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Electric Dipole Moments

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1.1 Activities at 2012 PXPS

In a one-day workshop during the Project X Physics Study (PXPS) we considered the fundamental physics prospects provided by intense yields of nuclear isotopes with large atomic number at the Project X facility, and how this could enable searches for permanent electric dipole moments (EDMs) of nondegenerate systems. Project X could also greatly enable experiments which search for the permanent EDMs of fundamental particles, such as the neutron or muon, *directly*, and we considered these possibilities briefly as well. Our opening session was joint with the muon working group because of our common interest in storage ring EDMs. An afternoon session with the lattice working group focused on prospects of calculating the neutron EDM, and we think that continued interactions of phenomenologists with lattice gauge theorists and experimentalists will be most useful. While the discovery of a non-zero EDM in any system is our primary motivation, it is certain that measurements in a variety of systems would be *essential* to elucidating the nature of the new sources of CP violation found.

We view enhanced EDM searches as a key step in the campaign to understand the fundamental nature of our Universe, particularly in regards to the manner in which it came to have such a markedly large cosmological baryon asymmetry (BAU). Sakharov tells us that particle physics is capable of a microscopic explanation of the BAU, but baryon number, C, and CP violation are all required in concert with a departure from thermal equilibrium in order to realize a non-zero result [1]. Interestingly, all the necessary ingredients appear in the Standard Model (SM), but numerical assessments of the BAU in the SM fall far short of the observed value [2, 3]. This motivates the ongoing hunt for new sources of CP violation. In 2012, we know as a result of the experiments at the B-factories, with key input from the Tevatron, that the Cabibbo-Kobayashi-Maskawa (CKM) mechanism serves as the dominant source of flavor and CP violation in flavor-changing processes [4, 5]. Nevertheless, these definite conclusions do not end our search because we have not yet understood the origin of the BAU.

A permanent EDM $\mathbf{d}$ of a nondegenerate system such as a neutron is necessarily proportional to its spin $\mathbf{S}$, yielding an interaction energy given by $\mathcal{H} = -d(\mathbf{S}/S) \cdot \mathbf{E}$, so that a non-zero EDM breaks both P and T symmetry. Under CPT invariance a search for d thus probes new sources of CP violation. Existing EDM limits, as we report in Table 1-1, are extremely sensitive probes of new physics; under dimensional analysis with $\mathrm{SU}(2)_L \times \mathrm{U}(1)$ gauge invariance the EDM of a system with mass m_f is crudely $d_f \propto \sin\phi_{\mathrm{CP}} e m_f/\Lambda^2$ [6], where Λ is the scale CP is broken and ϕ_{CP} is a CP-violating phase. Interestingly, if $\sin\phi_{\mathrm{CP}} \sim 1$, electroweak gauge invariance *lowers* the energy reach to roughly the TeV energy scale. The SM itself nominally has two sources of CP violation: through QCD by dint of a non-zero $\bar{\theta}$ term and through a single phase δ in the CKM matrix. The former appears with an operator of mass dimension 4 so that it is unsuppressed by any mass scale and need not be small – but experiment tells us $\bar{\theta} \ll 10^{-10}$ [9]. We will want to consider carefully how a nonzero $\bar{\theta}$ term can be distinguished from new electroweak physics. In the second mechanism the structure of the CKM matrix itself ensures that the EDMs thus generated are remarkably small. The first nontrivial contributions to the quark and charged lepton EDMs come in 3- and 4-loop order, respectively,

Table 1-1. *Upper limits on EDMs in three different categories.*

Category	EDM Limit ($e\cdot$cm)	Experiment	Standard Model value ($e\cdot$cm)
Electron	1.0×10^{-27}	YbF molecules in a beam [7]	10^{-38}
Neutron	2.9×10^{-26}	Ultracold neutrons in a bottle [8]	10^{-31}
Nucleus	3.1×10^{-29}	^{199}Hg atoms in a vapor cell [9]	10^{-33}

