Search for the neutron electric dipole moment

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November 2019

Abstract. Many experiments are underway in the world to search for a non-zero electric dipole moment (EDM) of a particle with spin 1/2 such as the neutron or the electron. EDM measurements are motivated by the high sensitivity to new physics beyond the Standard Model. Finding an EDM would reveal new sources of CP violation. This is currently needed to explain the origin of the matter-antimatter asymmetry of the Universe. This document presents the theoretical motivations for such a search and the nEDM experiment at the Paul Scherrer Institute (PSI) in which two IN2P3 laboratories are involved.

1. Introduction

The Hamiltonian of a spin 1/2 particle in an electric field is

$$\hat{H} = -\vec{d} \cdot \vec{E} = -d \,\hat{\vec{\sigma}} \cdot \vec{E}, \tag{1}$$

where d is the permanent electric dipole moment of the particle. This definition holds for any elementary or composite particle. Hence, the EDM of a simple particle quantifies the coupling between the spin and an applied electric field, in the same way that the magnetic dipole moment quantifies the coupling between the spin and a magnetic field. The coupling in Eq. (1) causes the spin to precess around the electric field direction. The spin precession in an electric field allows the distinction of the past and the future. The existence of a non-zero EDM would therefore constitute a violation of time reversal symmetry.

Despite decades of experimental efforts, the EDM measurements of various particles are all compatible with zero. Permanent EDMs, if they exist, are extremely tiny. For example, the current limit on the magnitude of the neutron EDM is [1]

$$|d_n| < 3 \times 10^{-26}\, e\,\mathrm{cm}\ (90\%\ \mathrm{C.L.}). \tag{2}$$

In a large electric field of 10 kV/cm, it would take more - much more? - than 80 days for the spin precession to complete one full turn. For more details on the experimental effort, the reader should consult the following reviews [2, 3, 4].

This document recalls the relevance of the EDM quest in particle physics and cosmology in sections 2 and 3. Then it focuses on the experimental efforts performed in the neutron EDM search (section 4) and ends by the description of the neutron EDM experiment at the Paul Scherrer Institute (section 5).

2. Relevance of the EDM quest in particle physics and cosmology

The time reversal violating Hamiltonian In Eq. (1) arises from the non-relativistic limit of a quantum field theory Lagrangian of the form :

$$\mathcal{L}_{\mathrm{EDM}} = -\frac{id}{2}\bar{f}_L \sigma^{\mu\nu} f_R F_{\mu\nu} + h.c. \tag{3}$$

which couples to the electromagnetic field $F_{\mu\nu}$ to the left (f_L) and right (f_R) chirality components of the fermion through an imaginary coupling. It is therefore a CP-violating Lagrangian (equivalent to T-violating through the CPT theorem). In addition it is non-renormalizable and can only be generated by the effect of virtual particle loops.

Three sources of CP-violation in the standard model could create EDMs of fermions : the complex phases in the CKM and PMNS matrices and the strong phase θ_{QCD}. The neutron EDM is related to quarks EDM. The CKM contribution is strongly suppressed due to the flavour structure of the electroweak theory: only diagrams involving all three generations of quarks in the loops can contribute to the EDM. It is expected to be of the order of $d_n^{CKM} \sim 10^{-31}$ e.cm. In contrast, the strong phase induces in principle large hadronic EDMs. The non-observation of the neutron EDM

