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# Nucleons, Nuclei, and Atoms

## 1.1 Overview

Despite the success of the Standard Model in explaining so many subatomic physics phenomena, we recognize that the model is incomplete and must eventually give way to a more fundamental description of nature. We have discovered massive neutrinos and associated flavor violation, which require the introduction of new mass terms in the Standard Model. We have an excess of baryons over antibaryons in our universe, indicating baryon-number-violating interactions and likely new sources of CP violation. We know from the inventory of matter and energy in our universe that the portion associated with Standard Model physics is only about 5% of the total. The rest remains unidentified and quite mysterious.

These “big questions” – the origin of matter, the nature of neutrino mass, the identification of dark matter and dark energy - have driven the two major thrusts of subatomic physics. One is the effort to probe ever shorter distance scales by advancing the energy frontier. Today that frontier is represented by CERN’s LHC. The alternative is to seek signals of the new physics in subtle violations of symmetry in our low-energy world – ultraweak interactions that might mediate lepton- or baryon-number violation, generate electric dipole moments, or lead to unexpected flavor physics. This second approach is the theme of this chapter: ultrasensitive techniques in atomic, nuclear, and particle physics that might reveal the nature of our “next Standard Model.” Like particle astrophysics and cosmology, the third leg of our efforts to find new physics, this second approach uses our world as a laboratory, and depends on precision to identify the new physics.

This field has a long and quite successful history. Tests of fundamental symmetries in experiments involving nucleons, nuclei, and atoms have played an essential role in developing and testing the Standard Model. The observation of parity-violation in the radioactive decay of  $^{60}\text{Co}$ , shortly preceding the observation of parity-violation in pion decay, provided the first experimental evidence that the weak interaction does not respect this symmetry, ultimately leading to the Standard Model description of charged weak currents as being purely left-handed. Similarly, the measurements of the parity-violating asymmetry in polarized deep-inelastic electron-deuteron scattering in the 1970’s singled out the Standard Model structure for the neutral weak current from among competing alternatives, well in advance of the discovery of the electroweak gauge bosons at CERN. And the non-observation of a permanent electric dipole moment (EDM) of the neutron and  $^{199}\text{Hg}$  atoms has placed stringent bounds on the possibility of combined parity and time-reversal violation (or CP-violation) in the strong interaction, motivating the idea of the spontaneously-broken Peccei-Quinn symmetry and the associated axion that remains a viable candidate for the cosmic dark matter.

Present and prospective fundamental symmetry tests with nucleons, nuclei and atoms are now poised to probe for possible new physics at the Terascale and beyond, making them a vital component of the Intensity Frontier. At the same time, these tests provide increasingly sophisticated probes of poorly understood features of long-distance strong interactions that are responsible for the structure of nucleons and nuclei. The potential for both discovery and insight has motivated the nuclear physics community to identify studies of fundamental symmetries and neutrino properties as one of the top-four priorities for the field in the 2007 Nuclear Science Advisory (NSAC) Long Range Plan [1], perhaps anticipating the present broader interest in

the Intensity Frontier that underlies this document. Below, some of the most compelling opportunities with nucleons, nuclei and atoms are summarized, drawing largely on input received from the nuclear and atomic physics communities.

In contrast to other subjects treated in this White Paper, fundamental symmetry tests with nucleons, nuclei, and atoms is remarkably diverse. In preparation for this report, the working group conveners received over 30 two-page written contributions outlining the progress and opportunities for the field. Given the limitations of space, it is not feasible in this chapter to include all of the detailed information received, so we refer the reader to the website where this input is available[2]. For similar reasons, we do not provide a comprehensive theoretical framework here, again referring the reader to recent review papers[3, 4]. Some theoretical context and basic terminology is included in each of the subsections below, though the primary focus falls on the experimental opportunities.

