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The neutron Electric Dipole Moment experiment at the Paul Scherrer Institute

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Abstract. The neutron Electric Dipole Moment (nEDM) is a probe for physics beyond the Standard Model. A report on the nEDM measurement performed at the Paul Scherrer Institute (Switzerland) is given. A neutron spin analyzer designed to simultaneously detect both neutron spin states is presented.

1. Introduction

The electroweak Standard Model (SM) of Particle Physics predicts a neutron Electric Dipole Moment (nEDM) at the level of $10^{-31-32}\,e \cdot \mathrm{cm}$, *i.e.* several orders of magnitude below the current best experimental upper limit $d_n < 2.9 \times 10^{-26}\,e \cdot \mathrm{cm}$ (90% CL) [1]. However, many extensions of the SM predict a nEDM just below the current experimental sensitivity in the $10^{-26} - 10^{-28}\,e \cdot \mathrm{cm}$ range [2]. The nEDM search is therefore an interesting probe for physics beyond the SM. At the new UCN source at the Paul Scherrer Institute (PSI) [3], our collaboration aims at improving the nEDM sensitivity by at least one order of magnitude in the next ten years. The experiment is at room temperature using UCNs in vacuum. At the moment, an improved version of the RAL-Sussex spectrometer [1, 4] from which the best nEDM upper limit has been achieved, is used. In the future, a new spectrometer will further improve the sensitivity.

2. Status of the nEDM measurement at PSI

The comissionning of the source has started in 2011. UCNs are produced by spallation in a Pb target with the PSI 2.2 mA proton beam. Produced neutrons are first thermalized in a heavy water volume and then cooled down to the UCN regime by phonon excitation in a 5 K solid ortho-deuterium. Then they are guided towards the nEDM apparatus and polarized by means of a 5 T superconducting magnet. There, they are stored in a precession chamber where electric and magnetic fields are applied. The UCN Larmor frequencies $\nu^{\uparrow\uparrow}$ and $\nu^{\uparrow\downarrow}$ for respectively parallel or anti-parallel magnetic and electric field configurations are measured using Ramsey's separated oscillating fields method (see [4] for details).

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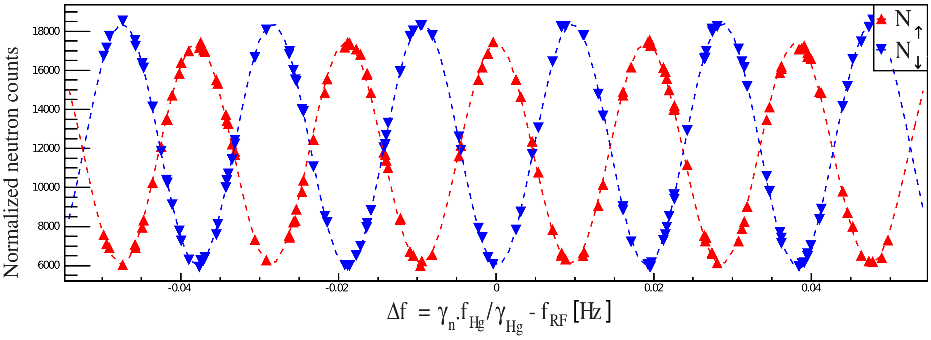

Figure 1. Ramsey pattern recorded at PSI in August 2013.

Table 1. Statistical sensitivity of the current spectrometer at PSI.

Mean values	E[kV/cm]	T [s]	N [10^5/day]	α [%]	σ_{d_n} [10^{-25} $e \cdot$ cm/day]
PSI 2012	7.9	200	8.1	57	4.0
PSI 2013	10.3	180	12.6	56	2.8

Spin up and spin down UCNs are counted and the neutron frequency is measured via a fit of the central fringe of the Ramsey pattern shown in Fig 1. The nEDM and its statistical sensitivity are given by:

$$|d_n| = \left| \frac{h(\nu^{\uparrow\uparrow} - \nu^{\uparrow\downarrow})}{4E} \right| \qquad \sigma_{d_n} = \frac{\hbar}{2\alpha E T \sqrt{N}} \tag{1}$$

where E is the applied electric field, α is the contrast of the central fringe (visibility), T the precession time and N the number of detected neutrons.

From 2012 to 2013, the daily statistical sensitivity has been improved from 4.0×10^{-25} to 2.8×10^{-25} $e \cdot$ cm (see Table 1). This is mainly due to larger applied electric fields and an icrease of the UCN source production of about 40%. With such performances, the expected reachable sensitivity amounts to 5.6×10^{-26} $e \cdot$ cm (95% CL) for 100 running days per year. Over the past two years, besides R&D efforts, 42 days of data have been taken. The data analysis is still ongoing.

As far as the systematic errors are concerned, the current estimation gives an induced false EDM $d_n^{\text{false}} = (0.6 \pm 2.0) \times 10^{-27}$ $e \cdot$ cm.

The PSI experiment has reached the same level of EDM statistical sensitivity per day as the experiment carried out at ILL from which the best limit has been achieved [1]. The next step is to improve the apparatus reliability in order increase the number of data taking days per year. Investigations are also ongoing in order to improve the initial UCN polarization with suited guiding fields, to increase the applied electric fields and the UCN density from the UCN source.

3. A new spin analyzer for the nEDM experiment

The current spin analyzing system is made of a magnetized iron foil and an upstream adiabatic spin-flipper (ASF). The analyzing foil lets only one spin component cross towards the detector. The ASF is switched ON (or OFF) to allow respectively the UCN spin up (or down) to be counted. The drawback of such a sequential analysis is that when a UCN spin component is analyzed, the other one is stored above the analyzing foil. As a result, UCN losses and depolarizations may occur, leading to a decrease of the statistical nEDM sensitivity. In order to reduce these problems, a new spin analyzing system has been designed using GEANT4-UCN [5] simulations to simultaneously detect the two neutron spin states. Such a technique had originally been pioneered in early EDM experiments at LNPI [6].

