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Nucleons, Nuclei, and Atoms

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7.1 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 in represented by the CERN Large Hadron Collider. The alternative is to seek signals of the new physics in subtle violations of symmetry in our low-energy world – ultra-weak 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: ultra-sensitive 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}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 1970s 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}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 Committee (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.

Fundamental symmetry tests with nucleons, nuclei, and atoms is remarkably diverse. In preparation for this report, the working group conveners received more than 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 the University of 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 report 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 report. 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 chapter 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 timescale. 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 of 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 timescale.

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 Institut Laue-Langevin (ILL) in Grenoble, France 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 (FEL) concept described below. Again, the omission of these and other international efforts merely reflects the timescale 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 worldwide 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.

7.2 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. 7-1). 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 $2.9 \times 10^{-26} e\cdot$cm [7].

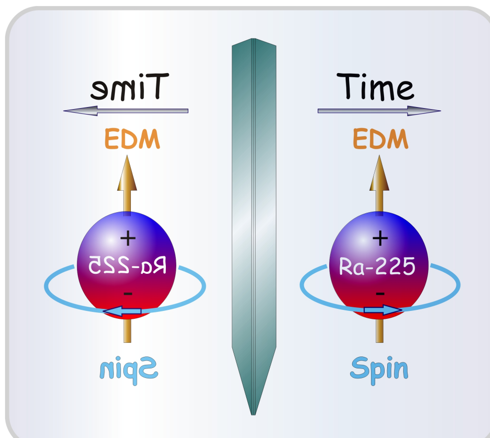

Figure 7-1. *EDM violates time-reversal symmetry. When time is reversed, the spin is reversed, but the EDM is not. Therefore, there is a measurable difference between the particle and its image in the time-reversed world.*

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 Supersymmetry (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 conditions 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 generate EDMs only 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

Table 7-1. *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 [9]	10^{-38}
Neutron	2.9×10^{-26}	ultra-cold neutrons in a bottle [7]	10^{-31}
Nucleus	3.1×10^{-29}	^{199}Hg atoms in a vapor cell [10]	10^{-33}

the neutron EDM is expected to be approximately 10^{-32} $e\cdot$cm, 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 ongoing experiments, including scenarios that would generate the cosmic baryon asymmetry with new Terascale CP-violating interactions (see, *e.g.*, [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 non-zero 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 into the scale of the next energy frontier.

The most sensitive EDM searches have so far been conducted on the neutron, neutral atoms (^{199}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 ultra-cold neutrons (UCNs) is becoming available. Their higher output in neutron flux will enable searches for the neutron EDM projected at a sensitivity level of 10^{-28} $e\cdot$cm, or two orders of magnitude below the current best limit. A survey of neutron EDM experiments is presented in this section. Also at the intensity frontier, future isotope production facilities such as the Facility for Rare Isotope Beams (FRIB) at Michigan State University (after upgrade) or Project X at Fermilab, will produce prolific amounts 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.

7.2.1 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 2.9×10^{-26} $e\cdot$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 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 ultra-cold neutrons 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 $\sigma(d_\mathrm{n}) = 2.6 \times 10^{-27}\, e\cdot\mathrm{cm}$, which corresponds to an upper limit of $d_\mathrm{n} < 5 \times 10^{-27}\, e\cdot\mathrm{cm}$ (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 $d_\mathrm{n} < 5 \times 10^{-28}\, e\cdot\mathrm{cm}$ [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 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}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.

7.2.2 ILL Neutron EDM

CryoEDM: The CryoEDM experiment at ILL uses resonant downscattering of **fix tex error**neutrons in a bath of superfluid ^{4}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 Petersburg Nuclear Physics Institute (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 diameter of 136 mm 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 cm^{-3}, shall lead to an EDM measurement with a counting statistical accuracy of 1.5×10^{-26} $e\cdot$cm during 200 days of operation at PF2.

7.2.3 SNS Neutron EDM

The goal of the SNS nEDM experiment, to be carried out at the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory, is to achieve a sensitivity of $< 3 \times 10^{-28}$ $e\cdot$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 [20], 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 protons and tritons, 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 [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}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.

7.2.4 TRIUMF Neutron EDM

The basic design of this 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^3 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}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 $d_n < 1 \times 10^{-26}$ $e \cdot$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 $d_n < 1 \times 10^{-27}$ $e \cdot$cm. The long-term goal, to be reached in 2018 and beyond, is $d_n < 1 \times 10^{-28}$ $e \cdot$cm. Experiments on the neutron lifetime and on neutron interferometry are also considered as candidates for the long-term physics program.

7.2.5 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 $d_n < 5 \cdot 10^{-28}$ $e \cdot$cm at 3σ and a corresponding control of systematic effects of $\sigma_{d,syst} < 2 \cdot 10^{-28}$ $e \cdot$cm(1σ). The source of UCN is placed in a tangential beam tube inside the reactor with a thermal neutron flux of 10^{14} 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 beamline 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 27 m 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 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 $T = 250$ s and an electric field $E = 18$ kV/cm, the statistical sensitivity goal can be achieved in 200 days. In addition, a co-magnetometer based on polarized ^{199}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.

7.2.6 Proton Storage Ring EDM

The storage ring EDM collaboration has submitted a proposal to DOE for a proton EDM experiment sensitive to $10^{-29} e\cdot$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 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; this serves as a limiting aperture. The collaboration has over the years developed the method and improved their understanding and confidence in it. Some notable accomplishments are listed below:

1. Systematic errors and the efficiency and analyzing power of the polarimeter have 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 $\sim 25\mu$m in the relative positioning of the E-field plates around the ring.

7.2.7 Mercury-199 Atomic EDM

The mercury atom provides a rich hunting ground for sources of CP violation. An EDM in ^{199}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 θ_{QCD}, the CP-odd term in the strong interaction Lagrangian. The current upper limit on the Hg EDM [10], $d(^{199}\text{Hg}) < 3.1 \times 10^{-29} e\cdot$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 $d(^{199}Hg)$ 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 of 10 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 10 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 10-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 10-fold increase in sensitivity to an Hg atom EDM. This would still be roughly a factor of 10 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 (*e.g.*, rectangular cells with a reduced electric field gap). An additional factor of five increase in sensitivity would be feasible.

7.2.8 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}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 $^{221/223}$Rn and ^{225}Ra are promising both for 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}Hg have been predicted by models using Skyrme-Hartree-Fock for ^{225}Ra [32] and Woods-Saxon and Nilsson potentials in the case of ^{223}Rn [33]. 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.

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 [34]. A number of techniques have been developed including spin-exchange-optical-pumping (SEOP) using rubidium and 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 on the order of 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 [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}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.

7.2.9 Radium-225 Atomic EDM

The primary advantage of ^{225}Ra is the large enhancement [33, 39, 40], 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 [42] and Kernfysisch Versneller Instituut (KVI) [38]. The scheme at Argonne is to measure the EDM of ^{225}Ra atoms in an optical dipole trap (ODT) as first suggested in [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 $10^{-30}e\cdot$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 $10^{-26}e\cdot$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 Phases 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 [43]. 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 7-2 summarizes the projected sensitivities.

Table 7-2. *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
$d(^{225}\text{Ra})$ $(10^{-28} e\cdot\text{cm})$	100	10	0.1-1
equiv. $d(^{199}\text{Hg})$ $(10^{-30} e\cdot\text{cm})$	10	1	0.01-0.1

7.2.10 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 11 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 of YbF have been used to measure eEDM at the highest level of precision reported so far, setting the upper limit at $d_e < 1.05 \times 10^{-27}\, e\cdot$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 $10^{-28}\, e\cdot$cm. The long-term plan aims to reach $10^{-30}\, e\cdot$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 Ω-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 1×10^{-28} $e\cdot$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 3×10^{-31} $e{\cdot}$cm.

7.2.11 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 that 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}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 $\mathbf{B}_{\rm mot} = \mathbf{v} \times \mathbf{E}/\mathbf{c^2}$ 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.

7.3 Weak Decays

The study of weak decays of hadrons built from light quarks continues to provide some of the most precise input for the Standard Model as well as stringent constraints of various Standard Model extensions. In particular, the most precisely determined element of the Cabibbo-Kobayashi-Maskawa matrix, $V_{\rm ud}$, is obtained from "superallowed" Fermi nuclear transitions, while tests of the universality of the charged-current weak interactions of leptons obtained with pion decays are approaching similar levels of precision. At present, there exists considerable effort in three directions involving semileptonic charged-current weak interactions of hadrons: studies of pion and kaon leptonic decays; ongoing measurements of weak interaction nuclear transitions; and studies of neutron decays and interactions. Here we survey some of the present activity and future opportunities.

7.3.1 Pion and Kaon Leptonic Decay

The absence of an explanation for the generation puzzle – why do we have exactly three versions of each quark and lepton? – is a major flaw in the highly successful Standard Model. Electron-muon universality, within the context of the SM, is the hypothesis that charged leptons have identical electroweak gauge interactions and differ only in their masses and coupling to the Higgs. However, there could be additional new physics effects, such as non-universal gauge interactions or scalar or pseudoscalar bosons with couplings not simply proportional to the lepton masses, that would violate universality.

One of the most sensitive approaches to seeking such new interactions is the study of the ratio of decay rates of pions [47]

$$R^{\pi}_{e/\mu} \equiv \frac{\Gamma(\pi \to e\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))} \tag{7.1}$$

which in the SM is predicted to be 1.2351(2) with an uncertainty of ± 0.02% [48, 49, 50]. New physics at scales as high as 1000 TeV can be constrained or conceivably unveiled by improved measurements of this ratio. One example [47] is a charged physical Higgs boson with couplings $g\lambda_{ud}/2\sqrt{2}$ to the pseudoscalar current $\bar{u}\gamma_5 d$ and $g\lambda_{l\nu}/2\sqrt{2}$ to the current $\bar{l}(1-\gamma_5)\nu_l$, $l = e, \mu$, where g is the $SU(2)_L$ gauge coupling and λ represents chiral breaking suppression factors. One finds

$$m_{H^{\pm}} \sim 200 \text{ TeV} \sqrt{\lambda_{ud}(\lambda_{e\nu} - \frac{m_e}{m_\mu}\lambda_{\mu\nu})} \tag{7.2}$$

If $\lambda_{e\nu}/\lambda_{\mu\nu} = m_e/m_\mu$, as in the minimal two-Higgs doublet model, there is no sensitivity to new physics. However, in more general multi-Higgs models such a chiral relationship is not necessary and λ may not be too suppressed. For example, in the case of loop-induced charged Higgs couplings $\lambda_{e\nu} \sim \lambda_{\mu\nu} \sim \lambda_{ud} \sim \alpha/\pi$, one finds a $R^{\pi}_{e/\nu}$ determination to ± 0.1% is sensitive to $m_{H^{\pm}} \sim 400$ GeV. If a discrepancy between theory and experiment is found in $R^{\pi}_{e/\mu}$, some type of charged Higgs explanation would be quite natural. However, such a result could also point to additional charged axial-vector interactions or loop effects due to new physics [51]. It could also be interpreted as the damping of one of the π_{l2} modes by heavy neutrino mixing. Analogous K decays,

$$R^{K}_{e/\mu} \equiv \frac{\Gamma(K \to e\nu(\gamma))}{\Gamma(K \to \mu\nu(\gamma))}, \tag{7.3}$$

can also probe high scales and have the added appeal of being particularly sensitive to the lepton flavor-violating decay $K^+ \to e^+ + \nu_\tau$, a process that might be induced through loop effects [52].