With this context in mind, it is useful to delineate three broad classes of studies with nucleons, nuclei, and atoms:

- (i) Rare or forbidden processes: observables that one expects – based on the Standard Model – to be either zero or far too suppressed to be observed. The observation of a non-zero signal in such a process would constitute “smoking gun” evidence for physics beyond the Standard Model. From the standpoint of this report, the permanent electric dipole moment of the neutron or a neutral atom represents the flagship example of such an observable. Other examples include tests of Lorentz symmetry or CPT (defined below).
- (ii) Precision tests: such studies seek to measure with high precision observables that are not suppressed within the Standard Model. Any significant deviation from the Standard Model prediction would again point to physics beyond the Standard Model, whereas agreement can imply severe constraints on various model possibilities. For this class of studies, obtaining robust theoretical Standard Model predictions is vital to the interpretation in terms of “new physics”, as one has already seen earlier in the discussion of the muon anomalous magnetic moment. As discussed below, the primary precision tests further break down into two classifications: those involving the charged current weak interaction (primarily weak decays) and weak neutral current processes, such as parity-violation in electron scattering.
- (iii) Electroweak probes of the strong interaction: the motivation for this set of studies is to exploit the unique sensitivity of electroweak observables to aspects of nucleon and nuclear structure that are not readily accessible with a purely electromagnetic probe. During the last two decades, for example, measurements of parity-violating asymmetries in fixed target, polarized electron-proton and electron-nucleus scattering have been performed at MIT-Bates, Jefferson Laboratory, and Mainz with the aim of determining the strange quark contribution to the electric and magnetic properties of the strongly interacting targets. The interpretation of these experiments treated the Standard Model weak neutral current interaction as sufficiently well known that it could be used to probe this interesting question in hadronic structure. Since the focus of this White Paper is on physics beyond the Standard Model, we touch only briefly on this third class of studies, but emphasize that it remains an area of considerable interest and high priority within the nuclear physics community.

Before proceeding, it is important to emphasize several additional points. First, there exists considerable overlap between the efforts of the nuclear and atomic physics communities described below and the studies described elsewhere in this White Paper. In particular, the 2007 NSAC Long Range Plan identifies both fundamental symmetry tests and neutrino studies as one of the top priorities for the field in the coming decade. Indeed, a substantial fraction of the nuclear physics community is playing a leading role in searches for neutrinoless double beta decay, neutrino mass measurements, and neutrino oscillation studies. Similar leadership roles continue to be filled by members of the nuclear physics community in muon physics and

“dark photon” searches. Conversely, members of the high-energy physics community are in some instances leading the experiments described below – perhaps most notably in searches for pion leptonic decays. One should not conclude from the organization of this White Paper that it reflects the self-organization of the various communities or the primary sources of federal research support.

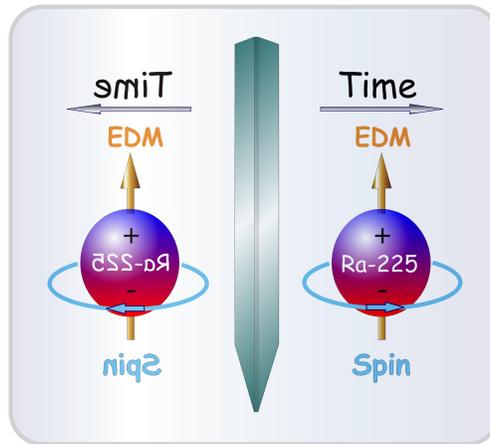
Second, the array of opportunities described below largely reflects the outcome of a process of “self-reporting”, wherein the conveners have attempted to incorporate information provided by members of the community on a voluntary basis in response to a call for input on a very short time-scale. The presence or absence of various topics does not, therefore, reflect any consensus on the part of the broader nuclear and atomic physics communities as to the top priorities for the future – except as they make contact with the NSAC Long Range Plan that emerged from a year-long process of town meetings and working group discussions. In some cases, what appears below constitutes a natural continuation the Long Range Plan content, while other content reflects new ideas that may not have been fully vetted by the community or a peer-review process. Moreover, some areas of study – such as parity-violation in purely hadronic and nuclear systems – have not been included even though they are the focus of considerable present effort. Such omissions do not imply any relative prioritization by the conveners but rather the ability of the relevant investigators to respond to the call for input on a short time scale.

Finally, one should bear in mind the international context for fundamental symmetry tests. The working group conveners have made efforts to reach out to the international community in order to provide this international context, and several investigators have responded quickly and graciously. However, significant omissions remain, including the highly successful program of neutron decay studies at the Institute Laue-Langevin and the ambitious future program involving investigators in Heidelberg, Vienna, and Munich. Similarly, a new high-intensity, low-energy electron beam has been proposed by colleagues in Mainz, providing an opportunity to carry out a measurement of the proton’s weak charge that is also the subject of a possible Jefferson Lab Free Electron Laser concept described below. Again, the omission of these and other international efforts merely reflect the time-scale for preparation of this document, the breadth of studies being carried out, and the limited availability of international colleagues to contribute to this process while carrying on their research programs locally. Indeed, fundamental symmetry tests with nucleons, nuclei, and atoms is a world wide effort, and significant partnerships and sharing of scientific expertise between the community in North America and elsewhere in the globe is vital to the overall scientific impact of this field.