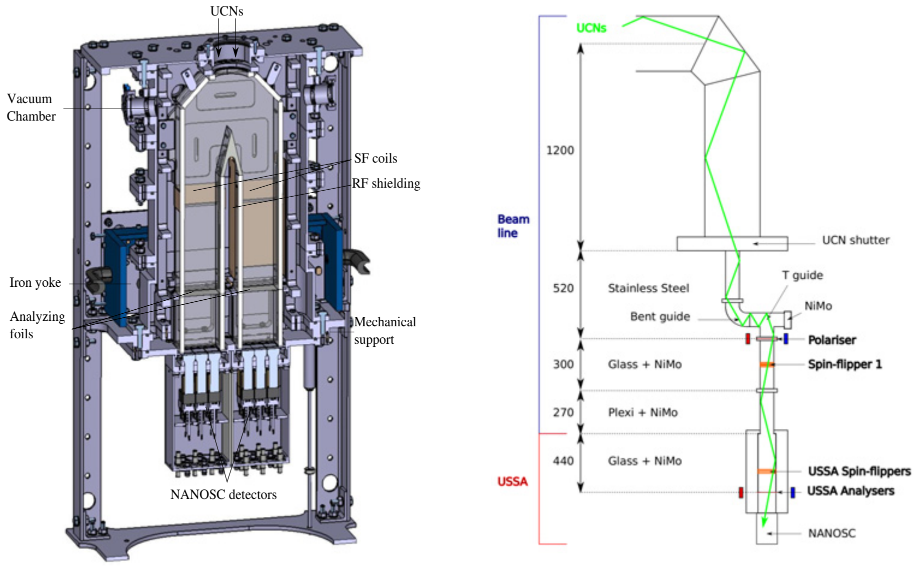

Figure 2. Left panel: vertical cut view of the USSA. Right panel: USSA experimental test setup.

3.1 Design of the simultaneous spin analyzer

A cut view of the U-shape simultaneous spin analyzer (USSA) is shown in the left panel of Fig. 2. UCNs enter at the top and fall down to the detectors into one of the two arms. Along their path, they bounce on the NiMo coated glass structure. Each arm is dedicated to the analysis of one spin component and is made of a spin analyzing foil, an ASF and a detector. The analyzing foils consist of a 25 μm aluminum substrate coated with a 400 nm sputtered iron layer. They are magnetized at about 2 T by a set of surrounding permanent magnets enclosed in a return yoke. ASF are made of one coil, wound around each arm, which produce an axial radio-frequency (RF) magnetic field. The transverse field is produced by the magnetizing system located downstream [7]. The spin down detection is performed in the arm with the ASF OFF, the spin up, in the arm with the ASF ON. RF cross-talk between the two arms is avoided using copper shielding (1 mm thick parallelepiped tubes) around each USSA's arm. Finally, UCNs are detected by two NANOSC detectors [8].

3.2 Experimental tests on the West2 beam line at PSI

A first USSA test has been performed on the West-2 beam line at PSI. The goals were to measure the transmission, the spin analyzing power, the spin-flipper efficiencies and the RF cross-talk between USSA's arms. The beam line setup is shown in the right panel of Fig. 2. UCNs come from the top, follow the bent and fall down into the USSA. A T-shape guide has been used in order to suppress the high UCN energy component. A magnetized iron foil is mounted below the T-shape guide for the UCN polarization.

The USSA spin-flipper efficiencies have been measured to be $\langle f_A \rangle = 97.0 \pm 1.2\%$ and $\langle f_B \rangle = 97.1 \pm 0.9\%$ respectively for the arms A and B. Possible RF cross-talk between the two arms has also been estimated. The number of detected UCNs in the non active arm (SF OFF) is not changed when the other spin-flipper is switched ON or OFF. The relative difference $\frac{N_{\mathrm{OFF}}-N_{\mathrm{ON}}}{N_{\mathrm{OFF}}}$ is consistent with zero: $0.15 \pm 0.62\%$.

The USSA analysis power has been measured to be $77.4 \pm 3.9\%$. This quite low spin analyzing power of the USSA can be explained by a high UCN energy component at the analyzers level.

Transmission measurements have been performed by replacing the USSA by a single NANOSC detector. The transmission is defined as the ratio between the number of detected neutrons with the USSA and the UCN neutron counts with a single NANOSC: $T = \frac{N(\text{USSA})}{N(\text{NANOSC})}$. These numbers are normalized with the number of detected neutrons by a Cascade detector mounted on the West-1 beam line. A transmission of $80.8 \pm 0.6\%$ has been measured.

4. Conclusions

Tests performed on the West-2 beam line at PSI have shown that all USSA subsystems work properly. As a result, the USSA will be installed below the nEDM spectrometer in order to quantify the possible improvement on the nEDM statistical sensitivity. In a next step, the NiMo coating could be replaced by diamond or ^{58}NiMo in order to increase the number of detected UCNs.

During the last two years, the PSI experiment has reached a daily nEDM statistical sensitivity of $2.8 \times 10^{-25}\, e \cdot \text{cm}$. Assuming 100 running days, a sensitivity of $5.6 \times 10^{-26}\, e \cdot \text{cm}$ (95% CL) could be reached per year. The false nEDM induced by systematic errors is estimated to $(0.6 \pm 2.0) \times 10^{-27} e \cdot \text{cm}$, which is low enough with respect to the current statistical sensitivity.

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