sensitivity

From  \[ d_n = \frac{\hbar \Delta \omega - \mu_n (B_{\uparrow \uparrow} - B_{\uparrow \downarrow})}{2 (E_{\uparrow \uparrow} + E_{\uparrow \downarrow})} \Rightarrow d_n = \frac{\hbar \Delta \omega}{4E} \]

\[ \text{if } 2\mu_n (B_{\uparrow \downarrow} - B_{\uparrow \uparrow}) \ll \hbar \Delta \omega = 4Ed_n \rightarrow \sigma(\Delta B) \ll \frac{2E\sigma(d_n)}{\mu_n} \]

\[ \sigma(d_n) = \frac{\hbar}{2\alpha ET\sqrt{N}} \]

\( \alpha \) Visibility of resonance (0.75)

\( E \) Electric field strength (12 kV/cm)

\( T \) Time of free precession (150s)

\( N \) Number of neutrons (350000)

For nEDM@PSI as planned per run:

\[ \sigma(d_n) = \frac{\hbar}{2\alpha ET\sqrt{N}} = 4 \cdot 10^{-25} \text{ ecm} \rightarrow \sigma(\Delta B)=100 \text{ fT per cycle (nEDM)} \]

\[ \rightarrow \sigma(\Delta B)=10 \text{ fT per cycle (n2EDM)} \]
Systematic effects

<table>
<thead>
<tr>
<th>Effect</th>
<th>Class (d/i)</th>
<th>Shift and $\sigma$</th>
<th>Shift and $\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$10^{-27}$ e $\cdot$ cm</td>
<td>$2012$</td>
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<tr>
<td></td>
<td></td>
<td>RAL/Sx/ILL</td>
<td></td>
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<tr>
<td>Leakage currents</td>
<td>d</td>
<td>0.0±0.1</td>
<td>0.00±0.04</td>
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<tr>
<td>$\nu \times E$</td>
<td>d</td>
<td>0.0±1.0</td>
<td>0.00±0.54</td>
</tr>
<tr>
<td>- First order</td>
<td>d</td>
<td>0.00±0.02</td>
<td>0.00±0.00</td>
</tr>
<tr>
<td>- Second order</td>
<td>d</td>
<td>0.0±0.4</td>
<td>0.00±0.00</td>
</tr>
<tr>
<td>Electric forces</td>
<td>d</td>
<td>0.00±0.01</td>
<td>0.00±0.00</td>
</tr>
<tr>
<td>AC fields</td>
<td>d</td>
<td>0.0±2.4</td>
<td>-0.46±0.36</td>
</tr>
<tr>
<td>Uncompensated B drifts</td>
<td>d</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **$^{199}$Hg atom edm**
  - **$^{199}$Hg light shifts**

- **Geometric phase effect**
  - Dipole fields
  - Quadrupole difference

- **Total**

$d$: direct effect on UCN

$i$: indirect effect

→ major systematic effects are related to the Hg co-magnetometer
→ one is directly related to the light source
Optical pumping of $^{199}\text{Hg}$ ETH Zürich

Goal: Measure residual magnetic field drifts via optically detected nuclear magnetic resonance

Spin polarize by optical pumping

Absorption cross section depends on the relative orientation of photon and atom angular momentum

Transmission modulation of circularly polarized light beam perpendicular to main magnetic field after $\pi/2$ flip
Hg co-magnetometer

Extract B field from Larmor frequency and correct UCN frequency (lamp data)

1.7 pt

23 pT

16 h
Goal: Measure residual magnetic field drifts via optically detected nuclear magnetic resonance (ODMR) with $^{199}\text{Hg}$ atoms

- Same volume as UCN!
- Same volume average as UCN?
  - Center of mass offset
  - Adiabaticity
- Hg specific “magnetic” field effects

- Hg co-magnetometer
- UCN precession chamber
- PMT
- polarization chamber
- circular polarizer unit
- 253.7 nm UV light, circularly polarized
- Hg source
Vector light shift in $^{199}\text{Hg}$

Atomic energy levels are influenced by the interaction with light.

Spin dependent part can be modeled as effective magnetic field (which only alters the Larmor frequency of the Hg atoms, not of the UCN).