7.3.1.1 Experimental Studies of $\pi \to e\nu$ and $K \to e\nu$ Decays

The most recent $\pi^+ \to e^+\nu$ (π_{e2}) branching ratio measurements and subsequent determination of the ratio $R^{\pi}_{e/\mu}$ were done at TRIUMF [53] and PSI [54] in the 1990s. The results from the two experiments are consistent and in good agreement with the SM expectation previously discussed,

$$R^{\pi-\text{TRIUMF}}_{e/\mu} = 1.2265(34)(44) \times 10^{-4} \qquad R^{\pi-\text{PSI}}_{e/\mu} = 1.2346(35)(36) \times 10^{-4}, \tag{7.4}$$

where the first and second uncertainties are due to statistical and systematic effects. The Particle Data Group (PDG) average value is $R^{\pi}_{e/\mu} = 1.230(4) \times 10^{-4}$ [55], which includes results from [56]. Two new experiments are under way at TRIUMF [57] and PSI [58] which promise to improve the precision of $R^{\pi}_{e/\mu}$ by a factor of 5 or more, thereby testing the SM prediction to better than ?0.1%. At that level of precision, new physics effects could appear as a deviation; in the absence of a deviation, strong new constraints would be imposed on such physics.

The PIENU experiment at TRIUMF [57] is based on a refinement of the technique used in the previous TRIUMF experiment [53]. The branching ratio will be obtained from the ratio of positron yields from the $\pi \to e\nu$ and from the $\pi \to \mu \to e$ decay chain. By measuring the positrons from these decays in a non-magnetic spectrometer, many normalization factors, such as the solid angle of positron detection, cancel to first order, so that only small corrections for energy-dependent effects, such as those for multiple Coulomb scattering (MCS) and positron annihilation, remain. Major improvements in precision stem from the use of an improved geometry, a superior calorimeter, high-speed digitizing of all pulses, Si strip tracking, and higher statistics. The improvements lead to an expected precision on the $R^{\pi}_{e/\mu}$ branching ratio of < 0.06 %, which corresponds to a 0.03 % uncertainty in the ratio of the gauge boson-lepton coupling constants g_e/g_μ testing electron-muon universality.

At PSI, the PIBETA CsI spectrometer [59], built for a determination of the $\pi^+ \to \pi^0 e\nu$ branching ratio and other measurements [60], has been upgraded and enhanced for the PEN [58] measurement of the $\pi \to e\nu$ branching ratio. The PEN technique is similar to that employed in the previous PSI experiment [54], which used a nearly 4π-sr BGO spectrometer. PEN began operations in 2007 and has observed $> 10^7$ $\pi \to e\nu$ decays. PEN completed data acquisition in 2010 and expects to reach a precision of $< 0.05\%$ in $R^{\pi}_{e/\mu}$.

Recent progress on $R^{K}_{e/\mu}$ has been made by KLOE [61] and NA62 [62], with current NA62 efforts aimed at reaching a precision of 0.4%. KLOE collected 3.3 billion K^+K^- pairs, observing decay products in a drift chamber in a 0.52T axial magnetic field surrounded by an electromagnetic calorimeter. The measurement of $R^{K}_{e/\mu}$ consisted of comparing the corrected numbers of decays observed from the $K \to e\nu(\gamma)$ and $K \to \mu\nu(\gamma)$ channels. The result, $R^{K\ KLOE}_{e/\mu} = (2.493 \pm 0.025(\text{stat}) \pm 0.019(\text{syst})) \times 10^{-5}$ [61], agrees with the SM prediction at the 1% level.

NA62 at CERN, using the setup from NA48/2, has embarked on a series of $K_{e2}/K_{\mu 2}$ measurements [62]. The K^+ beam is produced by the 400 GeV/c SPS. Positively charged particles within a narrow momentum band of (74.0 ± 1.6) GeV/c are selected by an achromatic system of four dipole magnets and a muon sweeping system and enter a fiducial decay volume contained in a 114 m long cylindrical vacuum tank, producing a secondary beam. The $K \to e\nu(\gamma)$ and $K \to \mu\nu(\gamma)$ detection system includes a magnetic spectrometer, a plastic scintillator hodoscope, and a liquid krypton electromagnetic calorimeter. As in KLOE, the experimental strategy is based on counting the numbers of reconstructed $K \to e\nu(\gamma)$ and $K \to \mu\nu(\gamma)$ events concurrently, eliminating dependence on the absolute beam flux and other potential systematic uncertainties. The result, $R^{K\ NA62}_{e/\mu} = (2.487 \pm 0.011(\text{stat}) \pm 0.007(\text{stat})) \times 10^{-5}$ [62], is based on 40% of the data acquired in 2007 and agrees with the SM prediction. The full data sample may allow a statistical uncertainty of 0.3% and a total uncertainty of 0.4-0.5% .

7.3.1.2 Future Prospects

If PIENU and PEN achieve their sensitivity goals there will still be a considerable window in which new physics could appear without complications from SM prediction uncertainties. Reaching the uncertainty 0.02%, the level of current SM calculations, would require a new generation of experiments capable of controlling systematic uncertainties at or below 0.01%. High-precision measurements of $R_{e/\mu}^{\pi/K}$ will be an important complement to LHC high-energy studies. High intensity beams with 100% duty factors and ultra-high intensities and purities will be important to ultra-high precision experiments on $\pi/K \to e/\mu$. Such experiments potentially could lead to breakthroughs in our understanding of $e-\mu$ universality and are sensitive to a variety of subtle non-SM effects. Project X would provide such beams for pions and kaons, while pion studies could continue with the beams available at PSI or TRIUMF.

7.3.2 Superallowed Nuclear Decay and CKM Unitarity

7.3.2.1 Goals of β-Decay Studies

Studies of weak interactions based on nuclear β decay are currently focused on probing the limits of the Standard Model: Both the conserved vector current (CVC) hypothesis and the unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) matrix are being tested with ever-increasing precision. To do so, it is necessary first to isolate the vector part of the combined vector and axial-vector ($V-A$) structure of the weak interaction, a requirement that is satisfied by superallowed $0^+ \to 0^+, \Delta T = 0$ nuclear decays, which are pure vector transitions. These transitions occur in a wide range of nuclei ($10 \leq A \leq 74$) and yield the vector interaction strength in each case. If CVC is valid, then the strength of the vector interaction is not renormalized in the nuclear medium but is a "true" constant; and, so far, the constancy of the strength is confirmed by these superallowed decays at the level of 10^{-4} [63]. With CVC satisfied, these results also lead to today's most precisely determined value of the CKM matrix element, V_{ud}: 0.97425 ± 0.00022 [63].

When V_{ud} is combined with the V_{us} and V_{ub} values obtained from kaon and B-meson decays, respectively, the sum of squares of the top-row elements of the CKM matrix provides the most demanding test available of the unitarity of the matrix. The result, currently standing at 0.99990(60) [64], agrees with unitarity; and its precision, which can still be improved, sets limits on extensions to the Standard Model that could break the three-term unitarity of the CKM matrix. Other tests of the weak interaction involve asking whether it is pure $V-A$ as assumed in the Standard Model or whether there are small components of S (scalar) or T (tensor) interactions. The $0^+ \to 0^+$ superallowed decays also set a limit on S but not on T. This topic is taken up further in the report of Savard and Behr [65].

7.3.2.2 Superallowed $0^+ \to 0^+$ Transitions

The study of β decay between $(J^\pi, T) = (0^+, 1)$ nuclear analog states has been a fertile means of testing the Standard Model. Because the axial current cannot contribute to transitions between spin-0 states, only the vector current is involved in these transitions. Thus, according to CVC, the experimental ft-value for each of these superallowed transitions should be simply related to the fundamental weak-interaction coupling constant, G_V. The ft-value itself depends on three measured quantities: the total transition energy, Q_{EC}, the half-life, $t_{1/2}$, of the parent state, and the branching ratio, R, for the particular transition of interest. The first of these can be measured in a Penning trap, where a very few ions are sufficient for high precision; however, both $t_{1/2}$ and R require large numbers of observed decays to achieve the required statistics. Currently, the best-known superallowed decays are from nuclei rather close to stability, which are easily produced. However, future improvements in precision will need comparable measurements on transitions from nuclei much farther from stability. Higher intensity beams will be required to produce them.

7.3.2.3 Superallowed $J \to J$ Transitions

The vector current also contributes to $J \to J$, $T = 1/2$ mirror decays, which can also, in principle, be used to determine the CKM matrix element, V_{ud}. The difficulty is that these transitions are not pure vector in character but include a mix of vector and axial-vector contributions. Thus a correlation experiment is needed to separate one from the other. Today's accuracy in correlation experiments is insufficient for this method to be competitive. Nevertheless, there are also many examples of $J \to J$ transitions, and the uncertainty can be reduced if enough are included in an average. Naviliat-Cuncic and Severijns [66] have studied $J \to J$ transitions between odd-mass mirror states in $T = 1/2$ nuclei. Their average from the five measured transitions leads to a V_{ud} value whose uncertainty is about 10 times larger than the result from superallowed beta decay. In future, further experiments on $T = 1/2$ mirror decays, both near and far from stability, can certainly improve the accuracy of this V_{ud} determination.

7.3.2.4 Neutron β Decay

Neutron β decay is conceptually the simplest example of a mixed vector and axial-vector $T = 1/2$ mirror decay. Unfortunately, the simplicity that this brings to its theoretical analysis is more than counterbalanced by the experimental difficulties encountered in confining the neutron long enough to measure its properties. At present there are conflicting results – well outside of statistics – for the neutron mean-life, a situation that has driven the Particle Data Group [67] to "call upon the experimenters to clear this up." The internal agreement among the correlation measurements is better, but is far from satisfactory since there has been a systematic drift in the measured central value of $\lambda = g_A/g_V$ over the past two decades. More measurements are clearly required.