so that for the down quark $d_d \sim 10^{-34}$ e-cm [10, 11], whereas for the electron $d_e \sim 10^{-38}$ e-cm [12] with massless neutrinos. In the presence of neutrino mixing, the lepton EDMs can be much larger, though orders of magnitude away from experimental bounds nonetheless [13]. We probe d_d through the neutron EDM, and in that context a plurality of nonperturbative enhancement mechanisms may well act. There is a well-known chiral enhancement, due to the presence of a π loop, which can bring the neutron EDM to $d_n^{\rm CKM} \simeq 10^{-31}-10^{-32}$ e-cm [14, 15, 16], and, very recently, the presence of virtual $c\bar{c}$ pairs in the neutron have been argued to mediate a "loopless" EDM of $d_n^{\rm CKM} \simeq 10^{-32}$ e-cm [17]. The two enhancements are physically distinct, and it is not impossible that they act in concert, to yield, naively, $d_n^{\rm CKM} \simeq 10^{-29} - 10^{-30}$ e-cm, with the implication that the ^{225}Ra experiment, e.g., for which both atomic and nuclear enhancements also operate, could well observe a signal at Project X even if only SM dynamics operate. It is clearly important to assess the various claims carefully. Unfortunately, the local operator in the $c\bar{c}$ mediated mechanism is of mass dimension 9; it may prove very challenging to evaluate it with lattice gauge theory.

Different models of electroweak symmetry breaking can also give rise to substantial EDMs. Models with weak-scale supersymmetry are a particular stand-out because they can potentially resolve the hierarchy problem and are sufficiently weakly coupled to be consistent with precision electroweak constraints. Moreover, supersymmetric models generically have many new sources of CP violation, and can produce a BAU in the electroweak phase transition more efficiently than in the SM [18], which in itself can be regarded as indirect support for supersymmetry. Weak-scale supersymmetry has significant implications for flavor physics, and, over the years, the non-observation of new chirality-changing interactions have constrained the appearance of the new degrees of freedom, their masses and mixings, and of both their real and imaginary parts, note, e.g., Ref. [19]. In the LHC era, it has been possible to probe such degrees of freedom directly, and all searches have yielded null results thus far. Ultimately, if no supersymmetric signatures are observed, we would not rule out supersymmetry per se, but rather the particular weak-scale scenarios which make it phenomenologically so very appealing. Blum discussed EDMs in the context of the LHC results and notes that light third-generation squarks are still possible [20, 21]; more severe bounds appear only in models in which the neutralino is not the lightest supersymmetric particle [22] – these parameters are particularly important for successful models of baryogenesis [23]. EDMs retain their interest even if no supersymmetric signals are observed at the LHC because a discovery would reveal, modulo theoretical uncertainties, the energy scale of new physics [23].

We now consider low-energy sources of CP violation beyond the SM. Thinking broadly and systematically we organize the expected contributions at in terms of the mass dimension of the possible CP-violating operators appearing in an effective field theory with a cutoff of ~ 1 GeV [24]:

$$\begin{aligned}\mathcal{L}_\Lambda = &\frac{\alpha_s\bar{\theta}}{8\pi}\epsilon^{\alpha\beta\mu\nu}F^a_{\alpha\beta}F^a_{\mu\nu} - \frac{i}{2}\sum_i d_i\bar{\psi}_i F_{\mu\nu}\sigma^{\mu\nu}\gamma_5\psi_i - \frac{i}{2}\sum_i \tilde{d}_i\bar{\psi}_i F^a_{\mu\nu}t^a\sigma^{\mu\nu}\gamma_5\psi_i \\ &+\frac{1}{3}wf^{abc}F^a_{\mu\nu}\epsilon^{\nu\beta\rho\delta}F^b_{\rho\delta}F_\beta^{\mu,c} + \sum_{i,j} C_{ij}(\bar{\psi}_i\psi_i)(\bar{\psi}_j i\gamma_5\psi_j) + \ldots \end{aligned} \tag{1.1}$$

with $i,j \in u,d,s,e,\mu$ as all heavier degrees of freedom have been integrated out. We neglect terms higher than mass dimension 6; the CKM mechanism under ${\rm SU}(2)_L\times{\rm U}(1)$ gauge invariance functionally yields contributions of dimension 8 [6, 24]. Various extensions of the SM can generate the low-energy constants which appear, so that, in turn, EDM limits thereby constrain the new sources of CP violation which appear in such models. Note, e.g., Ref. [25] for a recent analysis of the implications of EDM constraints for the CP-violating phases of the minimially supersymmetric SM. Perturbative techniques connect specific models of new physics to the low-energy constants. Additional theoretical analysis is required to evaluate the hadronic matrix elements of the operators which appear. For the neutron, the QCD sum rule technique, e.g., has been employed for the requisite matrix elements, note Ref. [26] for a comparative review of different methods. Lattice gauge theory has also been used, but only for the matrix element associated with $\bar{\theta}$ – Shintani reviewed this work, and both Shintani and Bhattacharya discussed future prospects at our workshop [27, 28]. The assessment of the hadronic matrix elements of the higher-dimension CP-violating operators with lattice techniques is a topic of high interest.