With these caveats in mind, we turn to an overview of the exciting opportunities to utilize nucleons, nuclei, and atoms as “laboratories” for tests of fundamental interactions and to uncover new clues about what may lie beyond the Standard Model.

## 1.2 Electric Dipole Moments

At a classical level, the permanent electric dipole moment (EDM) of a particle arises from the spatial separation of opposite charges along the axis of the particle’s angular momentum. The existence of an EDM would be a direct signature of the violation of both parity (P) and time-reversal symmetry (T) (Fig. 1-1). It would also probe physics of CP violation (C stands for charge conjugation) which necessarily accompanies T violation under the assumption of the CPT theorem. EDM measurements conducted in many laboratories around the world employing a variety of techniques have made tremendous progress, and all have so far obtained results consistent with zero EDM. For example, in the past six decades, the search sensitivity of the neutron EDM has improved by six orders of magnitude to reach the current upper limit of  $2.9 \times 10^{-26} e \cdot \text{cm}$  [7].



**Figure 1-1.** EDM violates time-reversal symmetry. When time is reversed, the spin is reversed, but the EDM is not. Therefore, there is a measurable difference between the particle and its image in the time-reversed world.

CP violation in flavor-changing decays of K- and B-mesons have been observed. The results can be explained, and indeed in many cases predicted, by the CKM mechanism within the framework of the Standard Model, in which all of the observed CP violation phenomena originate from a single complex phase in the CKM matrix that governs the mixing of quark flavors. While this elegant solution has been well established following a string of precise measurements, additional sources of CP violation are generally anticipated in extensions of the Standard Model. For example, in SUSY, the supersymmetric partners of quarks would naturally allow additional complex phases in the expanded mixing matrix and induce new CP-violating phenomena. Within the Standard Model, a CP-violating term is known to be allowed in the general form of the QCD Lagrangian, and would have CP-violating consequences specifically in the strong interaction. Additional CP-violating mechanisms are also called for by the observation that the baryon-to-photon ratio in the Universe is as much as nine orders of magnitude higher than the level that can be accommodated by the Standard Model. A much more significant matter-antimatter asymmetry is likely to have been present in the early Universe and provided the favorable condition for the survival of matter that we observe today.

A permanent EDM is a sensitive probe for new CP-violating mechanisms, and is generally considered to be one of the most promising paths towards new physics beyond the Standard Model. The CKM mechanism in the Standard Model can only generate EDMs at the three- and four- loop level, leading to values many orders of magnitude lower than the current experimental limits. For example, the Standard Model value for the neutron EDM is expected to be approximately  $10^{-32}$  ecm, or six orders of magnitude below the current upper limit. Any non-zero EDM observed in the foreseeable future would have to require either CP-violation in the strong interaction or physics beyond the Standard Model. Perhaps unsurprisingly, extensions of the Standard Model generally allow a range of EDM values that are within the reach of the on-going experiments, including scenarios that would generate the cosmic baryon asymmetry with new Terascale CP-violating interactions (see, *e.g.*, Ref. [5] and references therein). The scientific importance and discovery potential of EDM searches are strongly endorsed by the communities of both particle physics and nuclear physics. The Nuclear Science Advisory Committee (NSAC) proclaimed in the 2007 Long Range Plan [1] that “a nonzero EDM would constitute a truly revolutionary discovery.” The negative findings so far are also valuable. As was pointed out in the 2006 P5 report [6], *The Particle Physics Roadmap*, “the non-observation of EDMs to-date, thus provides tight restrictions to building theories beyond the Standard Model.” Specifically, the upper limits on EDM provide insight on the scale of the next energy frontier.