Effective magnetic field depends on:
- Light intensity
- Light polarization
- Light frequency
- Light beam alignment

All four parameters have to be under control for reliable calculations.
Vector light shift in $^{199}\text{Hg}$

Calculation for 5 $\mu$W UV circular polarized light in UCN chamber, 5 mm diameter, 1 mrad misalignment to the main magnetic field for a laser ($\sim 1$ MHz) and a Doppler broadened ($\sim 1$ GHz) readout light (W. Happer, B.S. Mathur, Phys. Rev. 163, 12 (1967))

$\rightarrow$ residual effect on resonance is $\sim 6$ ppb (6 fT) $\rightarrow$ good enough for n2EDM
Hg discharge bulbs

current UV light sources: $^{204}\text{Hg}$ (90%) discharge lamps

- **Advantage:** easy to run, emission line overlaps $^{199}\text{Hg} \; F=\frac{1}{2}$
- **Disadvantage:** many details unknown and prone to changes, possible vector light shifts, self-absorption

- Variable argon pressure
- Variable temperature
- Variable head geometry

→ Large uncertainty on the output frequency spectrum
→ Affects estimates of systematic effects
→ Well controllable light source important
UV FHG system

Fourth harmonic generator (IR→VIS→UV)
Toptica TA FHG installed in a test lab (20 mW @ 254 nm)
50 m away from the nEDM setup

MHz accuracy lock necessary to suppress vector light shift
Frequency stabilization by **Sub-Doppler Dichroic Atomic Vapor Laser Lock scheme (SD-DAVLL)**

Dichroism induced by an external magnetic field

Advantages:
- 1\textsuperscript{st} order independence of magnetic field changes
- Modulation free
SD-DAVLL spectrum I

~ 22 GHz

199\text{Hg} F=1/2

201\text{Hg} F=3/2

201\text{Hg} F=1/2

198\text{Hg}

200\text{Hg}

196\text{Hg}

204\text{Hg}

202\text{Hg}

199\text{Hg} F=3/2
Hg spectroscopy cells

Commercial prefilled spectroscopy cells degraded within hours/days

→ recover by heating, not convenient

Fill long quartz cells with enriched \(^{199}\text{Hg}\) ourselves

→ no darkening even after months of operation
SD-DAVLL spectrum II

Error signal

$^{199}\text{Hg}\, F=3/2$

$^{199}\text{Hg}\, F=1/2$

96 MHz

$^{204}\text{Hg}$
Jan 2013: first UV laser light in the nEDM setup
→ transport UV over 50 m multimode fiber to the experiment
Hg co-magnetometer
UV laser: First results

Result: six fold increase of normalized amplitude
Observed increase in signal amplitude is a combination of several effects

1) no Doppler-broadening of readout beam (factor 1.5)
2) Isotopic composition of the $^{204}$Hg lamp

- $\sim 90\%$ $^{204}$Hg
- $\rightarrow$ strong self absorption of $^{204}$Hg line
- $\rightarrow$ more than proportional $^{202}$Hg light fraction
3) Deformation of $^{204}\text{Hg}$ emission line due to self-absorption
→ reduction of effective absorption cross section,

→ we run the Hg bulbs also at 40°C
Improvement 4

4) Isotopic composition of the enriched $^{199}\text{Hg}$
The six fold gain in normalized amplitude modulation can be explained by the combination of four factors.

Signal/Noise was improved by a factor of 2-3 with active power stabilization in this first experiment
→ noise pickup on the 50 m of fiber
→ bring the laser closer to the nEDM
New possibilities

In-situ measurement of E field via quadratic Stark shift (Romalis et al.)

Recent improvements of UV single mode (!) fibers may allow stable light distribution on timescale of weeks
Conclusions

- Setup a frequency stabilized UV laser system for nEDM
- Factor six increase of modulation signal demonstrated

- Superior control of vector light shift effect

- Many new possibilities not in reach with the lamps used so far (e.g. E-field measurement, maybe different isotope).
Thanks to…

- the current and former members of the UCN group at PSI, the workshop staff at PSI
- the nEDM collaboration
- the members of the Precision Physics at Low Energy group at ETHZ