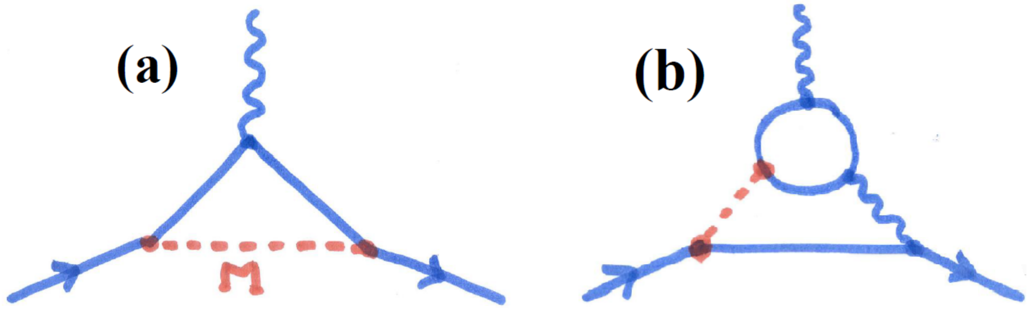

Figure 1. (a) Example of a one-loop diagram contributing to the fermion EDM. (b) Two-loop Barr-Zee diagram contributing to the fermion EDM.

results in the bound $|\theta_{\mathrm{QCD}}| < 10^{-10}$. The fact that the strong phase is measured to be unnaturally small constitutes the *strong CP problem*. It is believed that an unknown dynamics beyond the Standard Model is at play to set this phase to zero. EDMs are sensitive probes of CP violation effects beyond the Standard Model with practically zero background from the CKM phase.

Searching for new sources of CP-violation is of fundamental importance. First, this is a generic feature of models extending the SM, which inevitably come with additional complex (therefore CP-violating) free parameters. More compellingly, cosmology actually demands new CP violation sources to solve the baryon asymmetry puzzle. An appealing possibility, called *Electroweak baryogenesis*, poses that baryogenesis occurred at the electroweak phase transition epoch of the Universe, at a temperature of about 100 GeV (see Ref. [6] for a recent discussion on the subject). For baryogenesis to work, new CP-violating interactions must have been active at this temperature, therefore the mass of the new particles could not be much heavier than 1 TeV and and the CP-violating interaction they mediate should be sufficiently strong. The models therefore also predict sizable EDMs.

The simplest loop diagram generating a fermion EDM is presented in Figure 1 (a). It involves the virtual exchange of a heavy boson of mass M with a complex coupling $ge^{i\phi}$ to the fermion. It generates an EDM of $d \approx e\hbar c\, g^2/(4\pi)^2 \sin(\phi)\, m_f/M^2$. For a boson at the TeV scale ($M \approx 1$ TeV and $g^2/(4\pi) \approx 10^{-2}$) with maximal CP violation ($\sin(\phi) \approx 1$), we get $d \approx 10^{-25}\, e\,$cm for the lightest quarks ($m_f \sim$ a few MeV).

Another BSM example is given by CP-violating couplings of the Higgs boson h to fermions. The Higgs couplings are generically parameterized by the following Lagrangian

$$\mathcal{L}_h = -\frac{y_f}{\sqrt{2}} \left(\kappa_f \bar{f} f h + i\tilde{\kappa}_f \bar{f} \gamma_5 f h \right), \tag{4}$$

where y_f is the Yukawa coupling of the fermion f, κ_f and $\tilde{\kappa_f}$ are the CP-conserving and CP-violating coupling constants. The Standard Model predicts $\kappa_f = 1$ and $\tilde{\kappa}_f = 0$. This coupling generates EDMs though the two-loops diagram shown in figure 1 (b). Fundamental CP-violating couplings of order unity, relative to CP-conserving couplings, are already excluded except for the s quark, by combining limits on neutron EDM (sensitive to light quarks) and electron EDM (sensitive to heavy quarks).

Generic CP violation above the electroweak scale is positively detectable by EDM experiments and next generations of EDM experiments will push these limits down by an order of magnitude, constrain baryogenenis models or perhaps discover a signal induced by new sources of CP-violation.