7.3.2.5 Roadblocks and Opportunities

There are two roadblocks to the experimental quest for a more accurate V_{ud} value. First, there is a radiative correction to be included in the analysis, and a part of this, known as the inner radiative correction, is not well determined. A recent evaluation by Marciano and Sirlin [68] reduced its uncertainty by a factor of two; but, even so, the new uncertainty remains the largest contributor to the error budget for V_{ud}. Second, the use of the CVC hypothesis is valid only in the isospin-symmetry limit. In nuclei, the presence of the Coulomb force acting between protons breaks isospin symmetry, as does charge dependence in the nuclear force to a lesser extent. So an isospin-symmetry breaking correction, denoted δ_C, needs to be evaluated and this involves a nuclear-structure-dependent calculation. The estimated uncertainty in the model dependence of these calculations is the second largest contributor to the error budget for V_{ud}. There has been a lot of recent activity in δ_C calculations for the $0^+ \to 0^+$ superallowed decays [69, 70, 71, 72, 73, 74], with considerable disparity being evident among the results.

Fortunately, there is an opportunity here. Towner and Hardy [75] have proposed an experimental test rooted in the requirement that the δ_C calculations should yield results consistent with a conserved vector current. To date, shell-model-based calculations [74] satisfy this test the best, and it is these calculations that have been used in the extraction of V_{ud}. Further precise experiments could improve the test and reduce the uncertainty on V_{ud}. Calculations anticipate somewhat larger δ_C values for the decays of $T_z = \text{-}1$ superallowed emitters with $A \leq 42$, and much larger values for $T_z = 0$ emitters with $A \geq 62$. If experiment confirms these large calculated δ_C values, then it validates the much smaller values for the transitions now used to obtain V_{ud}. In particular, the different calculations give a range of predictions for mirror pairs of transition such as: ^{26}Si ($T_z = \text{-}1$) $\to$ ^{26}Al ($T_z = 0$) versus ^{26}Al ($T_z = 0$) $\to$ ^{26}Mg ($T_z = 1$). The decay of the $T_z = -1$ member of each pair requires a very difficult branching-ratio experiment to be performed but, if successful, the result would be very revealing for the δ_C calculations. For the other group of emitters with $A \geq 62$, only ^{62}Ga has so far been measured with the requisite precision. Experiments on lifetimes, branching ratios, and Q-values for ^{66}As, ^{70}Br and ^{74}Rb would be very welcome.

A recent bellwether experiment [76] focused on the beta decay of ^{32}Cl. One of its branches is a $J \rightarrow J$, $\Delta T = 0$ transition for which theory fortuitously predicts a negligibly small axial-vector component. Thus it could be analysed as if it were a pure Fermi transition. The result it yielded corresponded to a very large isospin-symmetry-breaking correction of order 5%. Being a nucleus with $A = 4n$, large isospin-symmetry breaking could be anticipated since the daughter state lies very close in energy to a state of the same spin and different isospin. As a consequence, the case provides a critical challenge to the δ_C calculations, a challenge that was successfully met by the same type of shell-model-based calculations used to analyze the $0^+ \rightarrow 0^+$ transitions. In future an examination of other $J \rightarrow J$ transitions from $A = 4n$ nuclei should be undertaken to seek other examples with small axial-vector contributions accompanied by large isospin-symmetry breaking.

7.3.3 Neutron Decay

Beta-decay studies provide a remarkable tool to probe the helicity structure and quark-lepton universality of the electroweak interaction, providing model independent constraints on the effective new physics energy scale in the multi-TeV range. Measurements of neutron beta-decay also provide basic parameters for the charged weak current of the nucleon.[77] In particular, neutron beta-decay measurements are the definitive source for g_A, the axial form factor, and provide a nuclear-structure-independent value for the CKM element V_{ud}. Although at present the $0^+ \rightarrow 0^+$ superallowed decays provide the most precise value for V_{ud}, the experimental data for the neutron continue to improve, and should become directly competitive with $0^+ \rightarrow 0^+$ during the next 10 years.

We note that g_A is important in our understanding of the spin and flavor structure of the nucleon[78, 79], a central target for high-precision lattice QCD studies[80, 81], an essential parameter for effective field theories[82], and one of a small set of parameters necessary in establishing high-precision predictions of solar fusion[83]. The neutron lifetime figures prominently in high precision predictions for big bang nucleosynthesis as well[84]. High precision values for g_A are also important for the reactor neutrino-anomaly question, one of the results driving current interest in short baseline oscillations studies[85]. The current value of g_A is $g_A = 1.2701(25)$.[86]

High precision neutron beta-decay studies also provide constraints on a large variety of extensions to the Standard Model. The most stringent constraints come through tests of the quark-lepton universality of the weak interaction, which within the Standard Model are equivalent to tests of the unitarity of the CKM quark mixing matrix. The strongest constraints come through unitarity tests on the first row: $V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.9999(6)$.[86] For any such test, the diagonal element dominates the sum, and a very high-precision ($<$ 0.02%) determination of this diagonal element (V_{ud} for unitarity tests of the first row of the CKM matrix) is necessary for a competitive unitarity constraint. Here beta decay also provides the highest-precision measurement of a diagonal CKM element, with the value extracted from $0^+ \rightarrow 0^+$ decay being $V_{ud} = 0.97425(22)$, and with the uncertainties from V_{ud} and V_{us} now contributing equally to the sum.[86]

The resultant constraints on (v,a) current interactions are quite stringent, with generic limits on the effective scale for new physics at roughly the 10 TeV level.[87] A large assortment of extensions to the Standard Model, including new Z' gauge bosons, generic Kaluza-Klein W* excitations, and charged Higgs bosons, are tightly constrained by the unitarity sum.[88] Flavor universality in supersymmetric extensions of the Standard Model are also constrained by the unitarity sum.[89] The robustness of these limits and enormous progress made in the kaon-sector in the precision and reliability with which V_{us} can be determined motivate continued effort on the experimental extraction of V_{ud}.[88] At present, the precision of V_{ud} from $0^+ \rightarrow 0^+$ decays is nominally limited by loop-level electroweak radiative corrections[90, 91]; however the nuclear-structur-dependent corrections for the $0^+ \rightarrow 0^+$ systems remain an area of active concern. Neutron beta-decay can provide a structure-independent value for V_{ud}, a significant contribution to the status of the current unitarity test.

The observables in neutron decay include a number of correlations (and the Fierz term, which influences the energy dependence of the total beta-decay rate) that provide multiple probes of non v-a interactions generated by Standard Model extensions.[77, 92] For example, constraints on (S, T) interactions arise from angular correlation measurements such as the neutrino asymmetry and the Fierz term. Because two observables with similar sensitivities to these terms are available, there is a consistency test within the neutron decay system itself for these effects. In particular, it is the aim of some beta-decay experiments (in the planning or construction phase at present) to reach sensitivities of a few parts in 10^{-4}. In this case, the model-independent constraints for interactions that only couple to electrons and induce scalar and tensor terms can be made quite stringent with next-generation beta decay experiments. For example, limits in the 5-10 TeV range which are significantly stronger than expected LHC limits are expected to be feasible. In addition, if a new particle resonance is discovered at the LHC, beta-decay experiments at this level of precision may provide complementary information on the quantum numbers and weak couplings of such a resonance, as was recently demonstrated for the case of a scalar resonance[93]. Relevant limits (complementary to those placed by LHC) can also be placed on supersymmetric couplings[94] and couplings to leptoquarks[95].

T-noninvariant angular correlations can also be probed in beta decay. These experiments can provide constraints on CP-violating phases beyond the Standard Model that are complementary to the ones derived from EDMs.[96, 97] In particular, a number of measurements have been performed of angular correlations proportional to complex, (V,A)couplings (parameterized by the "D" coefficient), with the ongoing work of the emiT[98] and TRINE[99] collaborations having established the basis for pushing sensitivities for T-violating phases to the final state effect level (10^{-5} level).

The past 10 years have seen significant growth in the number of physicists involved in neutron beta-decay measurements. Although it is beyond the scope of this brief summary to catalog all of the experimental activity in this subfield, it is characterized by often complementary experiments with cold and ultra-cold neutrons and has seen the emergence of precision measurements of radiative decay of the neutron [100] for the first time. A number of experiments are under way that target precisions near or at the 0.1% level in the next few years for the lifetime of the neutron[101], the electron-neutrino-asymmetry[102, 103] and the beta-asymmetry[104, 105]. Taken as a group, they provide a powerful consistency test for the form factors and Standard Model constraints that can be extracted at this level of precision[106].

Ongoing measurements have also set the stage for a number of ambitious experiments under development or construction that target precisions in the 10^{-4} range. For ultra-cold neutrons, for example, there are lifetime experiments based on material and magnetic trapping geometries[107, 108] and angular correlation experiments under development that are particularly sensitive to (S, T) interactions[110]. For angular correlation measurements with cold neutron beams, the PERC[111] collaboration based in Munich have as their goal polarimetry and other systematic errors ultimately in the low 10^{-4} range, and the Nab/ABba[112, 113] collaboration will be targeting systematic uncertainties below the 10^{-3} level for their measurements as well.

Intensity frontier development should provide the opportunity to optimize existing cold neutron beam delivery for fundamental neutron physics research, positively impacting beta-decay experiments as well as a variety of other fundamental neutron studies. For ultra-cold neutron-based experiments, the intensity frontier initiative could provide the opportunity to construct a next-generation source of extracted ultra-cold neutrons. Although work over the past 10 years has established viable strategies to significantly increase ultra-cold neutron densities, experiments remain strongly constrained by the ultra-cold neutron densities at existing sources. A next-generation source could permit the community to capitalize on the ongoing refinement of systematic errors in existing beta-decay, EDM and short-range interaction searches. In particular, for beta-decay studies, it should enable the next generation of beta-decay experiments with ultra-cold neutrons to reach sensitivities limited by systematic errors, and probe energy scales comparable to and in some cases above that planned for the LHC.

7.3.4 Neutron Lifetime

The decay of a free neutron is a semi-leptonic process that neatly probes the weak mixing of the quarks in the first generation of flavors. It provides a measurement of V_{ud}, the first of the elements of the CKM matrix, which quantifies the relative rotation between the weak eigenstates and the flavor eigenstates of quarks. The current best determination of V_{ud} comes from the combined analysis of 20 different $0^+ \rightarrow 0^+$ nuclear decays, which are ultimately limited by theoretical uncertainties in the knowledge of nuclear structure and corrections associated with isospin symmetry breaking [114]. Though experiments with free neutrons are less precise, improvements could yield independent information on V_{ud} useful for performing unitarity tests of the CKM matrix, an important part of the program of testing the Standard Model. In addition, neutron β-decay includes both Fermi and Gamow-Teller transitions. In the SM framework, the neutron decay amplitude is proportional to the linear sum of the squares of the weak vector and axial vector coupling constants (g_v and g_a). Calculations of the radiative corrections to the neutron lifetime have been recently revised to a precision of 0.04% [115]. Improving the experimental uncertainty to this level requires (1) the determination of the ratio of the vector and axial vector coupling constants ($\lambda \equiv g_a/g_v$) by measurement of one of the decay asymmetries (for example the β asymmetry A) to a precision of $\Delta A/A = 4\Delta\lambda/\lambda < 0.16\%$, and (2) the determination of the neutron lifetime to a precision of $< 0.04\%$ [115].