For the interpretation of experiments using atoms and nuclei it is necessary to formulate the CP-violating interactions of Eq. (1.1) in terms of pion and nucleon degrees of freedom. Here chiral and isospin symmetry serve as powerful tools in distinguishing the various possible interactions which appear [29]. Further theoretical work is needed to connect the low-energy constrants of the latter approach explicitly to those which appear in Eq. (1.1). Currently this connection has been made through the QCD sum rule technique [30, 24], though that for the isotensor CP-violating π-nucleon-nucleon coupling constant remains unevaluated; perhaps lattice techniques can also prove helpful.

Atomic and nuclear systems can evince various long-distance enhancements, in part because the EDM of a point-like, nonrelativistic atom is zero even if its constituents have non-zero EDMs [32]. The enhancements arise because this result, the Schiff theorem, can be strongly violated by relativistic and finite-size effects. For paramagnetic atoms, relativistic effects are most important, and studies in paramagnetic atoms or molecules are most sensitive to d_e. Atomic EDMs can also be induced by P-odd, T-odd nuclear moments – here finite-size effects play the more important role. These so-called Schiff moments are computed using nuclear structure theory with the CP-violating π-nucleon-nucleon coupling constants as fundamental inputs. Different enhancement mechanisms can operate simultaneously, and nuclear deformation and atomic state mixing can also give rise to enhancements. For example, in a heavy atom of a rare isotope, for which the nucleus has octupole strength or permanent deformation, the dipole charge distribution in the nucleus, characterized by the Schiff moment, may be significantly enhanced compared to ^{199}Hg. This enhancement is due to the parity-odd moment arising from quadrupole-octupole interference, and the enhanced E1 polarizability effected by closely spaced levels of the same J and opposite parity. The strongest octupole correlations occur near $Z = 88$ and $N = 134$ [31], and isotopes $^{221/223}$Rn and ^{225}Ra are promising for both practical experimental reasons and as candidates for octupole-enhanced Schiff moments. Enhancements of the nuclear Schiff moment by a factor of 1000 or more compared to ^{199}Hg [33] have been predicted by models using Skyrme-Hartree-Fock for ^{225}Ra [34] and Woods-Saxon and Nilsson potentials in the case of ^{223}Rn [35]. However, the uncertainties on the size of enhancements are quite large, in part due to uncertainty in the ^{199}Hg Schiff moment, and, in the case of $^{221/223}$Rn isotopes, the absence of nuclear structure data.

In the future, if a non-zero EDM is discovered in one particular system, the measurement of EDMs of other types is essential to resolving the underlying mechanisms of CP-violation. The neutron and heavy atom EDMs are thought to be most sensitive to different CP-violating sources [36]. In addition, the recently proposed storage ring EDM experiments of the proton and deuteron aim to probe combinations of CP-violating contributions which differ from those in the neutron EDM. Experiments with paramagnetic atoms or molecules are sensitive to the EDM of the electron and a possible new CP-violating electron-quark interaction.

1.2 Roadmap

The "roadmap" of activities projected for other working groups in regards to experimental conceptual design issues and detector R&D does not fit the arc of development anticipated for the EDM experiments. For the most part, the experiments are stand-alone and only require the isotope or neutron production facilities anticipated at Project X. No facility-wide detectors would be employed. Moreover, the Th target concept for isotope production as discussed by Jerry Nolen [37] utilizes the 1 GeV beam exclusively. The Project X Proton Performance document [38] states that the rough beam capabilities at 1 GeV in Stage 1 are to be retained in Stages 2 and 3 as well. Without doubt, Project X, already at Stage 1, would be a tremendous enabler for the planned nuclear studies. For example, at present, the ability to deliver ^{225}Ra is limited to 10^8 particles/sec, whereas this is anticipated to improve to 10^{13} particles/sec at Project X – for an increase in the sensitivity to the ^{225}Ra EDM to as much as 10^{-29} e-cm [39], for unprecendented sensitivity to new sources of CP violation once the Schiff enhancement is taken into account. It should be noted, too, that the SNS neutron EDM experiment would also benefit from the increased cold neutron intensity that the Project X facility would provide. The Project X Injector Experiment (PXIE) with proton beams of 40 MeV at 1 mA may also provide useful yields of isotopes for fundamental physics research, but this is still under study [37].

