An Improved Search for the Neutron Electric Dipole Moment

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A permanent electric dipole moment of fundamental spin-1/2 particles violates both parity (\(P\)) and time reversal (\(T\)) symmetry, and hence, also charge-parity (\(CP\)) symmetry since there is no sign of \(CPT\)-violation.

The search for a neutron electric dipole moment (nEDM) probes \(CP\) violation within and beyond the Standard Model. The experiment, set up at the Paul Scherrer Institute (PSI), an improved, upgraded version of the apparatus which provided the current best experimental limit, \(d_n < 2.9 \times 10^{-26} \, \text{e·cm} \) (90\% C.L.), by the RAL/Sussex/ILL collaboration: Baker et al., Phys. Rev. Lett. 97, 131801 (2006). In the next two years we aim to improve the sensitivity of the apparatus to \(\sigma(d_n) = 2.6 \times 10^{-27} \, \text{e·cm} \) corresponding to an upper limit of \(d_n < 5 \times 10^{-27} \, \text{e·cm} \) (95\% C.L.), in case for a null result. In parallel the collaboration works on the design of a new apparatus to further increase the sensitivity to \(\sigma(d_n) = 2.6 \times 10^{-28} \, \text{e·cm} \).

1. Introduction

The coexistence of a permanent electric, and magnetic dipole moment of the neutron, intrinsically violates both \(T\) and \(P\) symmetry, and assuming \(CPT\) conservation also \(CP\). The Standard Model (SM) of particle physics gives a satisfactory account for \(P\)-violation in weak interactions mediated by charged (\(W^\pm\)) and neutral (\(Z^0\)) weak currents as well as for \(CP\)-violation in the decay of K- and B-mesons. However, this source of \(CP\)-violation is far too weak to explain the observed baryon asymmetry of the universe. The discovery of a neutron electric dipole moment could thus help to explain and may even solve this discrepancy. The electroweak SM predicts a neutron electric dipole moment (nEDM) at \(d_n = 10^{-32} \, \text{e·cm} \). This sensitivity is beyond current experimental techniques, hence any experimental sign of an nEDM will also be a sign of physics beyond the Standard Model. Our collaboration pursues this quest in two overlapping phases:

- In a first step we will measure with an upgraded version of the original RAL/Sussex/ILL spectrometer. This apparatus is using UCN in vacuum at room temperature and delivered the last and most stringent limit so far on the nEDM of \(d_n < 2.9 \times 10^{-26} \, \text{e·cm} \), C.L. 90\%[Baker et al., 2006]. This result was statistically...
limited by the available UCN density at the Institut Laue Langevin (ILL). The new UCN source at Paul Scherrer Institute (PSI), now ramping up, will provide \( \sim 25 \) times higher UCN densities. Together with an improved control on systematic effects using both, localized and large area magnetometers will result in a sensitivity of \( \sigma(d_n) = 2.6 \times 10^{-27} e\cdot cm \).

- In parallel, an entirely new apparatus (n2edm) is being designed. It will make optimal use of the high UCN density of the PSI source, and will have an improved active and passive magnetic shielding. This will improve the upper limit to \( d_n < 5 \times 10^{-28} e\cdot cm \), C.L. 95% in the case of a null result.

### 2. Experimental Method

The electric dipole moment \( d_n \) of the neutron is measured by comparing the neutron precession frequency \( \omega_n \) in parallel (\( \uparrow \uparrow \)) and anti parallel (\( \uparrow \downarrow \)) electric \( E \) and magnetic field \( B \) configurations:

\[
h \omega_{n, \uparrow \uparrow} / \omega_{n, \uparrow \downarrow} = 2 \cdot |\mu_n B \pm d_n E|,
\]

where \( \mu_n \) is the magnetic moment of the neutron. Taking the difference of both measurements allows us to deduce the electric dipole moment:

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

The statistical sensitivity for measuring \( d_n \) is then given by:

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

where \( N \) is the number of neutrons, \( E \) the strength of the electric field, and \( \alpha = \alpha_0 e^{-\Gamma T} \) the neutron polarization at the end of the cycle. The polarization depends on \( \alpha \), the product of initial polarization and analyzing power, and the transversal depolarization rate \( \Gamma \). Increasing the UCN density by a factor 25 with the new UCN source and slightly improving \( \alpha \), \( T \), and \( E \) gives the goal sensitivity of \( \sigma(d_n) = 2.6 \times 10^{-27} e\cdot cm \) in 400 nights.