Measurements of the neutron lifetime have been approaching the 0.1% level of precision (~ 1 s uncertainty). However, several recent neutron lifetime results [116, 117, 119, 118] are up to 7 s lower than the PDG value before 2010 (885.70 ± 0.85 s) [120]. This $> 6\ \sigma$ deviation has not yet been resolved. Even though the new 2011 update of the PDG value (881.5 ± 1.5 s) [121] includes all these measurements, with the uncertainty scaled up by a factor of 2.7, the PDG questions this new world average and calls upon the experimenters to clear up the current state of confusion.

The precise determination of the neutron lifetime could also have a profound impact on astrophysics and cosmology. In the standard big bang nucleosynthesis (SBBN) model, the abundance of the light elements can be determined with a single cosmological parameter – the baryon-to-photon ratio η_{10}, together with the nuclear physics input of the neutron lifetime and 11 key nuclear reaction cross-sections [122]. The influence of the neutron lifetime on the abundance of the light species of primordial nuclei, in particular ^{4}He, is based on two effects. First, the neutron lifetime indirectly affects the neutrino-nucleon reaction rate and the neutron-to-proton ratio when the primordial neutrons decouple from the radiation field. Second, the lifetime directly affects the number of these neutrons left to participate in nucleosynthesis, which is delayed by photo-dissociation of deuterons in the hot radiation field. As the primordial neutrons are protected against β-decay by fusing with protons into deuterons and then into ^{4}He, a shorter neutron lifetime would result in a smaller ^{4}He abundance (Y_p). As a consequence, a 1% change in the neutron lifetime leads to a 0.75% change of Y_p [123]. With a precise determination of η_{10} from WMAP, the SBBN predicts Y_p with a 0.2 – 0.3% precision [124]. Of the primordial elements, Y_p is particularly sensitive to the expansion rate of the universe and to a possible lepton asymmetry in the early universe [125]. Information on Y_p is attained from either direct observations of the H and He emission lines from low-metallicity extragalactic regions or from the indirect measurements using the power spectrum of the cosmic microwave background (through its effect on the electron density at recombination). The current precision of these measurements is about 1

– 2% [124, 126]. With the anticipated improvement from the Planck experiment in Europe and the James Webb space telescope in the US, the interpretation of Y_p in SBBN will hinge on the accuracy of the neutron lifetime. In astrophysics, the weak axial coupling constant g_A of neutron β-decay is a key parameter in the standard solar model, which describes the *pp* fusion process and the CNO cycle that produce solar energy as well as generate the solar neutrinos that can be directly measured by terrestrial experiments. Solar neutrino fluxes thus depend indirectly on the neutron lifetime and its uncertainties. As more measurements of the solar neutrino flux become available [128, 129], the precise knowledge of the neutron lifetime will have a greater impact on the expected values. The same concern also applies to the estimate of the anti-neutrino flux used in many neutrino oscillation experiments based at reactors [130].

It seems that the only way to settle the controversy surrounding the value of the neutron lifetime is to perform independent measurements with 0.1 s precision and rigorous control of systematic effects. The difficulties with measuring the absolute neutron lifetime originate from the low energy of its decay products, the essential impossibility of tracking slow neutron trajectories in matter, and the fact that the lifetime is long. The lifetime of β-decay is comparable to the timescale of many surface effects that contribute to the loss of neutrons [131, 132]. To achieve a precision measurement of the β-decay lifetime, one has to control these additional sources of loss to levels better than the desired precision. Recent lifetime measurements, which succeeded in reducing the uncertainty to a few seconds, have used ultra-cold neutrons (UCN) trapped in material bottles. With small kinetic energies, UCN experience total reflection from material walls (with a small absorption coefficient) at any incident angle [133]. This property allows them to be trapped in material bottles for times comparable to the β-decay lifetime. In a typical UCN bottle experiment, the UCN are loaded into a bottle (or a trap) and stored for different periods of time, and the survivors are counted by dumping them into a UCN detector outside the trap. There is much controversy over how to reliably correct for the loss of UCN when they interact with material on trapping walls.

The UCNτ collaboration will measure the neutron lifetime using UCN in a novel magneto-gravitational trap [134]. This trap will eliminate interactions on the confining walls and the associated uncertainties by replacing the material bottle with a trap formed by magnetic fields on the sides and bottom, and closed by gravity at the top. Since the interactions of neutrons with magnetic fields and gravity are well understood (and can be reliably modeled in numerical simulations), the systematic uncertainties in this approach are expected to be smaller than (and independent of) those in earlier experiments using material bottles. The novelty of the experiment originates from the use of an asymmetric trap to facilitate (1) fast draining of the quasi-bound UCN [135], and (2) quick sampling of the entire phase space in order to suppress spurious temporal variation of the decay signals when coupled to a non-uniform detection efficiency. The room-temperature trap using a permanent magnet array avoids many engineering challenges of prior cryogenic experiments and allows fast turnaround time for detector prototyping. The design of the experiment, with an open top, provides ample room for implementing many novel detection techniques, allowing a comprehensive study of the systematic effects discussed above.

In the preliminary report of the 2011 review on fundamental neutron physics [1] conducted by the National Science Advisory Committee (NSAC), the committee strongly recommends the pursuit of the planned NIST beam experiment at the 0.1% level of accuracy, and encourages more R&D effort on the UCNτ experiment. The UCNτ experiment uses techniques complementary to the beam experiment, and has the potential to push the precision of the neutron lifetime beyond the current state of the art, towards the 0.01% level. The intensity frontier of Project X brings about the unique opportunity to install a world-class UCN source, driven by the planned proton source. This investment will add a new facet to strengthen the scientific program aimed to probe physics beyond the SM at the TeV scale, using complementary techniques with low energy neutrons, including the search for the neutron electric dipole moment, the $n\bar{n}$ oscillation, and a comprehensive program of precision β-decay measurements.

[1] http://science.energy.gov/∼/media/np/nsac/pdf/mtg-63011/Kumar_Neutron_Interim_Report.pdf

7.3.5 Nuclear Decay Correlations

Two tests of discrete symmetries are being considered at the National Superconducting Cyclotron Laboratory(NSCL) at Michigan State University via measurements of correlation terms in nuclear beta decay. The first project plans a differential measurement of the so-called polarization-asymmetry correlation in the decay of ^{21}Na as a tool to search for deviations from maximal parity violation. The second is the measurement of a fifth-fold correlation in ^{36}K decay that is sensitive to deviations from time reversal invariance. Both measurements require spin polarized nuclei that can be produced at the laser spectroscopy and beam polarization facility, BECOLA. The low energy (maximum 60 keV/q) polarized nuclei will be produced by first stopping the high energy fragments with suitable "stoppers" and then transporting the thermal beams towards the BECOLA beamline, where a collinearly overlapped laser light induces their polarization by the optical pumping technique.

7.3.5.1 The Differential Polarization-Asymmetry Correlation

Measurements of pseudo-scalar quantities in beta decay can probe possible deviations from maximal parity violation due, for instance, to the presence of right-handed bosons with vector and axial couplings or to the exchange of other bosons with exotic scalar and tensor couplings.

The most stringent tests of maximal parity violation in nuclear beta decay arise from measurements of polarization-asymmetry correlations in the decays of ^{107}In [136] and ^{12}N [137]. In comparison with the beta asymmetry parameter and with the longitudinal beta polarization, this observable offers an enhanced sensitivity to deviations from maximal parity violation resulting from the combination of two pseudo-scalar quantities contributing to the decay. In previous experiments, the nuclear polarization was obtained by either a low-temperature nuclear orientation technique or by polarization transfer in a reaction initiated with a polarized beam. All measurements so far have been carried out at fixed beta particle energies by selecting a window in the beta energy spectrum with magnetic spectrometers.

The longitudinal polarization of beta particles emitted from unpolarized nuclei has a constant sign and also a constant sensitivity to effects related to partial parity symmetry restoration. Beta particles emitted from polarized nuclei can, in contrast, exhibit a longitudinal polarization that changes sign as a function of the beta particle energy. In addition, the sensitivity to effects associated with parity symmetry restoration increases at lower beta particle energies. This offers a new window for tests of maximal parity violation in beta decay, provided the SM values can be controlled to sufficient accuracy.

A new positron polarimeter is being designed for a differential measurement of the longitudinal polarization of beta particles emitted from polarized ^{21}Na nuclei.

7.3.5.2 Search for Time Reversal Violation by a Fifth-Fold Correlation Measurement

The five-fold correlation $E_1\vec{J}\cdot(\vec{p}\times\vec{k})(\vec{J}\cdot\vec{k})$, where $\vec{J}$ is the nuclear spin, $\vec{p}$ is the beta particle momentum, and $\vec{k}$ is the photon momentum provides a means to the searches for time reversal violation [138, 139, 140] that is complementary to measurements of triple correlations in beta decay. The fifth-fold correlation is P-odd/T-odd and it is generally interpreted in terms of a possible imaginary phase between the vector and axial couplings. The most precise result so far for such a correlation was obtained with ^{56}Co nuclei and yielded $E_1 = -0.011 \pm 0.22$ [141]. This provides the weakest constraint compared with the other T-violating coefficients in beta decay. The transition of interest here is an isospin-hindered Gamow-Teller transition. The contribution from the Fermi matrix element is finite, though small, due to a breakdown of isospin symmetry or possibly through a contribution of second-class currents (SCC). If SCC –which are known to be zero so far [142]– were the source for the underlying mechanism for T-violation, the ^{56}Co decay provides an ideal test. However, no E_1 test has been performed so far in a mirror beta decay.

It has been pointed out [143] that the superallowed decay of ^{36}K is a good candidate to test T symmetry by a fifth-fold correlation measurement.

The low energy, polarized ^{36}K beam will be implanted in a host crystal placed under a magnetic field surrounded by a set of high-resolution germanium detectors. The decay of interest populates a 2^+, $T = 1$ state at 6.61 MeV in the ^{36}Ar daughter with a branching ratio of 42%. The excited state in ^{36}Ar decays to the ground state by emission of several gamma rays with energies larger than 2 MeV, providing the conditions needed for a $\beta\gamma$ angular correlation experiment.

To be competitive with present limits, the new T-invariance measurement will most likely require the higher beam rates like those expected at the future FRIB facility at MSU.

