Abstract. The current limits on physics beyond the SM come in large part from the non-observation of EDMs in the sensitive electric dipole moment experiments, like the neutron, $^{199}$Hg, and $^{205}$Tl. New systems with enhanced EDM sensitivity are coming online and promise a resolution of the baryon asymmetry of our universe (if an EDM is observed) or a severe constraint on physics beyond the SM by the end of the current decade.

1. Introduction
Our traditional approach to physics at the frontier is dual: 1) Energy frontier with FNAL until recently and currently CERN playing that role and 2) The precision Frontier with experiments like the muon g-2, electric dipole moment experiments, B-factories, etc. Those approaches are complementary and inter-connected. The next standard model (SM) is likely to emerge with input from both; it certainly has to accommodate observations from both approaches. Currently, one of the most intriguing indications of physics beyond the SM is the discrepancy of the experimental value of the muon g-2 value from the theoretically predicted value [1]. The discrepancy is of order of 3.5 standard deviations. For those enthusiasts prescribing to super-symmetry (SUSY) it would mean a neutralino mass range of 0.1 TeV – 0.5 TeV depending on the value of tanβ, the ratio of the vacuum expectation value of the two Higgs doublets.

SUSY as well as most of the beyond the SM models (BSM) happen to predict a large electric dipole moment with the current experimental limits being embarrassingly restrictive. So, even though we may have an indication of SUSY from the muon anomalous magnetic moment measurement we also have an anti-indication of SUSY from the current experimental limits on the electric dipole moments of fundamental particles, like the electron, neutron, proton, Mercury, etc. [2]. Certainly clever theorists could accommodate the EDM non-effect for specific SUSY models. So far the fine-tuning needed for this accommodation is of order $10^{-2}$ so the next round of EDM experiments will probably observe a non-zero value for the first time, or SUSY is in serious trouble. The next round of EDM experiments are set to increase their sensitivity level by about one order of magnitude (Mercury), to two orders of magnitude (neutron), to three orders of magnitude (proton and Deuteron), up to four orders of magnitude for the most ambitious electron searches. The time scale for the searches range is about three years (Mercury) to 10 years (deuteron and electrons) with the neutron and proton direct searches between those two extremes. The next decade is indeed promising to be very exciting with all the new opportunities opening up for breaking the EDM mystery.
The EDM searches commenced with two pioneers who set to look for parity violation in what was called then nuclear interactions [3] more than fifty years ago. As they stated their motivation “The question of the possible existence of an electric dipole moment of a nucleus or of an elementary particle … becomes a purely experimental matter”. They couldn’t be more correct even today, after several orders of improvement in the EDM experimental limits. After the discovery of parity violation Landau pointed out [4] that a particle EDM requires parity as well as time violation to be allowed. Assuming CPT conservation, T-violation also means CP-violation, which is believed to play an important role in our own existence and so EDM searches are even more motivated.

Ramsey and Purcell started their EDM search with the neutron in the fifties by applying an electric field and looking for the interaction energy between the E-field and the neutron EDM. In the sixties sensitive EDM searches on electrons started using specially prepared atomic systems. In the seventies an indirect storage ring EDM method was used to put a limit on the muon EDM. In the eighties people came up with systems (polar molecules) with large enhancement factors, which could provide enough sensitivity to the electron EDM. In the nineties we saw the first attempts to utilize the new methods with large enhancement factors as well as the first dedicated Storage Ring EDM method fully developed. Since then, several storage ring EDM lattices were developed for the proton and deuteron with sensitivity at the $10^{-29}$ e·cm level probing physics at the 3000 TeV scale for contact interactions and 300 TeV for SUSY-like new physics.

2. Theoretical Motivation
In quantum mechanics (QM) a non-degenerate system with spin is defined by its spin vector. If the particle has an EDM, its vector needs to be aligned with its spin vector, locked to its direction:

$$\vec{d} = d\hat{\sigma}$$

(1)

It needs to be either along the same direction or opposite but not both (non-degenerate) [5]. It is then and only then that the EDM of a particle with a spin violates both parity (P) and time (T) symmetries.

