BALKAN PHYSICS LETTERS

19 May 2009
BPL, **17**, pp. 339 - 352, 17045 (2009)

Storage Ring EDM Method: A Direct, Sensitive EDM Probe for the Proton and Deuteron Nuclei

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Abstract. - Electric dipole moments (EDM) set the current limits of CP-violating parameters and if discovered they can potentially solve the baryon asymmetry mystery of our universe. The storage ring EDM method, where polarized protons or deuterons are stored and have their spins monitored continuously as a function of time, provides the stage for the next generation EDM searches with a sensitivity below $10^{-29}\,\mathrm{e}\cdot\mathrm{cm}$. At this level they will be sensitive to new physics mass scale of order of 300 TeV. If there is SUSY-like new physics at the LHC scale, the sensitivity to CP-violating phase is at the 10^{-5} rad scale; a sensitivity level unparalled by any other experiment.

The electric dipole moments (EDMs) of fundamental particles have been searched for over fifty years without a hint of a non-zero value for any of them. Nonetheless they provide the current limits for CP-violation originating either from strong interactions or new physics beyond the SM. EDM searches started with N. Ramsey and E. Parcell [1] as a search for parity violation in nuclear interactions. Since then every decade has seen major advances in developing more sensitive EDM methods for both hadronic and leptonic systems.

The important stages in an EDM experiment are: 1) Polarization: It includes the preparation of the system of interest with a well defined state and as high intensity as possible. 2) Interaction with an electric field: The effective electric field needs to be the highest possible for the longest possible time, requiring long spin coherence times (SCT). 3) Analyze: High efficiency analyzer with high analyzing power is needed. 4) Physics interpretation of the result: It is easier for the simpler systems.

1. EDM Motivation

The physics at the frontier of science is accomplished by pursuing: a) The energy frontier, with the Fermilab's Tevatron collider being currently at the top, while the large hadron collider (LHC) at CERN/Geneva is about to push this frontier to new limits. LHC, with a mass scale reach of about 1 TeV has the potential to discover the Higgs particle, possibly new physics like, e.g., supersymmetry (SUSY) and/or extra dimensions or other new physics accessible at that energy. b) The precision frontier on the other hand provides a complementary approach to the search of physics beyond the standard model (SM), which many times is orders of magnitude more powerful than the direct approach. The deuteron and proton EDM experiments have a physics reach of 300 TeV or, if there is new physics at the LHC scale, they probe CP-violating phases at the level of 10μrad, an unprecedented sensitivity level.

Since EDMs are not very sensitive to the CP-violation rising from the SM, any observation of an EDM of a fundamental particle would mean the existence of physics beyond the SM. EDMs of hadronic systems like, e.g., the neutron, deuteron, proton, etc. are, in addition, sensitive to possible CP-violation originating from strong interactions. CP-violation is important because it is needed to explain the baryon asymmetry of our universe (BAU). In the history of our universe after the big bang, the disappearance of the anti-matter remains a mystery. If a non-zero EDM value of a fundamental particle is observed it will contribute to the solution of the baryon anti-baryon asymmetry mystery of our universe.

1.1 The EDM connection to CP-violation and the matter domination in our universe

Charge separation, i.e. EDM, exists all around us and we are accustomed to observe it in many systems. Electric dipole moments of fundamental particles, when connected to the spin of the particles, are of fundamental importance. The spin vector $\vec{\sigma}$ of the particle defines a unique direction and the EDM vector needs to be along the same direction. The EDM vector then becomes: $\vec{d} = d\hat{\sigma}$, with $\hat{\sigma}$ the unit vector along the spin vector. What this equation implies is that the EDM vector is locked to a specific direction, that of the spin. In such a case, a permanent EDM violates both the time (T) and parity (P) symmetries. This is evident when one considers the interaction energy (H) of the particle's EDM in the presence of an electric field (E):

$$H = -d\hat{\sigma} \cdot \vec{E} \rightarrow \text{applying } T \rightarrow -d(-\hat{\sigma}) \cdot \vec{E} = d\hat{\sigma} \cdot \vec{E}\,, \qquad (1)$$

and

$$H = -d\hat{\sigma} \cdot \vec{E} \rightarrow \text{applying } P \rightarrow -d\hat{\sigma} \cdot (-\vec{E}) = d\hat{\sigma} \cdot \vec{E}\,, \qquad (2)$$

In both cases, after the application of T or P symmetry the interaction energy changed sign, which means that either the EDM (d) is zero or the symmetries are violated.