7.3.6 Searching for Tensor Currents in ^{6}He

At the University of Washington, Seattle, there is a program to search for tensor currents in the decay of ^{6}He. In this case the coefficients a and b, neglecting radiative and recoil-order corrections, are given by:

$$a = -\frac{1}{3}\frac{\left(2|C_A|^2 - |C_T|^2 - |C'_T|^2\right)}{\left(2|C_A|^2 + |C_T|^2 + |C'_T|^2\right)}$$
$$b = \frac{2C_A\left(C_T + C'_T\right)}{\left(2|C_A|^2 + |C_T|^2 + |C'_T|^2\right)}.$$

a is sensitive *quadratically* to tensor currents of either chirality, while b is sensitive *linearly* to tensor currents, but only to those with no left-handed anti-neutrinos (or right-handed neutrinos). Here we aim at detecting a with a relative precision of $\sim 0.1\%$ and b with absolute precision of $\sim 10^{-3}$. Because of its linear dependence on the tensor couplings, b is more sensitive to tensor currents. However, because it is sensitive to only one chirality, a test concentrating solely on b would leave unchecked a large region of the parameter space with a particular bias. Although we do not have a concrete scenario for new physics that would show up with neutrinos with helicities opposite to that of the Standard Model, this possibility cannot be presently excluded. Fig. 7-2 shows the present limits and those that we aim to have from this work.

In the ^{6}He case, with a $0^+ \to 1^+$ beta decay, the connection between a, b and tensor currents is *direct*, as opposed to the case of mirror transitions, such as neutron decay, where a and b are sensitive, in addition, to the ratio of axial to vector current couplings and matrix elements plus potentially existing scalar currents. The decay of ^{6}He presents an excellent opportunity for these searches. The large Q-value allows for an exploration of the shape of the spectrum over a broad energy range. By comparison, neutron beta decay presents an endpoint smaller by a factor of about 3.5, and the potential problem that capture of neutrons in the environment will generate additional backgrounds. Being the lightest radioactive nucleus with a pure GT decay, the recoiling nucleus shows high sensitivity to the momentum carried by the leptons, which is good for a determination of the correlation coefficient. The system produces copious amounts of ^{6}He [146]: more than 10^9 atoms per second delivered to a low-background room.

Part of the program consists of using laser traps [147] to determine the electron-anti-neutrino correlation by coincidence detection of the beta and ^{6}Li recoil ion. There is already have a working MOT trap with ^{4}He atoms and hope to trap ^{6}He atoms by the end of 2011. The laser trapping requires exciting He to a

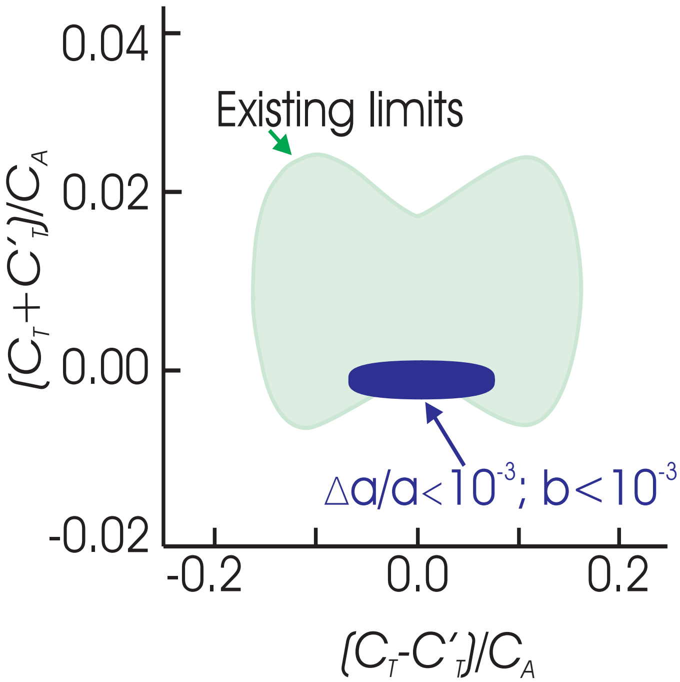

Figure 7-2. *95% confidence intervals: presently allowed region (from [145]) in green and, in blue, the limits one would get with measurements of* $\Delta a/a < 10^{-3}$ *and* $\Delta b < 10^{-3}$.

metastable state at ~ 20 eV and one expects to count only about 10 e-Li coincidences per second in this mode. Another part of this program is to determine the shape of the beta spectrum, for which use of the laser-trap system is not planned. An ISOL-type FRIB could provide up to three orders of magnitude higher production rates, allowing for further improvements in both the $e, \overline{\nu}$ correlation and the spectrum-shape measurement, which could then be done with trapped atoms.

7.3.7 β-Decay with Neutral Atom Traps I

Nuclear β decay correlation experiments helped establish the nature of the weak interaction, a theory with spin-1 bosons coupling only to left-handed leptons. Such measurements can still assist particle physics by determining first-generation lepton-quark couplings of possible new particles, but must reach excellent accuracy of 0.1%. Using atom trap technology, the TRIUMF Neutral Atom Trap collaboration (TRIUMF, Texas A&M U., U. Manitoba, Tel Aviv U., and U. British Columbia) is poised to complete two experimental programs reaching this accuracy in the next three years.

Confined in a 1 mm-sized cloud, the nuclei undergo beta decay, producing three products: a β^+, a ν, and a recoiling daughter nucleus. The daughter nucleus has very little kinetic energy and would stop in a nm of material, but it freely escapes the trap. By detecting it in coincidence with the β^+, the momentum and angular distribution of the ν can be measured [148].

The atom trap methods provide many unique tools to determine experimental systematics. Kinematic redundancy in most of the data set allows many consistency tests; for example, the construction of the β momentum from other observables tests simulations of the detector response. One measures the cloud dimensions and temperature by photoionizing a small fraction of the atoms and measuring their time of flight (TOF) and position on the same MCP that measures the nuclear recoils. Detection of shakeoff atomic electrons in coincidence provides a high-efficiency TOF trigger and suppresses backgrounds [149].

The process to spin-polarize nuclei and measure the polarization *in situ* of the decaying species by atomic methods independent of the nuclear decays has been established. A measurement of the ν asymmetry B_ν at 3% accuracy [150] has been published. The goals of our spin correlation program include a simultaneous measurement of β and recoil asymmetries A_β and $A_{\rm recoil}$ at part-per-thousand sensitivity, and eventually B_ν at 0.3%. For example, a week of counting of $A_{\rm recoil}$ would have statistical sensitivity to $C_t + C_t'$ at 0.002.

Limits on scalar interactions coupling to the first generation of particles could be improved by measuring the β-ν correlation in the pure Fermi decay of ^{38m}K [152]. The complete angular acceptance for recoils we have developed will minimize key systematic errors in our upgraded experiment, with a goal of reaching 0.1% accuracy in a and possibly $b_{\rm Fierz}$. We determine systematic errors for this experiment from statistics-limited kinematic observables that are independent of the angular correlation.

Concentrating on isobaric analog decays allows determination of small recoil-order Standard Model corrections from the electromagnetic moments of the nuclei. The Gamow-Teller/Fermi ratio in ^{37}K can be well-determined from measurements of the lifetime and branching ratio, as the community has achieved a reliable set of techniques for these experiments.

If successful, our correlation experiments would be complementary with constraints from radiative π decay [151] and indirect effective field theory (EFT) dependent constraints from π to e ν [153], and would begin to allow sensitivity to SUSY left-right sfermion mixing [154].

It is natural in the trap to measure the time-reversal violating D $\vec{I} \cdot \vec{p_\beta} X \vec{p_\nu}$. We have a conceptual design for a dedicated geometry with 20% β efficiency (it helps that the polarized light comes at 90$^{\rm o}$ to the β detectors helps) so 2x10^{-4} statistical error/week can be achieved. The best measurement in the decay of the neutron was recently published by emiT, achieving 2x10^{-4} sensitivity [155]. However, a recent effective field theory calculation has identified a mechanism for the electric dipole moment of the neutron to constrain leptoquark contributions to D (previously considered safe from EDM's [157]), and if there are no cancellations would imply D $<$ 3x10^{-5} [156]. Since there are many possible contributions to CP violation from new physics, D could still be complementary. We will study time-reversal systematics in our present ^{37}K geometry.

7.3.8 β-Decay with Neutral Atom Traps II

Recent advances in the techniques of atom and ion trapping have opened up a new vista in precision β decay studies due to the near-textbook source they provide: very cold ($\lesssim$ 1 mK) and localized ($\lesssim$ 1 cm^3), with an open geometry where the daughter particles escape with negligible distortions to their momenta.

Atom traps: Magneto-optical traps (MOTs) have demonstrated the ability to measure the angular distribution of short-lived radioactive neutral atoms. Experiments using MOTs have placed stringent direct limits on a possible fundamental scalar current in the charged weak interaction via a precise measurement of the $\beta - \nu$ correlation parameter, $a_{\beta\nu}$ [158, 159]. These experiments continue to improve, along with others being developed to extend to other cases (for example, see A. García *et al.*'s contribution to this workshop on searching for tensor interactions using trapped ^{6}He). Techniques are also being developed by the TRINAT collaboration at TRIUMF to highly polarize laser-cooled atoms via optical pumping. A proof-of-principle experiment measured the neutrino asymmetry parameter in ^{37}K [160], with an improved version planned to take beam at TRIUMF in the summer of 2012. The contributions by J.A. Behr, R.J. Holt and L.A. Orozco to this workshop describe other physics opportunities available using MOTs.

Ion traps: Penning traps of ions are best known for the incredible precision with which they can measure masses: relative uncertainties of $\Delta M/M \simeq 10^{-11}$ have been reported on stable species [161], and $\simeq 10^{-8}$ for very short-lived ($\gtrsim 10$ ms) exotic ions [162]. These mass measurements have impacts in many fields of science, including fundamental physics research (CKM unitarity, testing nuclear models, correlation studies, etc.). Penning traps are also used in other applications, including laser spectroscopy, QED effects, electron-capture studies and the astrophysical r-process, to name a few.

Opportunities at TREX: The group at Texas A&M University is in the process of constructing a new double-Penning trap facility, TAMUTRAP, which will take advantage of the radioactive ion beam capabilities of the upgraded Cyclotron Institute facility, TREX [163]. The layout of the institute's cyclotrons and experimental equipment is shown in Fig. 7-3, where the components that are currently being built as part of the TREX upgrade are: re-commissioning the K150 cyclotron to deliver high-intensity light particle and heavy ion beams; the light and heavy ion guide systems; the charge-breeding electron cyclotron resonance (ECR) ion source and coupling of it to the K500 cyclotron, to provide high quality re-accelerated rare beams of both neutron and proton rich isotopes in the 5 to 50 MeV/u range.