A permanent EDM violates both the time and parity symmetries:

$$H = -d\hat{\sigma} \cdot \vec{E} \rightarrow H = -d(-\hat{\sigma}) \cdot \vec{E} = d\hat{\sigma} \cdot \vec{E}$$

$$H = -d\hat{\sigma} \cdot \vec{E} \rightarrow H = -d\hat{\sigma} \cdot (-\vec{E}) = d\hat{\sigma} \cdot \vec{E}$$

(2)

From CPT conservation we have that T-violation also means CP-violation. CP-violation is important because it is a fundamental requirement to enable a universe initially containing equal amounts of matter and antimatter to evolve into a matter-dominated universe we see today [6]. CP-violation was discovered [7] at BNL in 1964 in the K-long decays by Jim Cronin, Val Fitch et al., and was confirmed in the decays of B-mesons. However, this CP-violation as was established to be described very well by a single complex phase in the CKM matrix [8], part of weak-interactions CP-violation, is way too small to account for the observed asymmetry of the matter-antimatter in our universe by several orders of magnitude. The ratio of the observed baryons to photons is

$$\frac{n_B}{n_\gamma} \approx 10^{-10}$$

(3)

whereas the expected level from the complex phase in the CKM matrix of the SM is only at the $10^{-18}$ level. A new CP-violating source is surely needed and EDMs could provide it.
EDMs are excellent probes of physics beyond the SM since most models predict values within the sensitivity of currently planned experiments: Those are SUSY, Multi-Higgs, Left-Right symmetric, etc. The SM contribution is negligible, with a caveat. There is an irony in the last statement, in that the quantum chromodynamic (QCD) part of the SM is actually predicting a much larger CP-violation than the current experimental limit from the neutron EDM. The CP-violating term in the QCD Lagrangian

\[ L \approx \frac{\alpha}{8\pi} G \tilde{G} \]

violates both parity and time symmetry, with \( \tilde{\theta} \) (theta-QCD) an angular parameter of order one. However, the current neutron EDM limit [9] of \( 10^{-26} \, \text{e} \cdot \text{cm} \) sets a very severe limit on \( \tilde{\theta} < 10^{-10} \). Since the value of \( \tilde{\theta} \) was expected to be of order one and the current limit is ten orders of magnitude less than that it is all but ignored! One way out of this issue is the solution of Peccei and Quinn [10] making it into a dynamical parameter that naturally takes a zero value. The breakdown of this symmetry gives rise to a particle dubbed the axion [11]. The only problem with this solution is that no axion is found yet, so even this so-called theta value should be treated as a purely experimental matter. Therefore if an EDM found it could potentially come either from the theta-QCD term or from some physics beyond the SM. The only way to tell the source is to probe the EDM value of several particles with different combination of CP-violating contributions. The complex phase of the CKM matrix of the SM contributes an EDM at the level of \( 10^{-31} \cdot 10^{-32} \, \text{e} \cdot \text{cm} \) for the neutron and proton and at the level of \( <10^{-38} \, \text{e} \cdot \text{cm} \) for the electron.

3. Experimental Approach
In the particle rest frame electric dipole moments couple only to electric fields and magnetic dipole moments couple only to magnetic fields

\[ \frac{d\vec{s}}{dt} = \vec{a} \times \vec{E} + \vec{\mu} \times \vec{B} \]

making the first complication apparent right away: even though one can study the magnetic moment of a charged particle at rest in a magnetic field, doing the same in an electric field is challenging. For this reason the first attempt to probe the EDM of a particle was focused on the neutron, which even though is neutral it does have a magnetic moment. A small magnetic field was applied to keep the neutrons polarized and precessing at a specific frequency. Then a very strong electric field was applied along the B-field direction and the neutron precession frequency was compared for two opposite electric field directions:

\[ d = \frac{\hbar (\omega_1 - \omega_2)}{4E} \]

which for \( d \) equal to \( 10^{-28} \, \text{e} \cdot \text{cm} \), \( E = 200 \, \text{kV/cm} \) implies an angular rotation frequency of \( 10^{-7} \, \text{rad/s} \) or about one turn per year.