3. Ab-initio theoretical calculations on the lattice

Calculating the neutron EDM from the quark EDMs and θ-term is a nonperturbative problem and a vivid topic of research in the lattice community. Powerful effective field theory methods allow to organize all possible effective CP breaking interactions on the sole basis of symmetry and dimension with no dependence on the unknown BSM theory. Current calculations are based on the the following extension of the QCD Lagrangian [36, 37]

$$\mathcal{L}_{\mathrm{QCD}} + i\theta \; G_{\mu\nu}\tilde{G}_{\mu\nu} + i\sum_q d_q^\gamma \; \overline{q}\sigma^{\mu\nu}\tilde{F}_{\mu\nu}q + \; i\sum_q d_q^G \overline{q}\sigma^{\mu\nu} \; \tilde{G}_{\mu\nu}q \; + d_G \, f^{abc}G^a_{\mu\nu} \; \tilde{G}^{\nu\beta,b}G^{\mu,c}_\beta,$$

containing the θ-term, quark EDMs and chromo-EDMs, and the Weinberg operator. Every lattice calculation starts from the contribution of the product of the electromagnetic current and the θ-term [38, 39]. Ideally the best way to compute such a matrix element would be to simulate the full theory in the presence of this CP breaking interaction added to the conventional action for QCD. These terms are known to be challenging to include in a lattice computation, and new approaches are being pursued to tackle this issue.

Computing the expectation value of the electromagnetic current between neutron states is already quite complicated due to the very small signal but could be conducted using promising novel methods of variance reduction. Once this contribution has been properly calculated, with all the necessary limits that are involved in the calculation duly taken into account, one could move to other BSM operators such as the last operator that is coined the Weinberg operator and it involves three insertions of the Yang-Mills field strength tensor. However, this operator is already much more complicated and its continuum limit should be taken with care due to mixing in the renormalization procedure. For more information on the recent efforts from the lattice community we refer the reader to Ref. [40].

4. The search for the neutron EDM worldwide

The history of neutron EDM search started in the 1950's (it was indeed the first EDM experiment). The basic idea is to use polarized neutrons and measure precisely the spin precession frequency f in parallel or anti-parallel magnetic and electric fields:

$$f = \frac{\mu}{\pi\hbar}B_0 \pm \frac{d}{\pi\hbar}E. \tag{5}$$

The EDM term can be separated from the much larger magnetic term by taking the difference of the frequency measured in parallel and anti-parallel configurations. The

EDM term is very small ($dE/\pi\hbar \approx 10^{-7}$ Hz for $d = 10^{-26}\, e\,\mathrm{cm}$ and $E = 15$ kV/cm) compared to the magnetic term (typically, $f = 29$ Hz for $B_0 = 1\,\mu$T). To detect such a minuscule coupling, one needs (i) a long interaction time of the neutrons with the fields, (ii) a high flux of neutrons and (iii) a precise control of the magnetic field. The first experiment by Smith, Purcell and Ramsey [7] used a beam of thermal neutrons passing in an electric field during $T \approx 1$ ms. Then, the precession time was greatly increased in the 1980's by using *ultracold neutrons* (UCNs). These neutrons can be stored in material traps because they undergo total reflection upon collision with the walls of the trap. The currently most precise measurement [1], performed at ILL in the period 1998-2002, used UCNs stored in a chamber during $T \approx 100$ s. Although the systematic error was a real concern, this measurement was mainly limited by the statistical error and thus by the intensity of the ILL/PF2 UCN source. During the last decade, several projects of new higher intensity UCN sources were launched worldwide. Most of them will start producing UCNs in the next few years. They are always coupled to an nEDM experiment [12, 14, 16, 17, 18, 19]. They aim at an improvement in sensitivity by a factor 10 to 100 compared to the previous measurement [1]. More details on nEDM searches can be found in the recent reviews [9, 10].

5. The nEDM project at PSI

The nEDM project at PSI was conjointly proposed with the development of a new intense Ultra Cold Neutron (UCN) source [13]. The source is now operating since 2011. The project is mainly organized in two phases. The first phase, nEDM, is over and will soon lead to a publication with a slightly improved measurement of the neutron EDM [8]. The second phase, n2EDM, is currently under construction and will start the data taking in early 2022 [14, 15]. Two IN2P3 laboratories, the LPC Caen and the LPSC, are participating to the n2EDM phase.