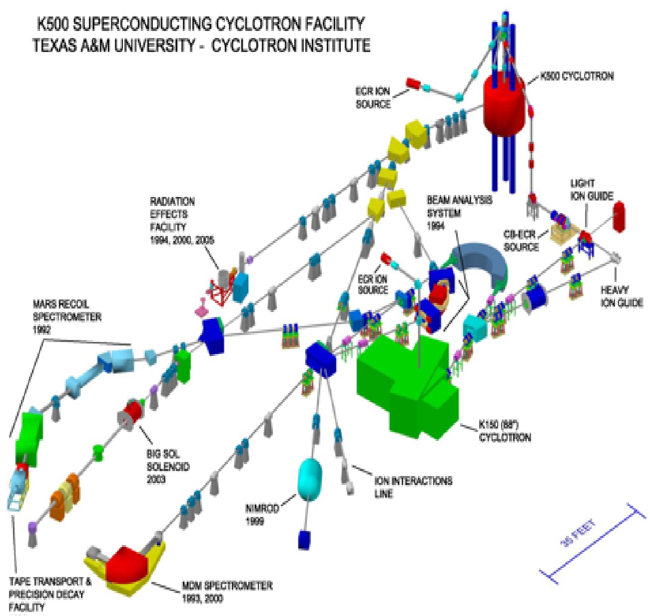

Figure 7-3. *Floorplan of the Cyclotron Institute showing the accelerators and equipment, including the TREX upgrade components.*

Figure 7-4 shows the plans for the Penning trap facility in relation to the TREX upgrade. Radioactive beams for TAMUTRAP will be produced using the K150 cyclotron which will provide a high-intensity primary beam that will react with a target in front of "BigSol", a large-acceptance 7-Tesla solenoid which will separate the desired products from deap inelastic reactions. An Argonne National Laboratory type gas-catcher [164] will collect these products and transport them via a dedicated low-energy beamline to TAMUTRAP at ~ 10 keV (or alternatively to the charge-breeding ECR for post-acceleration in the K500 cyclotron). The ions will be

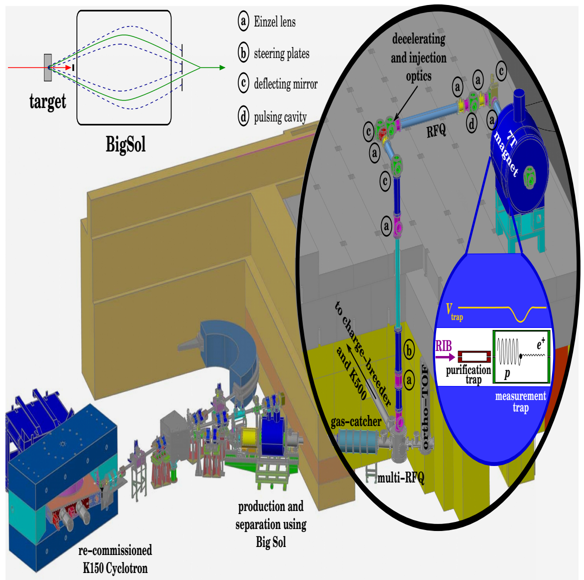

Figure 7-4. *Coupling of the K150 to the* TAMUTRAP *facility, including a schematic of the double-trap system and principle behind the $a_{\beta\nu}$ measurement.*

cooled and bunched using a segmented gas-filled RFQ and injected at 80 eV into the double-Penning trap with time and energy spreads of $1.2 - 1.6$ μs and $6 - 10$ eV, respectively.

Both Penning traps will be housed in the 210-mm-bore 7-Tesla superconducting magnet, which has been purchased from Agilent Technologies and has demonstrated to have better than 4 ppm homogeneity at full field. The first trap will be a gas-filled ($\lesssim 10^{-4}$ mbar) cylindrical Penning trap to (optionally) allow for further purification of the rare ion beam following the gas-catcher. The 2^{nd} cylindrical "measurement" trap will be unique in that it will have the largest diameter (180 mm) of any existing Penning trap. The purpose of this large-diameter bore is for the flagship program which will perform $\beta - \nu$ correlation studies and ft-value measurements on $0^+ \rightarrow 0^+$ transitions of the short-lived β-delayed proton emitters ^{20}Mg, ^{24}Si, ^{28}S, ^{32}Ar and ^{36}Ca. Measurements will start with ^{32}Ar since its decay has already been studied in detail [165, 166], but the others have similar decay schemes and so can be studied in a similar way. The Larmour radii of the βs from these decays ($\lesssim 5$ mm) is much less than the protons, allowing good spatial separation of the two when detected by position-sensitive Si detectors placed at either end of the measurement trap (see the schematic zoom-in of the magnet in the bottom-right of Fig. 7-4). The large bore of the magnet allows for complete radial confinement of up to 4.3 MeV protons, which spans the energies of interest produced in these decays. The shape of the proton's energy spectrum depends on the value of $a_{\beta\nu}$ and thus the $\beta - \nu$ correlation can be investigated in a manner similar to that done by Adelberger *et al.* at ISOLDE [165] where a precision of 0.5% in $a_{\beta\nu}$ was reached; one advantage over their experiment is the observation of the β's energy, as well as separation of events where the β and proton were emitted in the same/opposite hemispheres, which will help reduce systematics.

In addition to the superallowed program, the system is being designed to be flexible and allow for other fundamental physics studies, including the ability to perform precision mass measurements. Although not a user facility, the Cyclotron Institute has a long history of collaborating with outside users and we expect that with our existing and planned upgrade for extending our RIB capabilities, that collaborative efforts will continue to be formed with groups interested in using our facilities.

The intensity frontier: Both atom and ion traps provide extremely clean sources, so experiments can be performed with relatively small sample sizes owing to the very large signal-to-noise ratio. However, high intensities with relatively long access times to radioactive beams would be extremely advantageous to these experiments: most are systematics-limited, where the systematics are themselves statistics limited; *i.e.* systematic uncertainties could be considerably reduced if their sources could be investigated and minimized by using dedicated beamtime to characterize and quantify them. The TREX facility at Texas A&M University is not a user facility and so can offer better availability of beamtimes than, for example, FRIB or TRIUMF; however, the larger facilities can provide greater intensities. Ideally, one would like to have a facility that can provide both high intensities and long accessibility of beamtimes. Low-energy nuclear physics programs using both MOTs and Penning traps would be able to capitalize on such a facility and meaningfully add to probes of physics beyond the Standard Model.

7.3.9 High Intensity Neutron Sources

Experimentation using slow neutrons is an integral part of studies spanning fields as diverse as nuclear and particle physics, fundamental symmetries, astrophysics and cosmology, and gravitation. The field possesses a coherence that derives from the unique properties of the neutron as an electrically neutral, strongly interacting, long-lived unstable particle that can be used either as a probe or as an object of study. Experiments include measurement of neutron-decay parameters as tests of the Standard Model, the use of parity violation to isolate the weak interaction between nucleons, and searches for a source of time reversal violation beyond the SM. These experiments provide information that is complementary to that available from accelerator-based nuclear and particle physics facilities. Neutron physics measurements also address questions in astrophysics and cosmology. The theory of Big Bang Nucleosynthesis needs the neutron lifetime and the vector and axial vector weak couplings as input, and neutron cross sections on nuclei are necessary for a quantitative understanding of element creation in the universe.

The approach to this class of experiments requires performing measurements with a high degree of statistical precision. A large fraction of the experiments using slow neutrons are statistically limited. Thus, in order for progress to be made, it is critical that more intense sources of neutrons be made available. The experiments that probe these questions are largely performed at reactors or spallation sources that are able to generate large densities of cold or ultra-cold neutrons. For neutron decay experiments, there is a novel effort underway to create a high flux of electrons and protons from neutrons decaying upstream in a neutron guide and transport them to the measurement region. While it is not possible to survey all the experiments that would benefit from high neutron densities, this brief note mentions just a few areas of investigation that would benefit greatly from higher fluxes of cold neutrons. The reader is referred to the more specialized papers and reviews listed in the references for more details.

Neutron decay is an important process for the investigation of the Standard Model of electroweak interactions. As the prototypical beta decay, it is sensitive to certain SM extensions in the charged-current electroweak sector. Neutron decay can determine the CKM matrix element $|V_{\rm ud}|$ through increasingly precise measurements of the neutron lifetime and the decay correlation coefficients. The best determination of $|V_{\rm ud}|$ comes from superallowed nuclear decays [67], but neutron beta decay offers a somewhat cleaner theoretical environment than the superallowed transitions due to the absence of other nucleons (although some radiative corrections are common to both systems). Presently, the experimental uncertainties from the neutron measurements are significantly larger than those from superallowed decays and arise from systematic uncertainties; more specifically, there are disagreements among experiments. Once those systematic effects are sorted out, modest improvements in the statistical precision will enable the precision of neutron experiments to be comparable to that obtained from the nuclear decays.

Searches for violations of time-reversal symmetry and/or CP symmetry address issues that lie at the heart of cosmology and particle physics. The next generation of neutron EDM searches, which plan to achieve sensitivities of $10^{-27}\,e{\cdot}\mathrm{cm}$ to $10^{-28}\,e{\cdot}\mathrm{cm}$, is the most important of a class of experiments aiming to search for new physics in the T-violating sector. Thus far, all observations of CP violation can be entirely accounted for by a phase in the CKM matrix; however, this phase is insufficient to account for the known baryon asymmetry in the context of big bang cosmology and there is good reason to search for CP and the related time-reversal violation in other systems. Because neutron beta-decay is theoretically straightforward and final state interactions are generally small and calculable, the neutron is a clean system in which to look for the effects of new physics. Two T-odd triple correlations have recently been measured, $D\vec{\sigma}_n \cdot \mathbf{p_e} \times \mathbf{p}_\nu$ and $R\vec{\sigma}_n \cdot \sigma_e \times \mathbf{p_e}$, where $\vec{\sigma_n}$ is the neutron spin, $\vec{\sigma_e}$ is the neutron electron spin and $\mathbf{p}$ are the decay product momenta. Both experiments are currently believed to be statistically limited; thus it is interesting to consider the potential of higher fluence sources.

The D coefficient is the most sensitive probe of the phase, ϕ_{av}, between the axial-vector and vector currents and is also sensitive to scalar and tensor interactions that could arise due to beyond Standard Model physics. The most recent result, $D = (-0.96 \pm 1.89(stat) \pm 1.01(sys)) \times 10^{-4}$ [98], represents the most sensitive test of time-reversal invariance in beta decay. Within the Standard Model, the result can be interpreted as a measure of the phase $\phi_{av} = (180.013 \pm 0.028)^\circ$. The D coefficient can also be related to the neutron EDM. significantly constrains scalar couplings beyond previous limits. The systematic uncertainty, already a factor of three below the statistical uncertainty, is dominated by background subtraction, the characterization of which should improve with improved statistics. Any increases in available neutron fluence thus could lead to significantly improved limits on scalar couplings.

The rare decay $n \to \mathrm{H} + \bar{\nu}$ has been discussed in several articles going back to the early sixties. The branching ratio for this rare mode of decay is 4×10^{-6} of the total neutron β-decay rate, making it exceedingly challenging to detect. The hyperfine-state population of hydrogen after the bound-β-decay of the neutron directly yields the neutrino left-handedness or a possible right-handed admixture and possible small scalar and tensor contributions to the weak force. The detection of the neutral hydrogen atoms and the analysis of the hyperfine states can be accomplished using straightforward atomic physics techniques. The elegance and power of this approach makes it a very attractive way to test the Standard Model. A group is attempting such a measurement and hopes to improve current limits by a factor of 10. This is an experiment for which a high-intensity neutron source would be a great asset.