The statistical error is of the EDM value (\( d \)) is
\[ \sigma_d = \frac{bh}{EPA\sqrt{N} \tau T} \]  

where \( b \) is a numerical factor of order one depending on the details of injection, machine/measurement cycle time, \( P \) is the polarization at the start of the experiment, \( A \) is the analyzing power of the detection mechanism, \( N \) is the number of particles per particular measurement cycle, \( f \) is the detection efficiency, \( \tau \) is the polarization lifetime and \( T \) is the duration of the experiment.

3.1. Important issues in an EDM experiment

- **Polarization**: Preparation of the particular state, and intensity of beams
- **Interaction with a strong E-field**: The larger the field the better
- **Analyzer**: The detection efficiency and analyzing power are critical elements of the statistical sensitivity
- **Scientific interpretation of the result**: A simpler system makes the theoretical interpretation of any experimental result easier. A complicated system can even create disputes as to what it means and makes even harder to pin down the various CP-violating sources.

Of course any non-zero EDM observation that can satisfy Norman Ramsey’s criteria for his $5K award\(^1\) will be revolutionary and that may be well worth it.

3.2. EDM methods

One can distinguish various methods originating mainly from the specific particles those methods are applied to: neutrons, atomic and molecular systems, and storage ring EDM method for charged particles directly. In the neutron case one applies a small (holding) magnetic field, and a large E-field and probes the frequency shift with the E-field vector flipped. In the atomic and molecular systems one probes atomic and molecular transitions and compares them in different combinations of E and B-field directions. In the storage ring method one utilizes the rest-frame E-field of a moving particle in an electro-magnetic storage ring. Since the rest frame E-field is mostly in the radial direction keeping the spin along the momentum vector maximizes the sensitivity of the method. The EDM signal is the change of the vertical spin component as a function of time. Vertical here is defined as the plane perpendicular to the g-2 precession plane at the location of the polarimeter detector.

The recent advances of the various methods are: There have been improvements in reducing the effects of the stray magnetic fields, by applying spin dressing to equalize the neutron spin precession with the spin precession of the co-magnetometer, e.g. \(^3\)He. Another improvement is the higher ultra-cold neutron (UCN) densities that were made possible recently using a new production method. The projected neutron production should make possible using \(~10^6\) neutrons per measurement cycle.

In atomic/molecular systems there has been a continuous exploration of systems capable of providing an equivalent electric field between 1-100 GV/cm, in which case even a small number of molecules could be enough to provide the needed sensitivity for up to \(10^{-30}\)e.cm.

In the field of storage ring EDM systems, it turns out that \(10^8\) particles could be readily detected per measurement cycle. High electric fields in the lab frame are available as a result of extensive R&D for the international linear collider (ILC) and energy recovery linacs (ERL). Since polarized

\(^1\) Norman Ramsey announced a reward for $5K for anyone who detects a non-zero EDM in any system, and it is generally accepted as such. Additional criteria include that he needs to be alive when the discovery is made, and that he understands the method.
protons and deuterons were already utilized for other reasons at various accelerators around the world, the required tools have already been extensively developed.

The weaknesses of the various EDM methods can be summarized for the neutrons: Intensity is still an issue since eventually the experiment will be statistics limited. There is also high sensitivity to stray magnetic fields which has to be measured by other means to very high accuracy and finally the motional B-fields and geometrical phases are critical.

In atomic and molecular systems it is the intensity of the desired states that has plagued this development, and certainly in some systems the physics interpretation is the biggest obstacle.

For the storage ring EDM methods, depending on the particular method they are very sensitivity to either a net vertical E-field around the ring or a net radial B-field that could cause a problem.