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

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

The most sensitive EDM searches have so far been conducted on the neutron, nuclei ( $^{199}\text{Hg}$ ), and the electron (Table 1). On the one hand, experiments in these three categories all compete for the prize of being the first to observe a non-zero EDM. On the other hand, they complement each other as each category is most sensitive to different sources of CP violation. For example, the neutron is relatively more sensitive to the EDMs of its constituent quarks; heavy nuclei are more sensitive to the quark “chromo-EDM” (the CP-violating quark-gluon interaction) and other CP-violation mechanisms in the nuclear force. The recently proposed storage ring EDM experiments of the proton and deuteron aim to probe combinations of CP-violating contributions that differ from 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. In the future, if a non-zero EDM is discovered in one particular system, it would still be necessary to measure EDMs in other categories to help resolve the underlying CP-violation mechanisms.

At the intensity frontier, a new generation of sources for cold neutrons and ultracold neutrons (UCNs) are becoming available. Their higher output in neutron flux will enable searches for the neutron EDM projected at a sensitivity level of  $10^{-28} e \cdot \text{cm}$ , or two orders of magnitude below the current best limit. A survey of neutron EDM experiments are presented in this section. Also at the intensity frontier, future isotope production facilities such as FRIB after upgrade or Project X will produce a prolific amount of selected isotopes that possess enhanced sensitivities to the EDMs of the nuclei or the electron. Included in this section are the cases for the radium, radon, and francium isotopes.

### 1.2.1 PSI Neutron EDM

The search for the EDM of the neutron is considered one of the most important particle physics experiments at the low energy, high precision, high intensity frontier [11, 12]. The non-observation so far, with the most stringent limit of  $2.9 \times 10^{-26} e \cdot \text{cm}$  (90% C.L.) set by the Sussex-RAL-ILL collaboration [7], has far-reaching consequences: The extreme smallness of CP-violation in QCD, apparent in the smallness of the neutron EDM, is not understood at all and has led to the so-called ‘strong CP-problem’.

A nEDM experiment is being developed in steps at the Paul Scherrer Institute (PSI) [13]. The collaboration is pursuing a considerable technical R&D effort but also exploiting the complementary physics potential of the nEDM apparatus with respect to exotic interactions [14]. The experiment is located at the new source for ultracold neutrons (UCN) at PSI [15, 16]. This source uses neutron production via proton induced spallation on lead, moderation in heavy water and solid deuterium, and downscattering to UCN. Through an intermediate storage volume UCN can be distributed to three experimental beam ports. The performance of the source is continuously being optimized. Besides nEDM, the UCN source can also serve other experiments.

The collaboration is presently using the original but upgraded Sussex-RAL-ILL spectrometer [7]. In its configuration at the PSI UCN source, it is estimated to yield a factor of 25 higher statistics as compared to the earlier ILL setup. This increased statistical sensitivity needs to be accompanied by a comparable reduction of systematic uncertainties. The following improvements have been implemented: offline scanning for magnetic contaminations, surrounding magnetic field compensation, magnetic field correction coils, demagnetization,

optically pumped cesium atomic vapor magnetometers, and a mercury cohabiting magnetometer. The goal is to accumulate enough data in 2012 and 2013 to reach a sensitivity of  $\sigma(d_n) = 2.6 \times 10^{-27} e \cdot \text{cm}$ , which corresponds to an upper limit of  $d_n < 5 \times 10^{-27} e \cdot \text{cm}$  (95% C.L.) in case of a null result.

The next-generation neutron EDM experiment at PSI, named n2EDM, is being designed and will be constructed and offline tested in parallel to operating nEDM. It will be operated at room-temperature and in vacuum, aiming at a sensitivity of  $d_n < 5 \times 10^{-28} e \cdot \text{cm}$  [13] (95% C.L. limit in case of no signal). The setup is built around two stacked neutron precession chambers for simultaneous measurements of both E-field orientations. Precise control and measurement of the magnetic environment online inside the apparatus is possible via laser read-out Hg co-magnetometers, multiple Cs magnetometers as gradiometers surrounding the neutron precession chamber, and additional  $^3\text{He}$  magnetometer cells both above and below the neutron chambers. A multi-layer mu-metal shield will provide a passive shielding factor approaching  $10^5$  and will be surrounded by a multi-coil, multi-sensor, active compensation coil system. At present the setup area for the n2EDM apparatus is being prepared. Construction is scheduled to start in mid-2012. Transport to the beam position, depending on nEDM measurements and n2EDM progress, is foreseen for 2014. EDM-data taking could start in 2015 with first results in 2016.