Our discussions at the PXPS have focussed on two distinct classes of experiments. As we have described, the first would employ the isotope or neutron production facilities anticipated at Project X. The second concerns EDM measurements in a storage ring environment. Such is considered for the μ EDM as an off-shoot of the μ $g-2$ experiment, for a sensitivity of 10^{-21} e-cm; a dedicated experiment could reach 10^{-24} e-cm [40]. In addition, a dedicated proton storage ring experiment for the proton EDM is possible. Such an experiment could be executed at BNL, but there is a location at Fermilab, the old accumulator ring, which could house such an experiment and begin work now [41]. Project X could improve such an experiment's sensitivity. Note that it requires a *polarized proton source*. The existing proposal anticipates a sensitivity of 10^{-29} e-cm [42], which is more sensitive than the limits from planned neutron EDM experiments by an order of magnitude. Storage ring methods can also be used to tackle, directly, the EDMs of several light nuclei, though it should be noted that the all-electric ring concept proposed for the proton EDM would not suitable for all nuclear studies. A suitable "all-purpose" magnetic/electric ring for such studies is proposed at COSY-Jülich, and a precursor experiment is planned in the existing magnetic storage ring at COSY [43]. The pattern of results could potentially unravel the various sources of CP violation encoded in the low-energy constants associated with CP-violating effective operators at low energies. Such systematic studies would be key were an EDM discovered in any system; the highly leveraged nature of the enhancements in ^{225}Ra make this system an excellent bet for discovery.

Theory must make strides in order to take advantage of these experimental developments. Of course, at anticipated levels of sensitivity, there is little doubt that a non-zero EDM would be Nature's imprimatur of the existence of physics beyond the SM. However, one could hardly be content with knowing that just *something* is out there. There are different issues to consider. The interpretation of the EDM of a complex system such as ^{225}Ra – beyond discovery – involves hadronic, nuclear, and atomic theoretical uncertainties. The hadronic matrix elements of $\mathcal{L}_\Lambda$, Eq. (1.1), connect these sources of CP violation, most notably that due to the chromo-quark EDM $\tilde{d}_i$, to the CP-violating π-nucleon-nucleon coupling constants. The last are then used to compute the Schiff moment using nuclear structure theory, and finally the Schiff moment is used to compute the EDM of the atom using atomic structure theory [36]. Likely the weakest link in the chain is the evaluation of the hadronic matrix elements. The use of lattice methods may well be able to redress this.

1.3 Status of Selected Experiments

Here we review the current status of EDM experiments which may well profit from installation of Project X. We include experiments with radium, radon, and francium isotopes, as well as the SNS neutron experiment. For further details in regards to worldwide efforts, note the EDM section of the "Neutrons, Nuclei, and Atoms" chapter of the recent Intensity Frontier Workshop report [44].

1.3.1 SNS Neutron EDM

The goal of the SNS nEDM experiment, to be carried out at the Spallation Neutron Source (SNS), is to achieve a sensitivity $< 3 \times 10^{-28}\ e\cdot$cm. A value (or limit) for the neutron EDM will be extracted from the difference between neutron spin precession frequencies for parallel and anti-parallel magnetic ($\sim$ 30 mGauss) and electric ($\sim$ 70 kV/cm) fields. This experiment, based on Ref. [45], uses a novel polarized ^{3}He co-magnetometer and will detect the neutron precession via the spin-dependent neutron capture on ^{3}He. The capture reaction produces energetic proton and triton, which ionize liquid helium and generate scintillation light that can be detected. Since the EDM of ^{3}He is strongly suppressed by electron screening in the atom it can be used as a sensitive magnetic field monitor. High densities of trapped UCNs are produced via phonon production in superfluid ^{4}He which can also support large electric fields. This technique allows for a number of independent checks on systematics including:

1. Studies of the temperature dependence of false EDM signals in the ^{3}He.
2. Measurement of the ^{3}He precession frequency using SQUIDs.
3. Cancellation of magnetic field fluctuations by matching the effective gyromagnetic ratios of neutrons and ^{3}He with the "spin dressing" technique [45]).