Overall statistical sensitivity is critical, i.e. number of particles and spin coherence time and of course systematics originating from spurious magnetic fields, geometrical phases, etc. This is a very challenging field that a typical experimental cycle is ten to fifteen years, while the researchers tend to be intelligent with wide range of expertise and not hesitant to tackle tough problems.

3.3. Neutron EDM experiments

The current neutron EDM limit is $3 \times 10^{-26} e\cdot cm$ (90% C.L.) comes [9] from an experiment at ILL at Grenoble. Low energy neutrons from the reactor are guided in a vertical tube against gravity; where a so-called neutron turbine knocks them down to very slow velocities, see Fig. 1.

![The ILL reactor](image)

Figure 1. The ILL reactor with its neutron EDM experiment.
The new ultra-cold neutron (UCN) experiment at ILL, detail shown in Fig. 2, is going to use a superfluid helium bath of 0.5 K and improve the neutron density by a factor of 50. It also expects to improve the electric field strength by a factor of 4-6 and achieve longer spin coherence time. Overall it’s expected to achieve a factor of $\sim 10^2$ better sensitivity than the present neutron EDM limit.

A neutron EDM experiment at PSI is underway which uses the old ILL apparatus and the neutron spallation source available at PSI with a goal of improving the sensitivity by an order of magnitude over the current limits. With further improvements in statistics and neutron production procedure they plan to improve the limit by almost another order of magnitude [12].

A neutron EDM experiment is also underway at the spallation neutron source (SNS) at Oak Ridge National Laboratory in the US, using several pioneering techniques as proposed by Golub and Lamoreaux [13]. A large helium bath volume of $\sim 10^3$ lt. at 0.4 K with a dilution refrigerator is utilized. The previous UCN were in the tail of the Maxwell-Boltzmann distribution of cold neutrons resulting to densities of 5 UCN/cm$^3$. The new method, suggested first by Golub and Pendlebury [14], uses neutrons that are produced by thermal down scattering in superfluid $^4$He bath where they excite a phonon and lose $\sim 1$ meV of energy. After the neutron falls in the lowest energy state, momentum and energy conservation requirements are not favored for re-exciting it into the higher energy state. The method has been applied in a small scale and it has produced the promised improvements in UCN densities. Figure 3 below shows the free neutron and $^4$He dispersion curves.
Figure 3. The dispersion of the free neutron and that of $^4$He lattice cross at one specific point. A 1meV neutron can transfer its energy to the helium lattice with no further chance of interacting with it.

Another innovation in the method is the use of polarized $^3$He mixed-in with the superfluid $^4$He in a small concentration ratio of $\sim 10^{-11}$. The reason for this is that the UCN density is too small to be detected with a SQUID magnetometer. The cross section of the reaction

$$\tilde{n} + ^3\text{He} \rightarrow t + p + 764 \text{ keV}$$

(8)

depends very strongly on the relative direction between the spin of the neutron and that of $^3$He. In addition, the ratio of the magnetic moments of $^3$He and of the neutron is 1.11, i.e. they only differ by $\sim 10\%$ thus reducing the sensitivity to spurious magnetic fields by a factor of $\sim 10$. Special techniques, like spin dressing have also been developed by the collaboration to further reduce the background magnetic field sensitivity. The current timeline of the various neutron EDM experiments is shown in Fig. 4 below.

Figure 4. The neutron EDM experiments at ILL, PSI and SNS are planning to improve the experimental sensitivity by up to two orders of magnitude within the current decade.
3.4. EDM experiments in atomic/molecular and polar systems

A fundamental difference between magnetic dipole moment experiments and electric dipole moment experiments is the fact that a uniform magnetic field would not move a stationary charged particle whereas an electric field would. To look for an EDM of a charged particle, like the electron and the proton one has to come up with ways to balance the electric field force without cancelling the effect due to the particle EDM. At the beginning Ramsey and Purcell claimed that the EDM of a charged particle is difficult to probe. A free electron for example would get lost on the walls of the electric field plates right away, whereas in an atomic system with electrons it would be shielded by the atomic electrons. The average E-field it sees should be zero, otherwise it would move. Schiff and then Sandars came up with exceptions [15] to this rule, like relativistic effects could play a role and even though the average E-field is zero, the total EDM effect is non-zero. Another exception is the effect of the finite size of a nucleus, where again the total E-field on the nucleus is zero, but the EDM effect on the atom is finite.