### 1.2.2 ILL Neutron EDM

**CryoEDM:** The CryoEDM experiment at the Institut Laue-Langevin (ILL) in Grenoble, France, uses resonant downscattering of  $9\text{\AA}$  neutrons in a bath of superfluid  $^4\text{He}$  as a source of UCN. The UCNs are transported to magnetically shielded storage cells where, as in the previous generation of this experiment carried out at room-temperature, the Ramsey technique of separated oscillatory fields is used to measure the precession frequency of the neutron in parallel and antiparallel electric and magnetic fields. There are two Ramsey chambers: one has no electric field applied, and serves as a control. Magnetic-field fluctuations are monitored with SQUIDS. The neutrons are counted using detectors situated within the liquid helium [17].

The experiment is in its commissioning stage. It is anticipated that by 2013 the sensitivity will reach that of the room-temperature experiment [7], after which time it will be moved to a new beamline, where upgrades to various components of the apparatus should lead to an improvement of about an order of magnitude in sensitivity.

**PNPI/ILL nEDM:** Also at ILL, a PNPI/ILL experiment [18] to measure nEDM is currently being prepared at the UCN facility PF2. To enable an improvement of sensitivity, one of the PF2's beam positions has been equipped with new components for UCN transport, polarization and beam characterization, comprised of a superconducting solenoid-polarizer with a 4 Tesla magnetic field, a neutron guide system with a 136 mm diameter prepared in replica technology, and a novel beam chopper for time-of-flight analysis. The whole EDM apparatus is set up on a non-magnetic platform. A higher density of polarized UCNs at the experimental position, at approximately  $5 \text{ cm}^{-3}$ , shall lead to an EDM measurement with a counting statistical accuracy of  $1.5 \times 10^{-26} e \cdot \text{cm}$  during 200 days of operation at PF2.

### 1.2.3 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  $< 3 \times 10^{-28} e \cdot \text{cm}$ . 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. [20], uses a novel polarized  $^3\text{He}$  co-magnetometer and will detect the neutron precession via the spin-dependent neutron capture on  $^3\text{He}$ . The capture reaction produces energetic proton and triton, which ionize liquid helium and generate scintillation light that can be detected. Since the EDM of  $^3\text{He}$  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  $^4\text{He}$  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  $^3\text{He}$ .
2. Measurement of the  $^3\text{He}$  precession frequency using SQUIDs.
3. Cancellation of magnetic field fluctuations by matching the effective gyromagnetic ratios of neutrons and  $^3\text{He}$  with the “spin dressing” technique [20]).

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  $^3\text{He}$  polarization along with neutron storage time.
4. Understanding of polarized  $^3\text{He}$  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.

#### 1.2.4 TRIUMF Neutron EDM

The basic design of the experiment calls for a room-temperature EDM experiment to be connected to a cryogenic UCN source [24]. Neutrons will be moderated and converted into UCNs via down-scattering in superfluid He. The source will be operated at the Research Center for Nuclear Physics (RCNP, Osaka) and then moved to TRIUMF (Canada’s National Laboratory for Particle and Nuclear Physics, Vancouver). The goal is to achieve  $> 5000$  UCN/cm<sup>3</sup> in an nEDM measurement cell. A prototype nEDM apparatus has been characterized in beam tests at RCNP Osaka. Using this apparatus the collaboration has already demonstrated long UCN storage lifetimes, polarization lifetimes, and transverse spin relaxation times.

The EDM apparatus has a few unique features: A spherical coil within a cylindrical magnetic shield is used to generate the DC magnetic field; a  $^{129}\text{Xe}$  comagnetometer is used to address false EDMs due to a geometric phase effect; and due to the expected higher UCN density, the measurement cell size is designed

to be considerably smaller than the previous ILL apparatus. While having a negative impact on statistics, the reduced cell size limits systematic effects, particularly from the geometric phase effect.