The collaboration is continuing to address critical R&D developments in preparation for construction of a full experiment. Key issues being addressed include:

1. Maximum electric field strength for large-scale electrodes made of appropriate materials in superfluid helium below a temperature of 1 K.
2. Magnetic field uniformity for a large-scale magnetic coil and a superconducting Pb magnetic shield.
3. Development of coated measurement cells that preserve both neutron and ^{3}He polarization along with neutron storage time.
4. Understanding of polarized ^{3}He injection and transport in the superfluid.
5. Estimation of the detected light signal from the scintillation in superfluid helium.

The experiment will be installed at the FNPB (Fundamental Neutron Physics Beamline) at the SNS and construction is likely to take at least five years, followed by hardware commissioning and data taking. Thus first results could be anticipated by the end of the decade.

1.3.2 Proton Storage Ring EDM

The storage ring EDM collaboration has submitted a proposal to DOE for a proton EDM experiment sensitive to $10^{-29} e\cdot$cm [42]. This experiment can be done at Brookhaven National Laboratory (BNL) or another facility that can provide highly polarized protons with an intensity of more than 10^{10} particles per cycle of 15 minutes. The method utilizes polarized protons at the so-called "magic" momentum of 0.7 GeV/c in an all-electric storage ring with a radius of ~ 40 m. At this momentum, the proton spin and momentum vectors precess at the same rate in any transverse electric field. When the spin is kept along the momentum direction, the radial electric field acts on the EDM vector causing the proton spin to precess vertically. The vertical component of the proton spin builds up for the duration of the storage time, which is limited to 10^3 s by the estimated horizontal spin coherence time (hSCT) of the beam within the admittance of the ring.

The strength of the storage ring EDM method comes from the fact that a large number of highly polarized particles can be stored for a long time, a large hSCT can be achieved and the transverse spin components can be probed as a function of time with a high sensitivity polarimeter. The polarimeter uses elastic nuclear scattering off a solid carbon target placed in a straight section of the ring serving as the limiting aperture. The collaboration has over the years developed the method and improved their understanding and confidence on it. Some notable accomplishments are listed below:

1. Systematic errors, the efficiency and analyzing power of the polarimeter has been studied. The polarimeter systematic errors, caused by possible beam drifting, are found to be much lower than the statistical sensitivity.

2. A tracking program has been developed to accurately simulate the spin and beam dynamics of the stored particles in the all-electric ring [46]. The required ring parameters are readily available at BNL with current capabilities.

3. E-field can be measured at BNL using the technology developed as part of the international linear collider (ILC) and energy recovery linacs (ERL) R&D efforts [47]. Tests indicate that more than 100 kV/cm across a 3 cm plate separation can be achieved.

4. The geometrical phase effect can be reduced to a level comparable to the statistical sensitivity based on a position tolerance of commonly achievable $\sim 25\mu$m in the relative positioning of the E-field plates around the ring.

1.3.3 Radon-221,223 Atomic EDM

The RadonEDM collaboration are focusing on potential EDM measurements with radon isotopes for several reasons. Most importantly, precision measurements with polarized noble gases in cells have demonstrated the feasibility of an EDM experiment. For ^{129}Xe, it was measured that $d = 0.7 \pm 3.4 \times 10^{-27}\ e\cdot$cm [48]. A number of techniques have been developed including spin-exchange-optical-pumping (SEOP) using rubidium, construction of EDM cells and wall coatings that reduce wall interactions, in particular for spin greater than 1/2. The half-lives of $^{221/223}$Rn are of order 20-30 minutes, so an on-line experiment at an isotope production facility is essential. The proposed experiment (S-929) at TRIUMF's ISAC, an on-line isotope separator-facility, has been approved with high priority. The experimental program includes development of on-line techniques including collection of rare-gas isotopes and transfer to a cell, optical pumping and techniques for detection of spin precession based on gamma-ray anisotropy, beta asymmetry and laser techniques.