However, the sensitivity of the measurement is dominated by the second term of Eq. 2, the stability of the magnetic field in both configurations. Obviously, a very sensitive measurement of the magnetic field in the neutron precession region would allow to correct for the second term. Such a cohabiting large area magnetometer was first implemented in 1997 by the RAL/Sussex/ILL collaboration in the current experimental apparatus Baker et al. [2006]. It uses polarized \(^{199}\)Hg atoms precessing within the neutron precession chamber, for a description in more detail see Ref. Green et al. [1998].

However, severe systematic effects arising from magnetic field gradients within the precession chamber cannot be compensated for by a co-magnetometer. Due to their small kinetic energy, the centers of mass of UCN and of mercury atoms is separated by \( \Delta h = 2 - 3 \text{ mm} \). In a perfectly homogeneous magnetic field this would still make no difference, however in vertical magnetic field gradient the mercury atoms and the UCN will sense and average differently the magnetic field. Therefore, an array of 12 Cs optically pumped magnetometers (Cs-OPM) have been adapted to the special needs of the experimental apparatus, including vacuum and high-voltage compatibility Knowles et al. [2009]. It will give us an extra handle on systematic effects correlated to vertical magnetic field gradients.

### 3. The RAL/Sussex/ILL apparatus at PSI

Figure 1 is a sketch of the RAL/Sussex/ILL apparatus installed at the new UCN source at PSI. Neutrons come in from the left and are polarized to 100% by a 5 T superconducting solenoid. They are then guided through a UCN switch upwards into the precession chamber. Once an equilibrium UCN density has built up the UCN shutter on the bottom electrode is closed. Now a shutter is opened for 2 s such that polarized \(^{199}\)Hg atoms can also fill the chamber. Neutrons and \(^{199}\)Hg atoms are polarized parallel or anti parallel to the main vertical magnetic field \( B_0 = 1 \mu T \). First, the \(^{199}\)Hg atoms are spin flipped into the plain perpendicular to \( B_0 \), by
applying a \( \sim 8 \text{ Hz} \) \( \pi/2 \)-pulse, then the neutrons (30 Hz). Now both spin-1/2 species precess with their Larmor frequency within the precession chamber. After a time \( T \) a second 30 Hz pulse, in-phase with the first, is applied before the UCN shutter is opened. Meanwhile the switch has changed to a position connecting directly the precession chamber with the UCN detector. An iron foil in front of the detector together with an adiabatic spin flipping rf coil located further up stream allows to measure both spin states sequentially at the end of a cycle. Such a sequence of two neutron \( \pi/2 \)-pulses with the free precession time \( T \) in between is known as Ramsey’s method of separated oscillating fields and correlate the polarization measured with the free precession frequency and the frequency of the applied fields.

A circularly polarized light beam from a \(^{204}\text{Hg} \) discharge lamp (\( \lambda = 254 \text{ nm} \)) is used to polarize a vapor of \(^{199}\text{Hg} \) atoms by optical pumping in a cell adjacent to the main precession chamber. The \(^{199}\text{Hg} \) atoms dissociate from a solid \( \text{HgO} \) source heated to 200°C, and continuously fill the cell for the next Ramsey cycle.

A second circularly polarized light beam traverses the precession chamber and is used to read out the precessing frequency of the \(^{199}\text{Hg} \) atoms. Its intensity is measured by a solar-blind photmultiplier (PM). After application of the \( \pi/2 \)-pulse the precessing \(^{199}\text{Hg} \) atoms modulate the light intensity at the Larmor frequency of the precessing atoms proportional to the average magnetic field inside the chamber.