Under the assumption of the combined CPT (including charge (C)) symmetry conservation, T-violation implies CP-violation. CP-violation is one of the three conditions required to enable the universe containing equal amounts of matter and anti-matter to evolve into the matter dominated universe we observe today[2].

CP-violation has been discovered[3] at BNL in 1964 in the kaon system and recently in the B-system and one would think the issue is over. However, the CP-violation source originating from the CKM matrix, responsible for the observed CP-violation in weak interactions, is not nearly enough to explain the observed BAU of our universe of 10^{-9}. Theoretical models based on the weak interaction CP-violation produce an asymmetry of only 10^{-18}. Hence, a much stronger source is required and EDMs could point to it.

Most models beyond the SM like, e.g., SUSY, Multi-Higgs, Left-Right Symmetric, etc., predict EDM values within the sensitivity of current or currently planned experiments. Combined with the fact that the EDMs originating from the weak interactions (CKM) are negligible, EDMs are indeed ideal probes of CP-violation beyond that originating from the CKM matrix.

1.2 EDMs of neutrons, protons and deuterons

An EDM in hadronic systems can rise from various sources: 1) Quark electro-magnetic (EM), 2) Color (chromo) EDMs and/or 3) from the CP-violating parameter theta-QCD ($\bar{\theta}$). The first two contributions would have to be beyond the SM sources, e.g. SUSY, while the third one is part of the strong interactions theory within the SM.

The QCD Lagrangian includes a CP-violating parameter, theta-QCD:

$$L_{CPV} = \bar{\theta}\frac{\alpha_s}{8\pi}G\bar{G} \tag{3}$$

from which we can estimate within an order of magnitude the neutron EDM:

$$d_n(\bar{\theta}) \approx \bar{\theta}\frac{e}{m_n}\frac{m_*}{\Lambda_{QCD}} \approx \bar{\theta}\cdot(5\times10^{-17})\,\mathrm{e\cdot cm} \tag{4}$$

with

$$m_* = \frac{m_u m_d}{m_u + m_d} \tag{5}$$

the reduced mass of the up and down quarks. $\Lambda_{\rm QCD}$ is the QCD scale and m_n the neutron mass. When the estimation is done more precisely[4, 5] it becomes

$$d_n(\bar{\theta}) \approx \bar{\theta}\cdot(3.6\times10^{-16})\,\mathrm{e\cdot cm} \tag{6}$$

The present neutron EDM limit[9] of $3\times10^{-26}\,\mathrm{e\cdot cm}$ results to a limit on theta-QCD: $\bar{\theta}\leq 10^{-10}$. It is estimated[4, 5, 7] that the deuteron EDM has one third the neutron sensitivity (for the same nominal EDM limit) to theta-QCD and at $10^{-29}\,\mathrm{e\cdot cm}$ the deuteron would be sensitive down to $\bar{\theta}\leq 10^{-13}$.

On the other hand the quark electromagnetic (EM) and Color (chromo) EDM Lagrangian allows for CP-violation and the neutron, proton and deuteron EDM values are[4, 5, 7, 8] different combinations of quark and chromo-EDMs and thus complementary. Regarding the isovector part of the quark-chromo EDM the deuteron has

The physics strength comparison for a few hadronic EDM systems showing the current limit, future goal and the neutron equivalent of the future goal all in [e·cm] units.

System	Current limit	Future goal	Neutron equivalent
Neutron	$< 1.6 \times 10^{-26}$	10^{-28}	10^{-28}
^{199}Hg atom	$< 3 \times 10^{-29}$		$10^{-25} - 10^{-26}$
^{129}Xe atom	$< 6 \times 10^{-27}$	$10^{-30} - 10^{-33}$	$10^{-26} - 10^{-29}$
Deuteron nucleus		10^{-29}	$3 \times 10^{-29} - 5 \times 10^{-31}$
Proton nucleus	7×10^{-25}	10^{-29}	$4 \times 10^{-29} - 2.5 \times 10^{-30}$

20 times the neutron sensitivity. This has to do with the special structure of deuteron where a neutron and a proton can be held together by T-odd nuclear forces.