For polarized rare-isotope nuclei, the excited states of the daughter nucleus populated by beta decay are generally aligned, leading to a $P_2(\cos\theta)$ distribution of gamma-ray emission. The gamma anisotropy effect has been used to detect nuclear polarization in ^{209}Rn and ^{223}Rn [49, 50]. At TRIUMF, the large-coverage HPGe gamma-detector array TIGRESS or the new GRIFFIN array may be used. Alternatively, beta asymmetry can be used to detect nuclear polarization with a higher efficiency. Both the gamma-anisotropy and beta-asymmetry detection techniques have analyzing power expected to be limited to 0.1-0.2. The sensitivity of the EDM measurement is proportional to analyzing power, thus laser-based techniques are also under investigation. The collaboration is currently developing two-photon magnetometry for ^{129}Xe that may also be useful as a co-magnetometer in neutron-EDM measurements. The analyzing power for two-photon transitions can be close to unity as long as the density is sufficient.

EDM measurements in radon isotopes will ultimately be limited by production rates. The Project-X isotope separator scenario is projected to produce 1-2 orders of magnitude more than current facilities and provides a promising alternative to extracting rare-gas isotopes from the FRIB beam dump.

1.3.4 Radium-225 Atomic EDM

The primary advantage of ^{225}Ra is the large enhancement [35, 33, 34], approximately a factor of 1000, of the atomic EDM over ^{199}Hg that arises from both the octupole deformation of the nucleus and the highly relativistic atomic electrons. This favorable case is being studied at both Argonne National Laboratory [51] and Kernfysisch Versneller Instituut (KVI) [52]. The scheme at Argonne is to measure the EDM of ^{225}Ra atoms in an optical dipole trap (ODT) as first suggested in Ref. [53]. The ODT offers the following advantages: $\vec{v}\times\vec{E}$ and geometric phase effects are suppressed, collisions are suppressed between cold fermionic atoms, vector light shifts and parity mixing induced shifts are small. The systematic limit from an EDM measurement in an ODT can be controlled at the level of $10^{-30}e\cdot$cm [53].

The Argonne collaboration demonstrated the first magneto-optical trap (MOT) of Ra atoms [51], the transfer of atoms from the MOT to the ODT with an efficiency exceeding 80%, and the transport of atoms to an ODT in a measurement chamber 0.5 m from the MOT. In the near future, they plan a vacuum upgrade that should permit the lifetime of atoms in the ODT to improve from 6 s to 60 s, and begin the first phase of the EDM measurement at the sensitivity level of $10^{-26}e\cdot$cm, which should be competitive with $10^{-29}e\cdot$cm for ^{199}Hg in terms of sensitivity to T-violating physics. For phase 2 of this experiment, the collaboration plans to upgrade the optical trap. In the present MOT, the slower and trap laser operate at 714 nm where there is a relatively weak atomic transition rate. In phase 2, they would upgrade the trap to operate at 483 nm where a strong transition can be exploited for slowing and trapping.

In Phase 1&2, a typical experimental run will use 1-10 mCi of ^{225}Ra presently available. The next-generation isotope facility, such as FRIB after upgrade or Project X, is expected to produce more than 10^{13} ^{225}Ra atoms/s [37]. In this case it should be possible to extract more than 1 Ci of ^{225}Ra for use in the EDM apparatus. This would lead to a projected sensitivity of $10^{-28}-10^{-29}e\cdot$cm for ^{225}Ra, competitive with $10^{-31}-10^{-32}e\cdot$cm for ^{199}Hg. Table 1-2 summarizes the projected sensitivities.