A review article on this effect is published recently by Commins, Jackson, and DeMille [16], where they state that a heuristic explanation of this effect is the fact that the electric dipole moment of the electron changes its length when it’s Lorentz transformed from the electron to the atomic center-of-mass frame. The EDM length contraction depends on the electron’s velocity and the total (integrated) interaction energy of the electron EDM with the electric field is not zero when averaged over its path.

In paramagnetic atoms (with an unpaired electron in an $s_{1/2}$ or $p_{1/2}$ orbit) it is possible to get a large enhancement factor on the atomic EDM compared to the electron EDM. The enhancement factor is

\[ R \approx 10Z^3 \alpha^2 \]  

(9)

which can be larger than one for heavy atoms. For a Thallium atom it is estimated [17] to be -585. The current limit on the electron EDM, using thallium atoms [18] $^{205}$Tl is

\[ d_e < 1.6 \times 10^{-27} \text{e}\cdot\text{cm}, \text{90\% C.L.} \]  

(10)

In diamagnetic atoms (no unpaired electrons), like $^{199}\text{Hg}$ there is no enhancement factor. Rather there is a so-called Schiff-moment, which is of order of 10$^{-5}$ for $^{199}\text{Hg}$, i.e. an EDM limit on the atom corresponds to a limit 10$^3$ larger for the nucleus EDM. The (table top) experiment utilizes a laser beam to polarize and probe the spin precession frequency to be compared for different E-field orientations. The holding B-field is 22mG, the E-field ~20 kV/cm, while the B-field drift is taken out by utilizing a number of cells in close proximity, with different combination of E and B-field orientations. The reported limit [19] is

\[ \left| d \left( ^{199}\text{Hg} \right) \right| < 3.1 \times 10^{-29} \text{e}\cdot\text{cm}, \text{95\% C.L.} \]  

(11)

which is a factor of 7 improvement over the previous limit. The estimated total systematic error is 60% of the statistical error, so this experiment is mostly systematics limited. This experiment also sets the current (indirect) limit on the proton EDM of <10$^{-23}$e cm. An improvement of about a factor of 3-5 is expected at the end of the current round of experimental efforts.

There is a large effort to improve the sensitivity to the electron EDM by enhancing the effective E-field on the electron. This enhancement factor is achieved in several polar molecules: YbF, PbO, ThO, PbF, HBr, BaF, HgF, etc. Several times those fields are really impressive, e.g. up to 100 GV/cm in the combined paramagnetic molecule (radical) of Fr (paramagnetic atom) and Sr (diamagnetic...
atom). All these new efforts have in common the fact that the learning curve is very long like every new EDM effort has proven to be. Progress in the EDM experiments of Rn, Ra, and Xe is ongoing with large expectations.

3.5. Sensitive storage ring EDM experiments
In the face of all these EDM experiments it is natural to ask why the world needs another EDM experiment and a yet another method. It turns out the (indirect) storage ring EDM method has been with us for more than fifty years as a byproduct of the muon g-2 experiment [20]. Even in a storage ring with a pure magnetic field the particle in its own rest frame feels the presence of a very strong electric field. This is proportional to $\vec{v} \times \vec{B}$ and hence it is directed in the radial direction. For 1 T magnetic field this electric field is equivalent to 300MV/m. If there is a muon EDM then, this strong electric field would contribute to the spin precession in two ways [21]: 1) it would tilt the spin precession plane, and 2) it would alter the apparent g-2 spin precession rate. The vertical beam polarization change is described by the equation

$$\Delta P_y = P \frac{\omega_j}{\Omega} \sin(\Omega t + \theta)$$

(12)

with

$$\Omega = \sqrt{\omega_j^2 + \omega_a^2}$$

(13)

the total spin precession frequency, $\omega_j$ the spin precession frequency due to the muon EDM, and $\omega_a$ the spin precession frequency due to the muon anomalous magnetic moment.