Therefore if the neutron EDM experiments discover a non-zero EDM value, let's say at $10^{-28}\,\mathrm{e}\cdot\mathrm{cm}$, then if the source is theta-QCD the expected deuteron EDM value would be $d_D \approx 3 \times 10^{-29}\,\mathrm{e}\cdot\mathrm{cm}$. However, if SUSY is the EDM source and in particular the isovector part of the interaction, then the expected value would be $d_D \approx 2 \times 10^{-27}\,\mathrm{e}\cdot\mathrm{cm}$. Recently, W. Marciano presented[8] the case for the deuteron, proton, and neutron EDM experiments making the point that the three experiments together, with EDM sensitivity of $10^{-28}\,\mathrm{e}\cdot\mathrm{cm}$ each, can pin-point the CP-violating source should one of them discovers a non-zero value. Even if the neutron EDM experiments do not find a non-zero EDM value, the storage ring EDM experiments should go forward since they are more sensitive than the neutron in general, and for some T-odd interactions, they are better by a couple of orders of magnitude.

The physics motivation[8] for the deuteron EDM (dEDM), and proton EDM (pEDM) at $10^{-29}\,\mathrm{e}\cdot\mathrm{cm}$ is

1. $\bar{\theta}$: The current sensitivity is $\bar{\theta} \leq 10^{-10}$, with dEDM it will become $\bar{\theta} \leq 10^{-13}$, and with pEDM $\bar{\theta} \leq 3 \times 10^{-14}$.

2. Sensitivity to new contact interaction is at the 3000 TeV level.

3. Sensitivity to SUSY-type new physics:

$$d \approx 10^{-24}\,\mathrm{e}\cdot\mathrm{cm} \times \sin\delta \times \left(\frac{1\mathrm{TeV}}{M_{\mathrm{SUSY}}}\right)^2 \tag{7}$$

   At $10^{-29}\,\mathrm{e}\cdot\mathrm{cm}$ sensitivity level they have a reach of about 300TeV for SUSY-type new physics or, if new physics exists at the LHC scale, a sensitivity to CP-violating phases of 10^{-5}rad; an unprecedented sensitivity level.

Other hadronic systems are studied, like the ^{199}Hg atom and the ^{129}Xe atoms. However, due to the shielding of the nucleus by the atomic electrons their effectiveness are severely diminished. Table 1 shows the current limit, future goal and the neutron equivalent of the future goal for several hadronic systems[8].

In summary, the deuteron and proton EDMs are complementary to the neutron EDM and in certain occasions (isovector part of the T-odd nuclear forces) the deuteron has better sensitivity to CP-violation by an order of magnitude for the same nominal EDM value. Together the deuteron, proton and neutron can pin-point the CP-violating source. EDMs have high sensitivity to non-SM CP-violation with negligible contribution from the CKM CP-violating phase. If an EDM is observed it will significantly help explain the BAU mystery of our universe.

2. Storage ring EDM method

A dedicated storage ring EDM experiment for the proton and deuteron are very powerful. There are high intensity (a few 10^{11} particles /measurement cycle) polarized ($> 80\%$) sources already well developed and readily available. The analyzing power for 1 GeV/c (250 MeV kinetic energy for the deuteron) is very high, close to 0.5 for a detection efficiency of 1%. Long spin coherent time in accelerators are possible using well understood techniques.

The spin precession in a magnetic field is given by (in MKS units)

$$\omega_s = \frac{g}{2}\frac{eB}{m} \tag{8}$$

If the particle is stored in a magnetic storage ring its cyclotron angular frequency is given by

$$\omega_c = \frac{eB}{m} \tag{9}$$

In the non-relativistic case the difference between the spin precession rate and the cyclotron precession rate is

$$\omega_a = \omega_s - \omega_c = \frac{g}{2}\frac{eB}{m} - \frac{eB}{m} = \left(\frac{g-2}{2}\right)\frac{eB}{m} \Rightarrow \omega_a = a\frac{eB}{m} \tag{10}$$

with a the anomalous magnetic moment of the particle; ω_a is the angular g-2 precession frequency. It should be noted that the same equation holds for the relativistic case. In addition, ω_a is independent of momentum, for a specific particle it only depends on the magnetic field value. As we will see later when an electric field is involved, the spin precession depends strongly on momentum.