Table 1-2. *Projected sensitivities for ^{225}Ra and ^{199}Hg equivalent for three scenarios*

Phase	Phase 1	Phase 2 (upgrade)	FRIB after upgrade, Project X
Ra (mCi)	1-10	10	> 1000
$d(^{225}\mathrm{Ra})$ ($10^{-28}e\cdot$cm)	100	10	0.1-1
equiv. $d(^{199}\mathrm{Hg})$ ($10^{-30}e\cdot$cm)	10	1	0.01-0.1

1.3.5 Electron EDM with Francium

With francium comes a higher sensitivity to an electron EDM than any atom previously used. The large nuclear spin and magnetic dipole moment of ^{211}Fr, when combined with laser cooling, bring the potential benefit of the most complete systematic rejection of any eEDM experiment yet attempted. Magnetic fields that change synchronously with the electric field can mimic an EDM. Even in experiments where there is no net motion, the Lorentz transform due to the atom's motion through the electric field gives rise to a motional magnetic field $\mathbf{B}_{\rm mot} = \mathbf{v} \times \mathbf{E}/c^2$ that can lead to first-order systematic effects. These effects can be removed in first order if the atom is quantized in the electric field, no external magnetic fields are applied, and motional and remnant magnetic fields are made small. The remaining systematic effects scale as inverse powers of the electric field allowing one to quickly distinguish between a true EDM (linear in E) and the systematic effect (proportional to $1/E^3$). The ratio of systematic effect sensitivity to eEDM sensitivity in ^{211}Fr is two orders of magnitude smaller than in any other alkali atom.

What is presently lacking is a source of francium intense enough to make measurements sensitive enough to lower the electron EDM limit by three orders of magnitude and to test for systematics, both false positives and false negatives. The proposed Joint Nuclear Facility at Project X will have proton beam currents about two orders of magnitude larger than TRIUMF and ISOLDE, and may produce 10^{13} ^{211}Fr/s - sufficient to lower the electron EDM upper limit by a factor of 10^3.

References

[1] A. D. Sakharov, Pisma Zh. Eksp. Teor. Fiz. **5**, 32 (1967) [JETP Lett. **5**, 24 (1967)] [Sov. Phys. Usp. **34**, 392 (1991)] [Usp. Fiz. Nauk **161**, 61 (1991)].

[2] M. B. Gavela, P. Hernandez, J. Orloff, and O. Pene, Mod. Phys. Lett. A **9**, 795 (1994) [hep-ph/9312215, hep-ph/9312215]; M. B. Gavela, P. Hernandez, J. Orloff, O. Pene, and C. Quimbay, Nucl. Phys. B **430**, 382 (1994) [hep-ph/9406289]; P. Huet and E. Sather, Phys. Rev. D **51**, 379 (1995) [hep-ph/9404302].

[3] V. A. Kuzmin, V. A. Rubakov, and M. E. Shaposhnikov, Phys. Lett. B **155**, 36 (1985); M. E. Shaposhnikov, Nucl. Phys. B **287**, 757 (1987); G. R. Farrar and M. E. Shaposhnikov, Phys. Rev. Lett. **70**, 2833 (1993) [Erratum-ibid. **71**, 210 (1993)] [hep-ph/9305274].

[4] J. Charles *et al.* [CKMfitter Group Collaboration], Eur. Phys. J. C **41**, 1 (2005) [hep-ph/0406184]; see http://ckmfitter.in2p3.fr/ .

[5] G. Isidori, Y. Nir, and G. Perez, Ann. Rev. Nucl. Part. Sci. **60**, 355 (2010) [arXiv:1002.0900 [hep-ph]].

[6] A. De Rujula, M. B. Gavela, O. Pene, and F. J. Vegas, Nucl. Phys. B **357**, 311 (1991).

[7] J. J. Hudson et al., Nature **473**, 493 (2011).

[8] C. A. Baker et al., Phys. Rev. Lett. **97**, 131801 (2006).

[9] W. C. Griffith et al., Phys. Rev. Lett. **102**, 101601 (2009).

[10] I. B. Khriplovich, Phys. Lett. B **173**, 193 (1986).

[11] A. Czarnecki and B. Krause, Phys. Rev. Lett. **78**, 4339 (1997) [hep-ph/9704355].

[12] M. E. Pospelov and I. B. Khriplovich, Sov. J. Nucl. Phys. **53**, 638 (1991) [Yad. Fiz. **53**, 1030 (1991)].

[13] D. Ng and J. N. Ng, Mod. Phys. Lett. A **11**, 211 (1996) [hep-ph/9510306].

[14] M. Gavela et al., Phys. Lett. B **109**, 215 (1982).

[15] I. B. Khriplovich and A. R. Zhitnitsky, Phys. Lett. B **109**, 490 (1982).