What happened lately is to actually focus on the EDM itself and optimize the experimental conditions for it [22, 23, 24] utilizing the first from the two options given above. It is clear from eq. (12) that the vertical beam polarization buildup rate is maximized when $\omega_a$ is set very close to zero. In this extreme case the spin precession plane is completely vertical, instead of the horizontal we are accustomed to due to the g-2 precession alone. The $\omega_a=0$ can be accomplished in various ways depending on the value of the anomalous magnetic moment of the particle as it will become clear from the g-2 equation in an electromagnetic field:

$$\tilde{\omega}_a = -\frac{q}{m} \left\{ a\tilde{\alpha} + a - \left( \frac{m}{p} \right)^2 \frac{\tilde{B} \times \tilde{E}}{c} \right\}$$

(14)

with $q$, $m$ the charge, and mass of the proton, and $a$ its anomalous magnetic moment. For a positive $a$ and in the absence of magnetic fields one can easily see that there is one momentum, the so-called magic momentum $p = \frac{m}{\sqrt{a}}$ where $\omega_a$ would be zero independent of the electric field value. For a negative anomalous magnetic moment ($a$) there is no such momentum and one needs to include a combination of magnetic and electric fields. It turns out that it is possible to achieve very high sensitivity by using polarized deuterons ($a=-0.143$) or protons ($a=1.79$). The reasons for this high sensitivity are:

1) High beam intensities ($10^{10}$-$10^{11}$) per machine cycle, with high beam polarization (>80%), and low emittance are readily available.

2) Spin coherence times of order $10^3$’s are possible.

3) Large E-fields for large area electrodes are possible (100-200 kV/cm)

There is also another multiplying factor of $\gamma$, but this is cancelled when we estimate the spin precession rate in the lab frame.
4) High efficiency (~1%), and high analyzing power (50%) polarimeters are available for protons and deuterons around the momentum of interest of 1GeV/c.

As a matter of fact polarized proton beams have been utilized around the world to probe spin related physics and the developed expertise is quite extensive. The storage ring EDM collaboration has developed two proposals [23, 24] both claiming a sensitivity of $10^{-29}$ e\cdot cm for the deuteron and proton bare nuclei. The same method can also be applied to other particles, like $^3$He and so on as long as there is a possibility to obtain a polarized beam and build an efficient polarimeter for it.

The main reason of the asymmetry between the B and E-fields and storage ring EDMs is the fact that in the presence of B-fields the g-2 precession frequency is velocity independent:

$$\tilde{\omega}_a = -\frac{q}{m} a \tilde{B}$$  \hspace{1cm} (15)

This is in contrast to the E-field case where the g-2 precession frequency is strongly dependent on the particle’s velocity:

$$\tilde{\omega}_e = -\frac{q}{m} a \left[ a - \left( \frac{m}{p} \right)^2 \right] \tilde{\beta} \times \tilde{E}$$  \hspace{1cm} (16)

This is a consequence of the fact that particle EDMs, even if they are not zero, they are very small, whereas magnetic moments are large and are dominating the g-2 precession frequency. In the case of a moving particle in an electric field the particle feels the presence of a magnetic field (from Lorentz transformation), which acts on the particle magnetic moment and causes its spin to precess. The reverse, a moving particle in a magnetic field feels the presence of an electric field, which acting on a possible particle EDM it can only have a minor impact in its g-2 precession frequency.

As we mentioned above, the sensitivity to EDM is maximum when the particle spin is kept aligned to the momentum vector during storage as is shown in Figure 5.