The success of the muon g-2 experiment[10] has a lot to do with the simplicity of eq. 10. The accuracy with which the anomalous magnetic moment can be determined depends only on the accuracy of ω_a, B and e/m. Clearly the magnetic field determination is easier if the B-field where the muons circulate is as uniform as possible. A storage ring without field gradient does not have a good capture efficiency. It was understood[11] that electric field gradient could work well if the muon momentum was at about 3.1 GeV/c, the so called muon "magic" momentum. The electro-static quadrupoles needed to be pulsed[12, 13] in order to avoid low energy electron trapping, but it allowed for the current impressive measurement[10], demonstrating an impressive 0.5 ppm (part per million) sensitivity. This was made possible because at some muon "magic" momentum radial electric fields have the same influence to the muon spin as they do to the muon momentum, and thus canceling each other.

2.1 The spin precession rate in a radial electric field depends on the particle momentum

In contrast to a magnetic field orthogonal to the momentum vector, where the g-2 precession rate is independent of the muon relativistic γ-factor, the radial electric field effect on the g-2 precession rate is strongly dependent on it. This is a purely relativistic effect, the radial E-field is partially transformed into a magnetic field in the muon's rest frame depending on the muon's velocity. For a non-relativistic muon the effect of the radial E-field on the momentum is larger than the effect on its spin. For a highly relativistic muon, the radial E-field looks like a magnetic field where the spin precession leads the momentum. There is a momentum in between where the effect on the spin and momentum are equal. When the E-field is included, eq. 10 becomes

$$\vec{\omega}_a = \frac{e}{m}\left[a\vec{B} + \left[a - \left(\frac{m}{p}\right)^2\right]\frac{\vec{\beta}\times\vec{E}}{c}\right] \tag{11}$$

At $P = \frac{m}{\sqrt{a}} = 3.1$ GeV/c the effect of the E-field on the muon spin and momentum are equal and cancel as shown in Fig. 1. The last two muon g-2 experiments[11, 10]

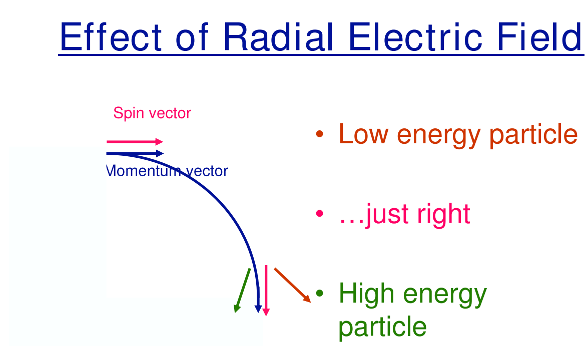

Figure 1: A longitudinally polarized muon beam is injected into a region where there is a radial E-field present. At the end of the field region, the spin of the muon may lead, trail or be aligned with the momentum vector depending solely on the value of the momentum.

run at the muon "magic" momentum of 3.1 GeV/c, where the spin and momentum vectors are kept aligned as a function of time in the presence of a radial electric field. Due to finite muon momentum spread there is a small correction of order 0.5 ppm and negligible uncertainty[10, 13] that needs to be applied to the experimental value obtained from the observed muon g-2 frequency. If the experiment was performed at a different momentum with the intend to apply a correction due to the radial E-field the uncertainty in the correction would be way too large compared to the statistical error.

2.2 Indirect, storage ring muon EDM method as part of the g-2 experiment

We have seen that electric dipole moments couple only to electric fields and magnetic dipole moments only to magnetic fields. The best way to understand the role of the electro-magnetic fields to the dipole moments of a particle is to transform the lab-frame fields to the rest frame of the particle. When this is done it becomes clear that even a purely magnetic field will couple to the EDM of the particle if the particle has a non-zero velocity value. The total result of B and E-fields as measured in the lab frame on the spin precession turns out to be

$$\vec{\omega}_{ae} = \frac{e}{m}\left[a\vec{B} + \left[a - \left(\frac{m}{p}\right)^2\right]\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)\right] \tag{12}$$

where η plays the same role for the EDM as the g-factor plays in the magnetic dipole moment case and it is equal to

$$\eta = \frac{m}{e}\frac{4dc}{\hbar}, \quad \eta = \frac{m}{e}\frac{2dc}{\hbar} \tag{13}$$

for spin 1/2 particles (like the muon and proton) and for a spin 1 particles (like the deuteron) respectively.