In 2012-13, the collaboration will develop an improved EDM experiment, including a new superconducting polarizer system for the UCN, and a demonstration of precision Xe comagnetometry. In 2013-14 the collaboration intends to complete an nEDM experiment at RCNP, with a targeted precision of  $d_n < 1 \times 10^{-26} e \cdot \text{cm}$ , a factor of three better than the present limit. The experiment and source will then be moved to TRIUMF and recommissioned (on a new proton beamline currently under development) in 2015-16. Further improvements to the magnetic shielding, comagnetometry, EDM cell, and detectors will be made, resulting in a precision of  $d_n < 1 \times 10^{-27} e \cdot \text{cm}$ . The long-term goal, to be reached in 2018 and beyond, is  $d_n < 1 \times 10^{-28} e \cdot \text{cm}$ . Experiments on the neutron lifetime and on neutron interferometry are also considered as candidates for the long-term physics program.

### 1.2.5 Munich Neutron EDM

At the new UCN source of FRM-II in Garching, Germany, a next-generation neutron EDM experiment aims to achieve a statistical limit of  $d_n < 5 \cdot 10^{-28} e \cdot \text{cm}$  at  $3\sigma$  and a corresponding control of systematic effects of  $\sigma_{d, \text{syst}} < 2 \cdot 10^{-28} e \cdot \text{cm}(1\sigma)$ . The source of UCN is placed in a tangential beam tube inside the reactor with a thermal neutron flux of  $10^{14} \text{ s}^{-1}$ . Solid deuterium is used as a super-thermal converter for the production of UCN [25]. Operation of the source at the reactor is expected in 2013. A beam line made from specially prepared replica foil tubes with a relative transmission of  $> 0.99$  per meter guides the UCNs to the nEDM spectrometer, which is placed outside the reactor building in a new experiment hall at 27 m distance from the solid deuterium source. Taking into account production, volumes and losses of all components and the EDM chambers, the projected polarized UCN density is  $> 3000 \text{ cm}^{-3}$  in the EDM experiment.

This experiment is based on UCN stored in two vertically aligned cylindrical vessels at room temperature and a vertical magnetic field  $B_0$ . In between the cells a high voltage electrode is placed to enable measurements with an electric field parallel and anti-parallel to  $B_0$  simultaneously. For EDM measurements, Ramsey's method of separated oscillatory fields is applied to these trapped UCN. With a precession time of  $T = 250 \text{ s}$ , an electric field  $E = 18 \text{ kV/cm}$ , the statistical sensitivity goal can be achieved in 200 days. In addition, a co-magnetometer based on polarized  $^{199}\text{Hg}$  vapor with a laser based optical system is placed in these cells [10]. In addition, external magnetometers are used to measure the field distribution online. Buffer gases can be added to all magnetometers to investigate various systematic effects and to eventually increase the high voltage behavior.

The construction work for the beam position, as well as the installation of clean rooms, compensation system and outer magnetic shielding is ongoing. Subsequently, the installation of magnetometry systems and the inner magnetic environment is scheduled for 2012, after finalizing ongoing tests of a small scale prototype.

### 1.2.6 Proton Storage Ring EDM

The storage ring EDM collaboration has submitted a proposal to DOE for a proton EDM experiment sensitive to  $10^{-29} e \cdot \text{cm}$  [26]. 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  $0.7 \text{ GeV}/c$  in an all-electric storage ring with a radius of  $\sim 40 \text{ m}$ . 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 [30]. 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 [31]. 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  $\sim 25\mu\text{m}$  in the relative positioning of the E-field plates around the ring.

### 1.2.7 Mercury-199 Atomic EDM

The mercury atom provides a rich hunting ground for sources of CP violation. An EDM in  $^{199}\text{Hg}$  could be generated by EDMs of the neutrons, protons, or electrons, by chromo-edms of the quarks, by CP-odd electron-nucleon couplings, or by  $\theta_{QCD}$ , the CP-odd term in the strong interaction Lagrangian. The current upper limit on the Hg EDM [10],  $d(^{199}\text{Hg}) < 3.1 \times 10^{-29} e\text{cm}$ , places the tightest of all limits on chromo-edms, the proton edm, and CP odd electron-nucleon couplings.

The statistical sensitivity of the current upper limit on  $d(^{199}\text{Hg})$  was limited by two noise sources: light shift noise and magnetic Johnson noise. The light shift noise was due to a combination of residual circular polarization of the probe light and a small projection of the probe light axis along the main magnetic field axis. This noise was subsequently reduced by a factor ten by better alignment of the probe light axis and will be further reduced by letting the atoms precess in the dark. The next data runs will be taken with the probe light on only at the start and end of the precession period. The magnetic Johnson noise was generated by thermally excited currents in the aluminum cylinder that held the windings of the main magnetic field coil. The aluminum coil form has been replaced by an insulating coil form, leaving magnetic field noise from the innermost magnetic shield as the dominant remaining noise source. If the dominant noise source in the next data runs is indeed noise from the magnetic shield, then a factor of ten improvement in statistical sensitivity can be achieved with the existing Hg EDM apparatus.