The neutron decays with the emission of a soft photon. At present, experiments are only probing the inner bremsstrahlung component of this decay due, in part, to the low rate of events that one obtains at the low energy photon threshold. With higher-intensity neutron sources, it would be interesting to pursue investigations into testing nonleading order corrections to the decay. In addition, there is recent work studying radiative beta decay in the context of the Harvey, Hill, and Hill interaction. In particular, they are looking at the triple correlation $\mathbf{l_p} \cdot (\mathbf{l_e} \times \mathbf{k})$, where $\mathbf{l_p}$ and $\mathbf{l_e}$ are the proton and electron momenta, respectively, and $\mathbf{k}$ is the photon momentum, as a possible source of time-reversal violation.

The last decade has also seen qualitative advances in both the quantitative understanding of nuclei, especially few-body systems, and the connection between nuclear physics and quantum chromodynamics (QCD). Low energy properties of nucleons and nuclei, such as weak interactions in n-A systems, low energy n-A scattering amplitudes, and the internal electromagnetic structure of the neutron (its electric polarizability and charge radius) are becoming calculable in the SM despite the strongly interacting nature of these systems. These theoretical developments are motivating renewed experimental activity to measure undetermined low energy properties such as the weak interaction amplitudes between nucleons and to improve the precision of other low energy neutron measurements. The ultimate goal is to illuminate the strongly interacting ground state of QCD, the most poorly understood sector of the SM, and to clarify the connection between the strong interaction at the hadron level and the physics of nuclei.

Independent of the theoretical model, several experimental approaches are required to narrow the range of the predictions. There are two mature experimental efforts that are able to provide input. One is an experiment to measure the parity-violating spin rotation of a polarized neutron beam in a liquid helium target, and the other is an experiment to measure the gamma-ray asymmetry in the process $p(n,\gamma)D$. The experiments are largely complementary in terms of their sensitivity to the effective field theory parameters (or meson exchange amplitudes). The uncertainties from initial results from both experiments are dominated by statistics and require running at more intense sources of cold neutrons to improve the ultimate precision. Improved measurements from both experiments are essential to produce parameters that can be extracted in a theoretically clean manner.

7.4 Neutral Currents

Experiments using intense beams of polarized electrons scattering from fixed targets, as well as those exploiting parity-forbidden atomic transitions, have played a vital role in developing and testing the electroweak sector of the Standard Model as well as in probing novel aspects of hadron and nuclear structure (for a review, see [168, 169, 170]). Most recently, a program of parity-violating electron scattering experiments at MIT-Bates, Mainz, and Jefferson Laboratory have yielded stringent limits on contributions from the strange quark sea to the nucleon's electromagnetic properties, while an experiment with parity-violating Møller scattering at SLAC has provided the most stringent test to date of the running of the weak mixing angle θ_W below the weak scale. Similarly powerful measurements have been carried out with atomic cesium, yielding the most precise determination of the nuclear weak charge and intriguing indications of the so-called nuclear "anapole moment."

These achievements have built on the steady improvements in experimental sensitivity since the pioneering measurements of parity-violating, deep inelastic electron-deuteron scattering [176] and atomic parity violation in the 1970s, together with refinements of the theoretical interpretation. The frontier of this field now promises a unique capability to probe possible new physics at the TeV scale, as well as explore previously inaccessible features of nucleon and nuclear structure. At the same time, the possibility to carry out a sensitive search for charged lepton flavor violation with unpolarized beams at an electron-ion collider (EIC) appears increasingly feasible. Below, we review some of the present efforts and future prospects for studies that exploit neutral current interactions with electrons.

To set the stage, we introduce the low-energy effective Lagrangian characterizing the parity-violating neutral weak electron-quark interaction:

$$\mathcal{L}^{PV} = \frac{G_F}{\sqrt{2}}[\bar{e}\gamma^\mu\gamma_5 e(C_{1u}\overline{u}\gamma_\mu u + C_{1d}\overline{d}\gamma_\mu d) + \bar{e}\gamma^\mu e(C_{2u}\overline{u}\gamma_\mu\gamma_5 u + C_{2d}\overline{d}\gamma_\mu\gamma_5 d)]. \quad (7.5)$$

In the Standard Model, the coefficients C_{1q} and C_{2q} can be predicted with high precision and depend critically on $\sin^2\theta_W$. A similar expression obtains for the parity-violating electron-electron interaction. One goal of the parity-violation experiments is to test these predictions. As with the muon anomalous magnetic moment, any deviation from the Standard Model predictions would indicate the presence of new physics to the extent that the theoretical predictions are sufficiently robust. Given the present level of experimental and theoretical uncertainties, the present generation of parity violation experiments are able to probe for new TeV scale physics.

From a complementary perspective, one may assume the Standard Model values for the C_{iq} are correct and use the interactions in Eq. (7.5) to access properties of the nucleon and nuclei that are not readily probed by the purely electromagnetic interaction. Indeed, the determination of strange quark contributions relies on different combinations of the light quark currents that enter electromagnetic and neutral weak currents. As discussed below, a number of additional interesting aspects of nucleon and nuclear structure can be uncovered using the parity-violating electron-quark interaction.

In much of the discussion below, the object of interest is the parity-violating asymmetry

$$A_{PV} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \quad , \tag{7.6}$$

where σ_+ (σ_-) denotes the cross section for scattering by longitudinally polarized electrons with positive (negative) helicity from an unpolarized target. The corresponding parity-violating observable in atomic physics depends on the specific setup, so we defer a description to the discussion of atomic experiments below.

7.4.1 Proton Weak Charge

The Qweak collaboration[171] is conducting the first precision measurement of the weak charge of the proton, Q_W^p, given in terms of the C_{1q} as

$$Q_W^p = -2\,(2C_{1u} + C_{1d}) \quad . \tag{7.7}$$

At leading order in the Standard Model, $Q_W^p = 1-4\sin^2\theta_W$. Inclusion of higher-order electroweak corrections leads to a Standard Model prediction with $\mathcal{O}(1\%)$ theoretical error[172, 173]. This experiment is being performed at Jefferson Laboratory, building on the technical advances made in the laboratory's parity violation program and using the results of earlier measurements to constrain hadronic corrections. The experiment measures the parity-violating longitudinal analyzing power in e-p elastic scattering at $Q^2 = 0.026\ (GeV/c)^2$ employing 180 μA's of 86% polarized electrons on a 0.35 m long liquid hydrogen target. The measurement will determine the weak charge of the proton with about 4.1% combined statistical and systematic errors. This corresponds to constraints on parity-violating new physics at a mass scale of 2.3 TeV at the 95% confidence level. This also allows $\sin^2\theta_W$ to be determined to 0.3% accuracy, providing a competitive measurement of the running of the mixing angle. In combination with other parity-violation measurements, a high-precision determination of the weak couplings C_{1u} and C_{1d} significantly improves on the present knowledge as shown in Figure 7-5. Letting Q^2 denote the four-momentum transfer, $\tau = Q^2/4M^2$ where M is the proton mass and θ the laboratory electron scattering angle, for forward-angle scattering where $\theta \to 0$, $\epsilon \to 1$, and $\tau << 1$, the asymmetry can be written as[168]:

$$A_{PV} = \left[\frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\right]\left[Q_W^p + F^p(Q^2,\theta,E)\right] \to \left[\frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\right]\left[Q_W^p + Q^2 B(Q^2) + C(E)\right] \ , \tag{7.8}$$

where F^p is a form factor that includes a dependence on the beam energy E beyond the Born approximation. The first term, proportional to Q^2, is for a point-like proton. The second term $B(Q^2)$, proportional to Q^4, is the leading term in the nucleon structure defined in terms of neutron and proton electromagnetic and weak form factors. Ideally one would like to measure at a low enough Q^2 that the proton would look like a point and hadronic corrections would be negligible. An accurate measurement of $\sin^2\theta_W$ thus requires higher-order, yet significant, corrections for nucleon structure. Nucleon structure contributions in $B(Q^2)$ can be suppressed by going to lower momentum transfer and energy. The numerical value of $B(Q^2)$ has been constrained experimentally by extrapolation from existing forward angle parity-violating data at higher Q^2. The importance of the additional E-dependent contributions arising from the exchange of two vector bosons between the electron and proton remains a topic of ongoing theoretical scrutiny.

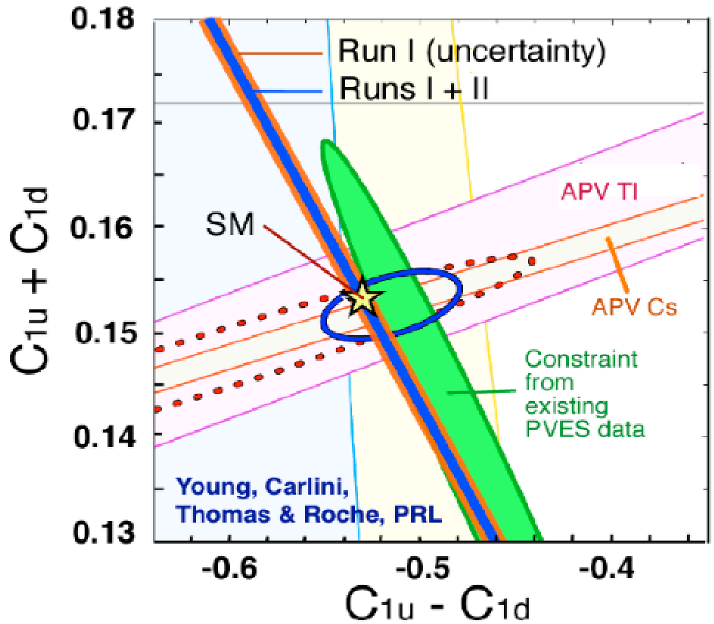

Figure 7-5. *Knowledge of the neutral-weak effective coupling constants. The dotted contour displays the previous experimental limits (95% CL) reported in the Particle Data Group Review[174] together with the prediction of the Standard Model (yellow star). The filled ellipse denotes the present constraint provided by recent high precision PVES scattering measurements on hydrogen, deuterium, and helium targets (at 1σ), while the solid contour (95% CL) indicates the full constraint obtained by combining all results[175]. All other experimental limits shown are displayed at 1σ. The striking improvement possible from the future Jefferson Laboratory Q_W^p measurement is shown as the blue line for Standard Model predictions.*

7.4.1.1 Possibility of a Second Generation Measurement at the JLab FEL Accelerator Complex

Initial simulations indicate that it is technically feasible to perform ∼2% ultra-low Q^2 measurement of Q_W^p by using the existing apparatus with approximately 0.5mA of 200 MeV beam potentially available at the JLab FEL accelerator complex. The value of such a measurement would really come from its impact on a global fit. It would be another point, at a much lower Q^2, but with different systematic and theoretical uncertainties, rather than simply smaller ones. This would allow a better global extraction of a final result. Such a measurement would have approximately 100 times the rate of "Qweak-1" but with an average Q^2 about 10 times lower, implying a smaller figure of merit (FOM). Another advantage in FOM would come from the suppression of the dilution terms (magnetic moment, plus any strange quark, etc.) and considerably smaller E-dependent hadronic effects.