Running at the magic momentum, eq. 12 becomes

$$\vec{\omega}_{ae} = \frac{e}{m}\left[a\vec{B} + \frac{\eta}{2}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)\right] \tag{14}$$

then, assuming $\vec{E} \ll c\vec{\beta}\times\vec{B}$, it becomes

$$\vec{\omega}_{ae} = \frac{e}{m}\left[a\vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B}\right)\right] \Rightarrow \vec{\omega}_{ae} = \vec{\omega}_a + \vec{\omega}_{edm} \tag{15}$$

and the two effects due to a possible non-zero EDM value become obvious: 1) The g-2 frequency becomes

$$\omega_{ae} = \omega_a\sqrt{1 + (\frac{\eta\beta}{2a})^2} \tag{16}$$

and 2) the spin precession plane is tilted by an angle $\eta\beta/2a$ everywhere around the ring. Specifically the tangent of the angle is equal to

$$\tan\theta = \frac{\omega_{edm}}{\omega_a}. \tag{17}$$

The muon spin precession plane is tilted by an angle proportional to the particle's EDM value. The tilt is highest for small g-2 frequencies.

The significance of this effect is that the spin precession plane is tilted everywhere around the ring, very much like there is a net radial magnetic field integrated around the ring that is not zero. In a ring with purely magnetic field for a stored particle the average radial B-field is zero (the particle adjusts its vertical position to ensure this). However, in the presence of other forces, like vertical E-fields, gravity, etc., this is not strictly true and has to be taken into account for systematic error estimation. A major tool against this type of systematic errors is the clock-wise (CW) and counter-clock-wise (CCW) injections where the non-magnetic forces are kept the same while the EDM signal changes sign.

2.3 Frozen spin method

One way to improve the sensitivity of the storage ring EDM method is to reduce the ω_a since, as is indicated by eq. 17, the tilt angle of the spin precession plane becomes larger. The g-2 spin precession rate can be manipulated at will by using radial electric fields as equation 12 suggests. With some algebra it can be shown that the radial E-field required to frieze the muon spin is

$$E = \frac{aBc\beta\gamma^2}{1 - a\beta^2\gamma^2} \simeq aBc\beta\gamma^2 \tag{18}$$

The maximum sensitivity of the experiment is obtained when the g-2 frequency is reduced to nearly zero, hence the name "frozen spin" method. There are two different variations of the method, depending on the value of the anomalous magnetic moment, one for large values and one for small.

Large and positive anomalous magnetic moment case

A storage ring with purely electric field can be used for an EDM experiment. Eliminating the B-field from eq. 12, it becomes

$$\vec{\omega}_{ae} = \frac{e}{m}\left[\left[a - \left(\frac{m}{p}\right)^2\right]\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\frac{\vec{E}}{c}\right] \tag{19}$$

The g-2 (i.e. in plane) spin precession can be made zero at a momentum[14]:

$$p = \frac{m}{\sqrt{a}} \tag{20}$$

which for any particle other than the electron it means that for the ring size to remain within affordable limits the anomalous magnetic moment needs to be large. For the proton ($a = 1.8$) the magic momentum is 0.7 GeV/c. Recent advances in achieving large electric field gradients[15] using high pressure water rinsing (HPR) combined with the fact that proton beam emittances can be very effectively cooled using electron cooling, makes this method very promising.

HPR has been used in the past to enhance the effective E-field in RF cavities. The method has now been applied to enhance the E-field gradient in DC applications by a factor of two to three over previous limits. The electric field sustainable between two plates depends on the distance d between them, and follows a $1/\sqrt{d}$ rule[16]. Assuming 15MV/m for a 2cm plate separation the ring circumference (including the straight sections needed for instrumentation) would be of order of 200m.