An increase in statistical sensitivity requires a corresponding increase in the control of systematic errors. The dominant systematic error has been imperfect knowledge about the magnetic fields produced by leakage

currents across the Hg vapor cells when high voltage is applied across the cells. Recently, it was found that most of the leakage current flows along electric field lines in the dry nitrogen gas exterior to the cells; these gas currents can be amplified and have been shown to not produce measurable systematic errors. Roughly 10% of the total current flows along the cell walls and will be a source for concern. However, by maintaining these cell wall leakage currents below 0.01 pA, as has been achieved in earlier EDM measurements, a ten-fold improvement in the leakage current systematic error can be achieved.

In summary, unless unforeseen problems emerge, the existing Hg EDM apparatus can provide a ten-fold increase in sensitivity to an Hg atom EDM. This would still be roughly a factor of ten larger than the shot noise limit of the current apparatus. If warranted, a new apparatus could be developed to go further. A larger diameter and thicker walled innermost magnetic shield would reduce the magnetic field noise and additional magnetometers could be installed to provide further information about the field stability. Redesigned vapor cells could reduce the leakage currents and better direct their paths (eg rectangular cells with a reduced electric field gap). An additional factor of five increase in sensitivity would be feasible.

### 1.2.8 Radon-221,223 Atomic EDM

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  $^{199}\text{Hg}$ . 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  $N = 134$ , and isotopes  $^{221/223}\text{Rn}$  and  $^{225}\text{Ra}$  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 100 or more compared to  $^{199}\text{Hg}$  have been predicted by models using Skyrme-Hartree-Fock for  $^{225}\text{Ra}$  [32] and Woods-Saxon and Nilsson potentials in the case of  $^{223}\text{Rn}$  [33]. However, the uncertainties on the size of enhancements are quite large, in part due to uncertainty in the  $^{199}\text{Hg}$  Schiff moment, and, in the case of  $^{221/223}\text{Rn}$  isotopes, the absence of nuclear structure data.

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  $^{129}\text{Xe}$ , it was measured that  $d = 0.7 \pm 3.4 \times 10^{-27} e \cdot \text{cm}$  [34]. 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  $^{221/223}\text{Rn}$  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  $^{209}\text{Rn}$  and  $^{223}\text{Rn}$  [35, 36]. 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  $^{129}\text{Xe}$  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. Fragmentation can produce useful quantities of these isotopes for development, and the beam-dump at FRIB may be a source for harvesting large quantities for an EDM measurement. Isotope-separator techniques, such as those used at TRIUMF and ISOLDE, have direct yields that are much higher, and would be a great advantage for the future of the RadonEDM program.

### 1.2.9 Radium-225 Atomic EDM

The primary advantage of  $^{225}\text{Ra}$  is the large enhancement [33, 39, 40], approximately a factor of 1000, of the atomic EDM over  $^{199}\text{Hg}$  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 [42] and Kernfysisch Versneller Instituut (KVI) [38]. The scheme at Argonne is to measure the EDM of  $^{225}\text{Ra}$  atoms in an optical dipole trap (ODT) as first suggested in Ref. [41]. 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  $10^{-30} e \cdot \text{cm}$  [41].

The Argonne collaboration demonstrated the first magneto-optical trap (MOT) of Ra atoms [42], 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  $10^{-26} e \cdot \text{cm}$ , which should be competitive with  $10^{-29} e \cdot \text{cm}$  for  $^{199}\text{Hg}$  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  $^{225}\text{Ra}$  presently available. The next-generation isotope facility, such as FRIB after upgrade or Project X, is expected to produce more than  $10^{13}$   $^{225}\text{Ra}$  atoms/s [43]. In this case it should be possible to extract more than 1 Ci of  $^{225}\text{Ra}$  for use in the EDM apparatus. This would lead to a projected sensitivity of  $10^{-28} - 10^{-29} e \cdot \text{cm}$  for  $^{225}\text{Ra}$ , competitive with  $10^{-31} - 10^{-32} e \cdot \text{cm}$  for  $^{199}\text{Hg}$ . Table 1-2 summarizes the projected sensitivities.