![Figure 5](image)

Figure 5. The optimum sensitivity to EDM is obtained when the spin is kept aligned with the momentum vector for the duration of the storage time.
The spin vector alignment with the momentum vector is going to be monitored with internal polarimeters sensitive to the transverse spin component of the beam [22, 23, 24]. If the transverse spin component is found to be larger than a pre-determined value, a feedback signal will be issued and a corrective action will take place. That means that there is a requirement to monitor the spin at all times during storage. Occasionally the spin will be let to rotate completely (multiples of $2\pi$) without a significant loss of sensitivity. The EDM signal is any change in the vertical component of the spin as a function of storage time. The way it shows up in the polarimeter detector is as a change in the ratio $(L-R)/(L+R)$, where $L, R$ correspond to the counts from the left and right counters respectively, see Figure 6.

![Figure 6](image_url)  

Figure 6. This is M.C. data showing how the data from the polarimeter would look as a function of time, when an appropriate ratio of the left (L) and right (R) detector counts is formed. The non-zero value of the slope of $(L-R)/(L+R)$ as a function of time is a clear indication of the change in the vertical spin component. The slope shown above corresponds to approximate five sigma EDM signal.

The statistical sensitivity of the proton EDM experiment is given in eq. (7) with $b=1.4$. The values of the parameters are: $E=10.5\,\text{MV/m}$, $A=0.6$, $P=0.8$, $N=4\times10^{10}/\text{p/cycle}$, $T_{\text{tot}}=10^{7}$s, and $f=0.5\%$. This results to $1.4\times10^{-29}\,\text{e} \cdot \text{cm/year}$, where 1 year is defined as $10^{7}$s. The collaboration expects to run one year to study the systematics and set a sensitivity goal of better than $10^{-28}\,\text{e} \cdot \text{cm}$, and another three years to collect more than enough statistics for $10^{-29}\,\text{e} \cdot \text{cm}$ sensitivity.

3.5.1 beam preparation. The proton beam is to be prepared at the polarized proton source location that already exists and operates at BNL. The protons are then accelerated in the LINAC and injected into the accumulator for further acceleration (up to the kinetic energy of 233 MeV) and bunching. The beam polarization is to be kept in the vertical direction until the beam is injected into the EDM ring of ~250m circumference. In the EDM ring the beam is let to de-bunch and then re-bunched by adiabatically turning on an RF system with harmonic $h=1$. At this point an RF-solenoid is turned on as well to precess the beam polarization vector from the vertical direction into the horizontal direction.
resulting to two bunches with opposite polarization for polarimeter systematic error considerations. At this point another RF-system turns on with harmonic $h=100$ as needed to keep the proton spins in the forward direction for the duration of the storage. When the average spin precesses too long to the left or to the right of the momentum vector, it will be noticed by the polarimeter detector as a change in the $(d-u)/(d+u)$, where $u$ and $d$ correspond to the up and down counters, and a feedback signal will be issued. Hence the longitudinal spin will be oscillating like a wind shield wiper, the opening angle of which will depend on the polarimeter statistics.

3.5.2 Systematic errors. The systematic errors of a typical EDM experiment include spurious magnetic fields and the so-called geometrical phase and are also present in the storage ring EDM experiments. Other effects include spin and beam dynamics resonances, which the collaboration plans to study both analytically and by using specially developed tracking software. The main systematic error for the proton at the magic momentum comes from spurious B-fields, especially a non-zero radial B-field.