Twelve Cs-OPM, four high voltage compatible ones on the charged electrode the others beneath the ground electrode, measure the magnetic field throughout the cycle. Although the intrinsic sensitivity of the magnetometers is of the order of 10 \( \text{fT/Hz} \), technical noise and the magnetic environment presently limit the sensitivity to \( \sim 1 \text{ pT/}\sqrt{\text{Hz}} \).

4. Systematic effects

Decreasing the statistical uncertainty by a factor five also requires to decrease uncertainties from systematic effects accordingly. This can be achieved by realistic technical modifications and upgrades [Altarev et al. 2009]. In the last two years we were trying to assess most of these systematic errors by measurements without neutrons. In the remainder of these proceedings we will focus in more detail on the uncompensated field drift and give just a brief status of systematic effects directly correlated with changing the polarity of the upper electrode:

Leakage currents which might flow from the charged top electrode to the ground electrode are monitored with a custom made A/V amplifier, protected by an in-house designed protection circuit. This device allows us to measure and monitor leakage currents with a resolution of some 10 \( \text{pA/}\sqrt{\text{Hz}} \). It was used during an intensive test.

Figure 1: Sketch of the present nEDM apparatus set up at the Paul Scherrer Institut.
Figure 2: False nEDMs from uncompensated field drifts, measured with two pairs of Cs-OPM (Cs1-Cs2: ◊, Cs3-Cs4: ○). The horizontal line is the weighted mean of the combined data sets. The dotted line indicate the weighted standard deviation.

5. Measurement of the uncompensated field drift

‘Uncompensated field drift’ refers to systematic effects which arise from higher order magnetic fields the mercury co-magnetometer can not completely compensate for. These drifts can arise from charging currents magnetizing parts of the apparatus while changing the polarity of the high voltage. This creates a change in the local magnetization and hence a change of the vertical magnetic field gradient $\Delta G = (\frac{\partial B}{\partial z})_{\uparrow\downarrow} - (\frac{\partial B}{\partial z})_{\uparrow\uparrow}$ dependent on the polarity of the high voltage. This effect yields a false nEDM signal of:

$$d_t = \left| \frac{\gamma_n}{\gamma_{Hg}} \right| \frac{h\omega_{Hg}\Delta h}{4EB_0} \Delta G. \quad (4)$$

In autumn 2010, we searched directly for a change in the vertical gradient of the magnetic field with four Cs-OPM. Always a pair separated by $\sim 20$ cm in height, one on the top electrode, the other below the bottom electrode, was taken as gradiometer (Cs1-Cs2, Cs3-Cs4). The magnetic background field was set to $B_0 \approx 1 \mu$T. The polarity of the electric field ($E = \pm 100$ kV) was changed every 350 s with the system’s maximum ramping speed of 1 kV/s. In Fig. 2 data sets for a false $d_t$ for both Cs-OPM pairs, taken during $\sim 70$ h, are shown.
A linear correlation analysis shows that both data sets can be combined. This first test gives a preliminary value of $d_\ell = 2.9 \pm 8.6 \times 10^{-27} \text{e}\cdot\text{cm}$. Our goal is to improve this value by a factor $\sim 10$ which seems possible in one week of measurements by optimizing the measurement sequence to 260 s (instead of 1100 s), increasing the maximum voltage to $\sim 120 \text{kV}$, and using four independent pairs of Cs-OPM. At the same time we will use an active compensation system around our apparatus to better compensate external magnetic field changes.

6. Conclusion and Outlook

While the new PSI UCN source is ramping up our collaboration is prepared to take first nEDM data in autumn 2011. During the winter shutdown of the accelerator we plan to continue our study of crucial systematic effects. By the end of 2013 we expect to have reached our required sensitivity through 400 nights of good quality data. This then would result in the case of a null result in a new upper limit of $d_n < 5 \times 10^{-27} \text{e}\cdot\text{cm}$ (95 C.L.). In parallel we are constructing the next generation apparatus.

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