Small anomalous magnetic moment case

In the small anomalous magnetic moment case or when its value is negative like, e.g., it is $a = -0.143$ for the deuteron, a combined E and B-field case is applied. Even though the radial electric field used is $E \simeq aBc\beta\gamma^2$ the effective E-field (i.e. the rest frame E-field devided by γ) acting on the EDM is $\vec{E} + c\vec{\beta} \times \vec{B}$. It can be shown that the effective E-field $E_1^* - EF \times E$ with EF the enhancement factor given by

$$EF = \frac{1}{a\gamma^2}\,(1+a) \tag{21}$$

Clearly the method is better for smaller a. The enhancement factor can be significant and in the deuteron case it is about a factor of five (see section on statistics).

Dedicated deuteron EDM experiment with $10^{-29}\,\mathrm{e\cdot cm}$ sensitivity

A longitudinally polarized deuteron beam will be stored in the EDM ring with combined dipole magnetic and radial electric fields (BE-sections). The fields will be tuned so that the spin will remain frozen in the horizontal plane during the storage time of about 10^3 s. Small horizontal spin precession will be allowed for systematic error studies. If there is an EDM, the motional electric field, i.e. the rest frame electric field will act on it and will precess the spin out of plane. A polarimeter based on elastic nuclear scattering off ^{12}C nuclei, will continuously monitor the spin precession in both the vertical and horizontal planes. The scattering target will be about 5 cm long placed at one specific azimuthal location and will be the limiting aperture. We will be using a controlled mechanism for increasing the emittance of the beam as a function of time to maximize the EDM sensitivity. One way to extract the beam is by adding white noise on the beam emittance using stripline electrodes mounted in a straight section of the ring. The polarimeter consists of a solid target made out of ^{12}C, where the deuterons elastically scatter before they are captured by the detector designed to detect particles scattered by 3-20 degrees off the forward direction. The electric field will be 120 kV/cm for a 2 cm aperture and the magnetic field will be 0.5 T for 1 GeV/c deuterons (see eq. (18)). Several straight sections will be interleaved between the BE-sections with focusing and de-focusing quadrupoles as well as sextupoles. The sextupoles are used to prolong the spin coherence time of the beam to about 10^3 s. Two long straight sections, about 9 m in length, will be located on either side of the ring for the injection kickers, polarimeters and a beam transfer focusing de-focusing (FODO) quadrupole magnet system. Sextupole magnets are used to cancel the second order effects responsible for the finite spin coherence time of order of 1 s. A fine-tuned sextupole magnet system should be able to prolong it to about 10^3 s, based on similar experimental work at Novosibirsk[17].

The vertical spin polarization as a function of time is

$$\Delta P_V = P\frac{\omega_{\mathrm{edm}}}{\Omega}\sin\left(\Omega t + \theta_0\right) \tag{22}$$

where

$$\Omega = \sqrt{\omega_{\rm edm}^2 + \omega_a^2} \tag{23}$$

and θ_0 the angle between the spin direction and momentum vector. Clearly, the vertical polarization development is maximum when the g-2 frequency is minimized and θ_0 is either 0 or π.

The main ingredients of the deuteron EDM experiment are:

Polarized deuteron source that is capable of producing high intensity (few 10^{11} particles/cycle), highly polarized beam ($> 80\%$). The beam will be accumulated and bunched in the booster and accelerated to 1 GeV/c. In the AGS it will undergo modest cooling resulting to a vertical emittance (95%) of 5π mm-mrad, a horizontal emittance 3π mm-mrad and a maximum momentum spread (base) $\Delta P/P = 10^{-3}$. The bunch is then injected into the EDM ring where the beam polarization will be kept horizontal for maximum sensitivity.

A polarimeter based on elastic nuclear scattering off ^{12}C nuclei has the best average efficiency (better than 1%) and an asymmetry of $\simeq 40\%$. Data[18] based on deuteron scattering off a solid ^{12}C target shows large asymmetry and efficiency values. Two separate bunches with opposite polarization will be stored per ring. The EDM signals from the two bunches will be opposite and they will be used to minimize the polarimeter systematic errors.

The spin coherence time (SCT) of an un-bunched beam would be of order of 10 ms due to momentum spread. A normal-conducting RF-cavity will be used to keep the beam bunched so that, on average, the particle momenta will be kept nearly the same bringing the SCT closer to 1 s. Second order effects originating from finite transverse motion and second order momentum related effects will be corrected for by using sextupole magnets located at specific places around the ring with a target goal for SCT of 10^3 s.