The goal of the n2EDM experiment is to measure the neutron EDM with a sensitivity of $10^{-27}\, e\,\mathrm{cm}$ in the next five years and then to explore the $10^{-28}\, e\,\mathrm{cm}$ range from 2025-2030. The experiment will be performed at room temperature with a stack of two precession chambers (see Fig. 2 for the description of the experiment core). The neutron frequencies will be simultaneously measured in the top and bottom precession chambers for both electric and magnetic field configurations. This feature allows to a considerable reduction of the influence of systematic effects. With respect to the first phase, the gain in statistical sensitivity will be achieved with a larger number of stored neutrons (the chambers are larger and the height difference between the UCN source output and the n2EDM spectrometer input is optimised). In addition, the electrodes arrangement (the HV electrode located is nearly insulated from the rest of the experiment) allows a 40 % higher electric field intensity to be reached.

The improvement of the statistical sensitivity comes along with a better control of the systematics. Most of them are related to the magnetic field uniformity and stability. Therefore, several parts of the apparatus are devoted to its control and/or monitoring. A

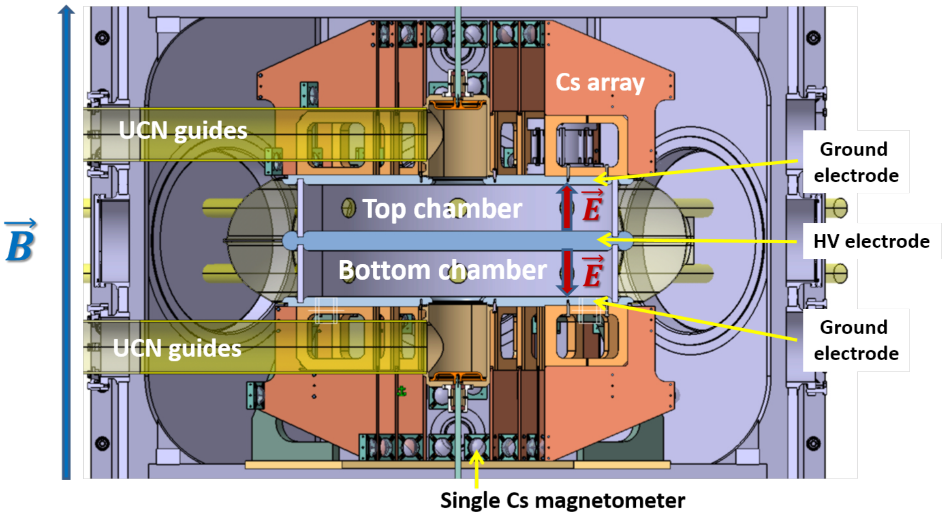

Figure 2. Scheme of the precession chambers stack. UCN are coming from the left and are stored in the top and bottom chambers where an electric and a magnetic fields are applied.

large magnetically shielded room (MSR) coupled to an array of coils (located outside of the MSR) will be able to suppress the external static and dynamic field components. In the MSR, a complex system of 64 coils was designed in order to produce a very uniform 1 μT magnetic field. The remaining field non-uniformities will be monitored by an array of 100 Cs magnetometers located around the precession chambers stack (see Fig. 2). In the chambers, a Hg co-magnetometer will record the magnetic field experienced by the UCN. Finally, offline magnetic field mapping will be performed before and after the data taking.

From 2025-2030, the experiment will be upgraded with larger precession chambers in order to further improve the statistical sensitivity. In addition, the use of a higher magnetic field close to 10 μT which allow the suppression of the main systematic effect [35].

6. Conclusion

The search for a non-zero fundamental electric dipole moment is an interdisciplinary field. The motivation comes from particle physics and cosmology. A possible reduction of the upper bound on the nEDM from ongoing and upcoming experiments and the possibility of measuring a nonzero value is one of the most challenging and interesting problems in nuclear and particle physics. It would allow for an explicit verification of the CP-symmetry larger than the one allowed by the SM. The calculation of matrix elements of CP-breaking operators from the lattice community will force stringent bounds on different BSM phenomenological scenarios. The diversity of the experiments together with the theoretical guidance promise exciting prospects for the future, and maybe a discovery of fundamental importance.

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