A net radial B-field will induce a spin precession just like an EDM would. However, at the same time it would also split apart the counter-rotating beams. Sensitive BPMs are needed to be developed in order to probe that split. A net-radial B-field of 0.2pG could cause an EDM-like signal at the claimed sensitivity level. This magnetic field will cause a vertical split that depends on the vertical tune, i.e. the vertical betatron oscillation frequency divided by the revolution frequency as shown in equation below:

$$y = \sum_{N=0}^{\infty} \frac{\beta R_0 B_N}{E_0 \left(Q_v^2 - N^2\right)} \cos(N\theta + \phi_N) = \frac{0.6 \times 3 \times 10^5 \text{m/s} \times 40 \text{m} \times 0.2 \text{pG}}{10.5 \text{MV/m} \times 0.12} = 1 \text{pm} \quad (17)$$

where $Q_v = 0.1$ is the vertical tune, $N$ is the radial magnetic field harmonic number around the ring and $R_0$ is the ring radius. The numerical example is an estimation for $N=0$, i.e. the DC component. For $N=1$ the vertical shift is 10^2 times less. One way to detect this split is to place magnetometers around the ring that can sense the magnetic field due to this offset. To facilitate this observation the vertical tune can be modulated by ~10% at a specific frequency, in a region where the magnetic field noise is relatively small.

The geometrical phase effect stems from the fact that spin rotations don’t commute in three dimensions. When the particle spin rotates in, let’s say, first quarter of the ring with respect to the vertical axis, then in the second quarter of the ring it rotates with respect to the longitudinal axis, and then continue with spin rotations with respect to the vertical and longitudinal axes but in the opposite directions than in the first half of the ring the total effect is not zero. Even though the total magnetic field, vertical and longitudinal in this case, would add to zero when integrated around the ring, their effect on the spin is a net rotation with respect to the third axis, radial in this case. The strength of this effect has been estimated by Y. Orlov to be proportional to the product of the two spin rotations [23], i.e. second order. As long as the $N=1$ of the average vertical and longitudinal B-field components are below 1µG, this effect is much less than the claimed sensitivity level. From eq. 17 it is clear that the sensitivity to the $N=1$ for the vertical B-field will be much greater than needed to eliminate this systematic error.

Other systematic errors related to the beam modulation are under consideration, but so far the collaboration hasn’t found a show stopper. Special attention needs to be put on noise generated due to the RF and the quad modulation voltages around the ring, ground loops, etc. These kinds of systematic errors can be probed with the beam off and so they are easy to differentiate from the beam-induced signals. The collaboration had two technical reviews so far, one in December 2009 and one in March 2011. Both of them were great, producing a lot of good recommendations and, so far, no surprises. Every time the recommendation was to encourage the collaboration to continue this work. The collaboration is now eager to send the proposal to DOE.
4. Summary and Outlook
Clearly there have been major improvements in several fronts of searching for an EDM of a particular system. Two labs, BNL in NY and COSY in Jülich/Germany, are working towards proposals on the proton and deuteron EDM experiments respectively with high sensitivity. This decade promises to be the one that either observes or sets severe limits on popular extensions of the SM. Figure 7 shows that first we expect new results from the neutron and Hg systems. Since the CP-violating phases of physics beyond the SM are currently limited by the EDM experiments they may very well find a non-zero result already by 2015. It is expected that in the second part of the decade several new methods will start coming online and will be probing new territory. By the end of the decade the probability to discover a non-zero EDM value for one or several new systems is quite high.

Figure 7. The past experimental sensitivity as well as the expected sensitivity of several experimental methods is shown here. The various electron EDM efforts have a similar goal as the Xe, Rn and Ra efforts and at approximately the same time period. The physics reach of the different systems varies. At present, the physics limits are dominated mostly by the $^{199}$Hg, but also $^{205}$Tl (at $1.6 \times 10^{-27} \text{e} \cdot \text{cm}$ for the electron, see text) and neutron EDM results.

The physics sensitivity of Hg, and Xe suffers by a large factor of about $10^3$, whereas the electron EDM is about a factor of ten less sensitive than the neutron EDM for the same nominal value due to the mass ratio of the bare quark to the electron mass. Nonetheless by the end of the decade it looks like all systems may be able to answer whether Electroweak Baryogenesis [2] plays a significant role in the baryon asymmetry of our universe (BAU). We can certainly look forward to such a noble goal.

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