The average vertical E-field is a major systematic error. The force due to that field would be compensated by a radial magnetic field from the focusing system, which will also precess the spin out of plane resulting to an EDM-like signal. We are planning to cancel this effect by clock-wise (CW) and counter-clock-wise (CCW) consecutive injections into the storage ring. CW and CCW will only work if the beam sees the same E-fields and this requirements sets the specifications on the vertical E-field uniformity and stability. The required E-field plate parallelism is of the order (on average) of 10^{-7} rad. We are planning to use a trolley to measure the relative distance between the two plates with nm level resolution. It is currently possible to measure relative distances with sub-nm resolution, using capacitive measurements[19, 20].

Storing particles CW and CCW will require flipping the B-field direction while the E-field direction remains the same. We will be monitoring the E-field plates using very high resolution Fabry-Perot resonators especially to make sure the plate distance is not influenced by the magnetic field direction[7].

The effect of geometrical phases possible due to the non-exact local g-2 spin precession. For this error to become small there is a requirement of very good E and B-field alignment and good local matching to reduce the g-2 precession in every BE-section. The local B & E-field cancellation requirement is of order of 10^{-4}, which can be accomplished by shimming the fields in order to match them along the azimuth. Storing particles CW and CCW also cancels this effect as long as they remain the same.

Dedicated proton EDM experiment with $10^{-29}\,\mathrm{e}\cdot\mathrm{cm}$ sensitivity

From eq. 19 it is clear that at the magic momentum of 0.7 GeV/c for the proton the spin will be frozen independent of the E-field value as long as the average momentum is kept constant to the correct value. In order to eliminate the vertical E-field background we will still have to inject CW and CCW. The focusing of the system is still based on magnetic quadrupoles since the elimination of small stray magnetic fields would be very strict otherwise and very expensive to achieve. When magnetic focusing is used and in the absence of vertical forces, the average radial B-field seen by the particles is zero, if the particle is stored.

The differences in running protons and deuterons are: 1) For the protons we only need a radial electric field whereas for the deuterons we need combined E & B-field sections with their field intensities matched well. 2) There is a need to flip the dipole magnetic field for CW and CCW deuteron injections, which is absent for the protons. 3) A sensitive (state of the art) Fabry-Perot resonator is needed for the deuteron run to ensure that flipping the B-field does not influence the E-field direction in a systematic way. For the proton run there is no need for such sensitive Fabry-Perot resonator development. 4) The local g-2 phase cancellation is much easier in the proton case since we only need to deal with the E-field plates. 5) The proton polarimeter is simpler (only vector polarization) as compared to the deuteron that has both vector and tensor components. 6) The estimated ring circumference for the proton is about 200 m, much longer than the estimated 85 m for the deuteron case. 7) The physics sensitivity of the proton EDM is generally somewhat smaller than the deuteron EDM (see table 1). 8) Running costs for the proton are smaller due to the absence of the dipole B-field magnets. 9) Overall it will take less effort, resources and time to develop the experiment for the proton EDM than for the deuteron.

Statistics

The statistical sensitivity of the experiment depends on the time dependence of the collected data and the time constants of the machine cycles compared to the lifetime of the particle and/or the spin coherence time. Since the muon lifetime is much shorter and that of the deuteron and proton much longer than the time constants of the accelerator cycles we distinguish two different cases in analyzing the statistical sensitivity of the storage ring EDM experiments.

It turns out that the statistical uncertainty of the muon EDM is

$$\sigma_d = \frac{1}{2}\frac{\hbar}{\tau P A E_1^* \sqrt{N_{\mathrm{tot}}}} \tag{24}$$

P is the polarization, A the analyzing power, E_1^* is the rest frame electric field divided by the relativistic Lorentz factor γ, and τ is the particle lifetime in the lab-frame. $N_{\rm tot}$ is the total number of particles detected over the duration of the experiment.

The statistical error for the proton (spin 1/2) at the magic momentum is given by (assuming an extraction rate proportional to the instantaneous stored population-a more optimum extraction rate is possible and is under study)

$$\sigma_d = \frac{4\hbar}{PAE_1^*\sqrt{N_{\rm tot,c}T_{\rm tot}\tau_p}} \tag{25}$$

for the protons and for the deuteron (spin 1)

$$\sigma_d = \frac{8\hbar}{PAE_1^*\sqrt{N_{\rm tot,c}T_{\rm tot}\tau_p}} \tag{26}$$

where $N_{\rm tot,c}$ is the total number of particles detected per machine cycle. $T_{\rm tot}$ and τ_p is the total time the experiment is run and the polarization lifetime respectively.