[16] Xiao-Gang He, Bruce H. J. McKellar, and Sandip Pakvasa, Int. J. Mod. Phys. **A4**, 5011 (1989) [Erratum-ibid. **A6**, 1063 (1991)]

[17] T. Mannel and N. Uraltsev, Phys. Rev. D **85**, 096002 (2012) [arXiv:1202.6270 [hep-ph]].

[18] M. S. Carena, M. Quiros, and C. E. M. Wagner, Phys. Lett. B **380**, 81 (1996) [hep-ph/9603420].

[19] W. Buchmuller and D. Wyler, Nucl. Phys. B **268**, 621 (1986).

[20] K. Blum, private communication.

[21] Note Fig. 6 of https://cdsweb.cern.ch/record/1432203/files/ATLAS-CONF-2012-036.pdf and Fig. 2 of http://arxiv.org/pdf/1112.3832v2.pdf .

[22] See http://arxiv.org/pdf/1205.0272.pdf .

[23] K. Blum, talk at PXPS, June, 2012.

[24] M. Pospelov and A. Ritz, Ann. Phys. **318**, 119 (2005).

[25] Y. Li, S. Profumo, and M. Ramsey-Musolf, JHEP **1008**, 062 (2010) [arXiv:1006.1440 [hep-ph]].

[26] S. Narison, Phys. Lett. B **666**, 455 (2008) [arXiv:0806.2618 [hep-ph]].

[27] E. Shintani, talk at PXPS, June, 2012.

[28] T. Bhattacharya, talk at PXPS, June, 2012.

[29] E. Mereghetti, talk at PXPS, June, 2012.

[30] M. Pospelov, Phys. Lett. B **530**, 123 (2002) [hep-ph/0109044].

[31] P. A. Butler and W. Nazarewicz, Rev. Mod. Phys. **68**, 349 (1996).

[32] L. I. Schiff, Phys. Rev. **132**, 2194 (1963).

[33] S. Ban, J. Dobaczewski, J. Engel, and P. Shukla, Phys. Rev. **C82**, 015501 (2010).

[34] J. Dobaczewski and J. Engel, Phys. Rev. Lett. **94**, 232502 (2005).

[35] V. Spevak, N. Auerbach, and V. V. Flambaum, Phys. Rev. **C56**, 1357 (1997).

[36] J. S. M. Ginges and V. V. Flambaum, Phys. Rept. **397**, 63 (2004) [physics/0309054].

[37] J. Nolen, talk at PXPS, June, 2012.

[38] See http://projectx-docdb.fnal.gov/cgi-bin/ShowDocument?docid=1061 .

[39] M. Dietrich, talk at PXPS, June, 2012.

[40] See http://www.bnl.gov/edm/muon_edm.asp .

[41] Y. Semertzidis, talk at PXPS, June, 2012.

[42] The proposal is available from http://www.bnl.gov/edm .

[43] See http://www2.fz-juelich.de/ikp/en/future_projects.shtml .

[44] J. L. Hewett et al., http://arxiv.org/abs/1205.2671 .

[45] R. Golub and S. Lamoreaux, Phys. Rep. **237**, 1 (1994).

[46] S. Mane, Nucl. Instr. Meth. **A596**, 288 (2008) and independently by Yuri Orlov, Internal EDM presentations.

[47] B.M. Dunham et al., TUPMS021, Proceedings of PAC07, Albuquerque, NM, USA, 2007.

[48] M. Rosenberry and T. Chupp, Phys. Rev. Lett. **86**, 21 (2001).

[49] E. R. Tardiff et al., Phys. Rev. **C77**, 052501 (2008).

[50] M. Kitano et al., Phys. Rev. Lett. **60**, 2133 (1988).

[51] J. R. Guest et al., Phys. Rev. Lett. **98**, 093001 (2007).

[52] S. De, U. Dammalapati, K. Jungmann, and L. Willmann, Phys. Rev. **A79**, 041402 (2009).

[53] M. V. Romalis and E. N. Fortson, Phys. Rev. **A59**, 4547 (1999).

[54] B. C. Regan et al., Phys. Rev. Lett. **88**, 071805 (2002).

[55] N. R. Hutzler et al., Phys. Chem. Chem. Phys. (2011) DOI: 10.1039/c1cp20901a.

[56] A. C. Vutha et al., J. Phys. **B43**, 074007 (2010).