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

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

### 1.2.10 Electron EDM with polar molecules

**YbF:** Although the Standard Model predicts that the EDM of the electron is far too small to detect, being some eleven orders of magnitude smaller than the current experimental sensitivity, many extensions of the Standard Model naturally predict much larger values of eEDM that should be detectable. This makes the search for eEDM a powerful way to search for new physics and constrain the possible extensions. Cold polar molecules YbF have been used to measure eEDM at the highest level of precision reported so far, setting the upper limit at  $d_e < 1.05 \times 10^{-27} e \cdot \text{cm}$  (90% C.L.) [9].

Previous eEDM measurements were performed on neutral heavy atoms such Tl [44]. Dipolar molecules have two great advantages over atoms. First, at a modest operating electric field the interaction energy of YbF due to eEDM is 220 times larger than that obtained using Tl in a much larger electric field. Second, the motional magnetic field, a source of systematic error that plagued the Tl experiment, has a negligible effect on YbF. Because of these advantages, it is possible to improve on the Tl experiment by using YbF molecules, even though the molecules are produced in much smaller numbers. The collaboration is developing a cryogenic source of YbF that yields a higher flux of molecules at three times slower velocity. With this new source, the eEDM sensitivity is likely to be pushed down to  $10^{-28} e \cdot \text{cm}$ . Long-term plan aims to reach  $10^{-30} e \cdot \text{cm}$  with the development of a molecular fountain based on laser cooling of YbF.

**ThO:** The Advanced Cold Molecule EDM (ACME) collaboration uses a newly-developed cryogenic technique for creating molecular beams of unprecedented brightness [45], hence allowing large improvements in statistical sensitivity to an eEDM. ACME studies thorium monoxide (ThO), which combines the most favorable features of species used in other experiments [46]. In particular, the measurement takes place in the metastable  $H^3\Delta_1$  state of ThO; here the effective electric field acting on the eEDM is the largest known (104 GV/cm). This state has  $\Omega$ -doublet substructure, which makes it possible to spectroscopically reverse the internal E-field within the molecule; this in turn enables powerful methods for rejecting most anticipated systematic errors. Finally, in the  $H^3\Delta_1$  state there is a near-perfect cancellation of magnetic moments due to spin and orbital angular momenta; the resulting small magnetic moment ( $< 0.01$  Bohr magnetons) makes the experiment insensitive to systematic errors and noise due to uncontrolled magnetic fields.

The initial phases of apparatus construction are complete, and the entire apparatus is working robustly. Based on the recent data, the collaboration projects that the statistical sensitivity will be at least at the level of  $1 \times 10^{-28} e \cdot \text{cm}$  by 2013. Quantitative projections for systematic error limits are difficult in the absence of extensive data, but the collaboration is hopeful that the many built-in features for identifying and rejecting systematics will allow them to make a statistics-limited measurement. In the longer term, the collaboration has identified a host of methods to improve the molecular beam flux and the efficiency of state preparation and detection. Upgrades to signal size will be incorporated into the experiment after the initial measurement with the current apparatus. Overall, the collaboration projects a sensitivity that could ultimately reach  $3 \times 10^{-31} e \cdot \text{cm}$ .

### 1.2.11 Electron EDM with Francium

An eEDM experiment using francium atoms can challenge SUSY with unambiguous results. There are no hadronic effects that need to be subtracted out. The relation between an EDM of an alkali atom and of an electron is the simplest and most reliably calculated EDM effect in any multi-electron system. The calculations have been performed using different techniques and by different authors with numerical

differences typically less than 20%. Moreover, the calculations are similar to those used for calculating parity violating effects in atoms and so have indirectly been validated by experiments.

With francium comes a higher sensitivity to an electron EDM than any atom previously used. The large nuclear spin and magnetic dipole moment of  $^{211}\text{Fr}$ , 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  $\mathbf{B}_{\text{mot}} = \mathbf{v} \times \mathbf{E}/c^2$  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  $^{211}\text{Fr}$  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  $10^{13}$   $^{211}\text{Fr}/\text{s}$  - sufficient to lower the electron EDM upper limit by a factor of  $10^3$ .

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