The rest frame electric field divided by γ for the proton case is equal to the lab-frame electric field. For the deuteron case the rest frame E-field divided by γ is equal to

$$E_1^* = \beta c B - E\ , \tag{27}$$

due to the negative sign on the anomalous magnetic momentum of the deuteron, i.e. the radial electric field reduces the overall effective E-field. Taking into account eq. 18 the effective E-field becomes

$$E_1^* = E\left[\frac{1}{a\gamma^2}\,(1+a)\right] \simeq -4.7 \times E \tag{28}$$

for 1 GeV/c deuterons.

Let's assume the following parameters for the proton and deuteron EDM experiments: 1) Polarization lifetime is 10^3 s. 2) The asymmetry observed by the polarimeter $A = 0.5$ for 0.7 GeV/c protons and $A = 0.4$ for 1 GeV/c deuterons. 3) The beam polarization at injection into the EDM ring $P = 0.8$. 4) The number of particles per cycle $N_{\rm tot,c} = 4 \times 10^{11} \times f$, with f the detector detection efficiency. 5) The total measurement time $T_{\rm tot} = 10^7$ s per year. 6) The efficiency of the polarimeter $f = 0.01$, which will multiply the number of particles injected into the ring to obtain the number of detected particles. 7) The lab frame electric field 15 MV/m for the proton and 12 MV/m for the deuteron[1].

The total statistical error then becomes $\sigma_d \simeq 5.5 \times 10^{-30}\,\mathrm{e\cdot cm}$ per year for the deuteron. The deuteron EDM ring will have combined E&B sections in about 60% of the ring and therefore the error needs to be divided by the same factor, and it

[1]In the deuteron case we assume the presence of the dipole magnetic field will restrict the maximum E-field we will be able to deliver to the plates but this may not prove to be true in practice.

will become $\sigma_d \simeq 0.9 \times 10^{-29}\,\mathrm{e} \cdot \mathrm{cm}$ per year. For the proton case we will have $\sigma_d \simeq 7 \times 10^{-30}\,\mathrm{e} \cdot \mathrm{cm}$ per year. The working lattice for the proton has an electric field coverage of about 80% so the sensitivity becomes ame efficiency for the ring coverage with E-field plates we will have $\sigma_d \simeq 0.9 \times 10^{-29}\,\mathrm{e} \cdot \mathrm{cm}$ per year.

3. Final remarks

I regard knowing both Professor Engin Arik and the Ph.D. student O. Berkol Dogan my privilege and honor.

I met Engin in the summer of 1994 at CERN when I was a fellow working with the SMC collaboration. Engin was a very active member of the SMC collaboration and she visited for the summer accompanied by many of her students from Turkey. I remember her warmth and delight with which she reacted to me being of Greek origin. Right there and then she set the tone of our collaboration. She is responsible for me getting to know and become a very close friend with one of her students, Cenap Ozben, currently an associate professor at Istanbul Technical University, and had the opportunity to learn about modern Turkey. In that regard I owe her a great deal. She made me recognize that in every place and country of the world there is a constant struggle going on regarding ideas and ideology and sometimes one side wins over the other. But the struggle goes on all the time. Her vision was to see Turkey an integral part of modern Europe. She was dynamic, smart, full of positive energy. Her untimely loss is a great loss for Turkey, for the Balkans, for Europe and for all of us. We sorely miss her.

Berkol was a member of the CAST experiment at CERN and I still remember him as the nicest person I met in my life. I did my Ph.D. thesis on axions and I still remember the excitement working in a very hard but very rewarding topic. When I met Berkol I recognized the enthusiasm and hard work he was putting in the project. He had a very promising future. I felt him like my younger brother and really cared about him. But life was very unfair to him and his family. I hope Berkol's loving family finds courage from the fact that his short life was nonetheless full of enthusiasm, hard, honest, pioneering work and the fact that his kindness affected many people.

May their memory be everlasting.

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