A significant point to note is that the existing Qweak toroidal spectrometer design will not produce magnetic fields strong enough to polarize the proton target, which is essential for such a low Q^2 measurement. The existing cryogenic target system will work up to 0.2 mA and perhaps much more. It also appears feasible to augment the experimental technique to help suppress target boiling noise at these higher beam currents by increasing the helicity flip rate to perhaps 2 KHz and by using an radio-frequency beam current cavity (BCM) downstream of the target as a transmitted beam current monitor. A possible experimental layout at the JLab FEL accelerator complex is shown in Figure 7-6 .

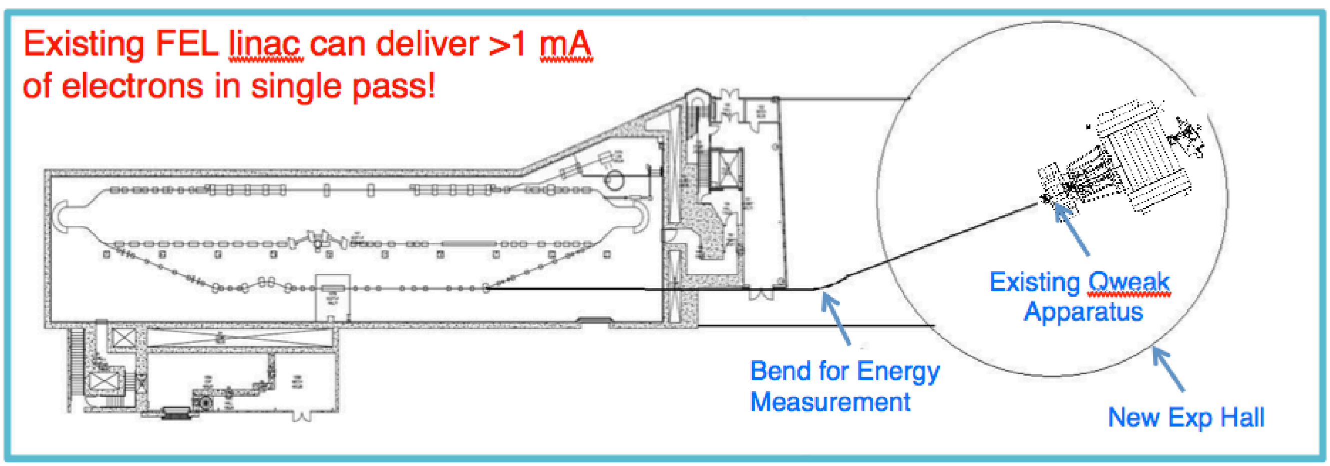

Figure 7-6. *The basic layout of a second-generation ultra-low Q^2 measurement of the proton's weak charge at the existing JLab FEL accelerator complex.*

Realizing this capability would require the construction of a new endstation (similar in size to the existing Hall B at JLab), the addition of a polarized injector, beam polarimetry and some upgrade work on the FEL accelerator. If the existing Qweak apparatus were simply used with 200 MeV beam it would have the following characteristics: $Q^2 = 7 \text{ x } 10^{-4}$ $(GeV/c)^2$, with an effective detector rate of 1.5 GHz/μA of beam incident on the hydrogen target. The layout shown also avoids major modifications to the installed optical beamline at the FEL. A suitable transport line would consist of 3 triplets between the existing FEL and wall, a 4 period FODO arc (using the GW dipoles now in Lab 1 for LIPSS), and then a scaled clone of, say, the transport into Hall C.

7.4.2 Parity Violating Deep Inelastic Scattering

At JLab, an experiment to measure parity violation in the deep inelastic scattering (PVDIS) of polarized 11 GeV electrons from deuterium has been approved. The goals of the experiment are: (1) measure the C_{2q} coefficients with high precision; (2) search for charge symmetry violation (CSV) at the quark level; (3) search for quark-quark correlations in the nucleon.

7.4.2.1 Physics of PVDIS

In 1978, Prescott *et al.* [176] showed that parity violation could be observed in neutral currents by measuring the asymmetry (7.6) in the deep inelastic scattering (DIS) of polarized electrons from deuterium. By extending the kinematic range, the same group later published results that were able to exclude alternative theories to the Standard Model that were considered reasonable at the time. The PVDIS asymmetry is sensitive to both the axial-vector (vector) electron couplings C_{1q} and C_{2q}, whereas the emphasis for the Q-Weak experiment is on the C_{1q}. For deuterium, one has

$$A^{PV} = -\left(\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\right)\left[a_1 + \frac{1-(1-y)^2}{1+(1-y)^2}a_3\right]; \quad a_1^D(x) = -\frac{6}{5}(2C_{1u} - C_{1d}); \quad a_3^D(x) = -\frac{6}{5}(2C_{2u} - C_{2d}), \quad (7.9)$$

where $y = \nu/E$. By observing the dependence of A_{PV} on y, the Prescott experiment was sensitive to both the C_{1i}'s and the C_{2i}'s.

As discussed above, there has been great progress more recently in the precision of the measurements of the C_{1q}'s with the advent of the Qweak experiment and precision atomic physics measurements. On the other hand, progress with the C_{2i}'s has been slower because at low energies, uncertain radiative corrections involving the long-distance behavior of hadrons are large. However, in DIS, these corrections are tractable since the relevant energy scale implies that all corrections can be computed perturbatively. Hence the motivation for a new precise experiment in PVDIS from deuterium. The sensitivity of the JLab experiment to new physics is given by Kurylov *et al.* [178].

The collaboration at JLab plans to build a new solenoid called SoLID, that will enable one to obtain statistical precision of $< 0.5\%$ for a number of bins with $0.3 < x < 0.75$, $4 < Q^2 < 10$ (GeV/c)^2, and $y \sim 1$ [177]. By designing the apparatus for large y, one can maximize the sensitivity to the C_{2i}'s. The expected sensitivity is given in Figure 7-7.

7.4.2.2 Hadronic Corrections

The NuTeV experiment published a test of the Standard Model in neutrino-nucleus DIS . The result differed from the prediction of the Standard Model by about 3σ [179], generating considerable controversy and causing a serious re-evaluation of the work. Corrections, including changes in the value of V_{us}, strange sea-quarks, and improved radiative corrections have been made. Including these effects has not substantially mitigated the discrepancy. Another possible explanation of the NuTeV result is charge symmetry violation (CSV) in the parton distribution functions (PDFs)[180, 181]. Various authors have presented the case that this is a reasonable explanation, citing the effects of PDFs [182], QCD effects [183, 184, 185, 186], and QED effects [187, 188].

The JLab PVDIS experiment is also sensitive to CSV. If the x dependence of the CSV falls more slowly than that of the PDFs, the asymmetry should display a clear x dependence. Moreover, these results will provide an important test of the CSV explanation for NuTeV. More details are given in the proposal [177].

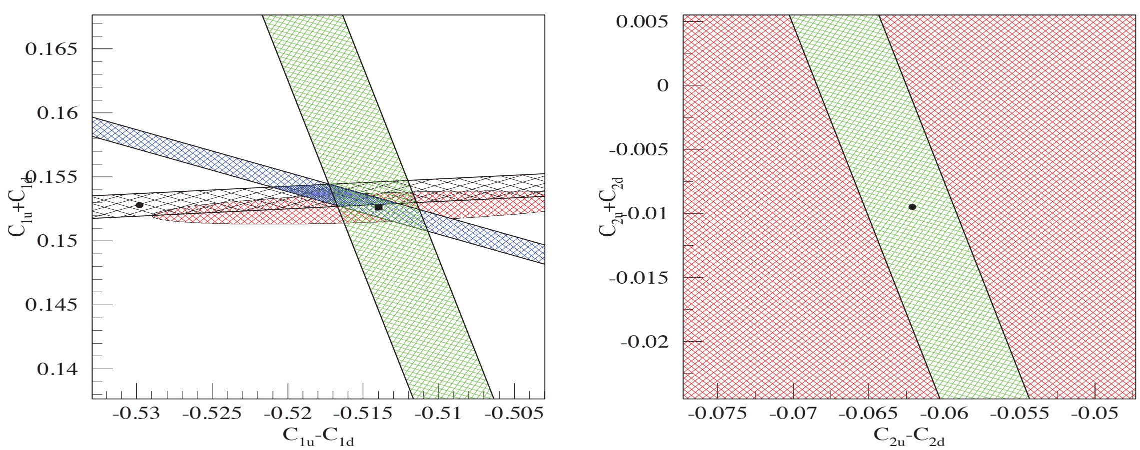

Figure 7-7. *Left plot: Constraints on the Standard Model from parity violation experiments. The black crossed band presents the results from atomic parity violation in Cs atoms, the blue band is the expected result from Qweak, the red ellipse is a PDG fit, while the green band shows the anticipated JLab limit. Right plot: The anticipated error band from the JLab experiment. All limits are 1 standard deviation.*

There are additional important corrections to Equation 7.9 [189]. In particular, the cross sections in this kinematic angle have significant scaling violations due to higher-twist effects [190]. However, as pointed out by Bjorken [191] and more recently by Mantry *et al.* [192], the higher twist terms cancel in the a_1 term unless they are due to quark-quark correlations. The observation of diquarks in the nucleon, if found, would be an exciting discovery. The higher twist contribution of the a_3 term can be subtracted from the asymmetry by using data on charged neutrino scattering [191].

7.4.2.3 Apparatus

The apparatus will use a large solenoid; presently the CLEOII magnet is being considered. Polarized electrons with an energy of 11 GeV will strike a liquid deuterium target. Scattered electrons with energies above 2 GeV will pass through a series of baffles and then strike a detector package consisting of tracking chambers, a Cherenkov counter to reject pions, and a calorimeter to serve as a trigger and provide additional pion rejection. The data will be taken with a deadtime-less flash ADC system with 30 independent sectors. The tracking detectors will be GEM with a total area of 25 m^2 [193].

7.4.3 Parity Violating Møller Scattering

A collaboration at JLab has proposed to measure A_{PV} in Møller scattering with longitudinally polarized electrons off unpolarized electrons, using the upgraded 11 GeV beam in Hall A at JLab to an overall fractional accuracy of 2.3%. Such a measurement would constitute more than a factor of five improvement in fractional precision over the only other measurement of the same quantity by the E158 experiment at SLAC [194].

The electron beam energy, luminosity, and stability at JLab are uniquely suited to carry out such a measurement. After the energy upgrade, a 11 GeV JLab beam provides a compelling new opportunity to achieve a new benchmark in sensitivity. The physics motivation has two important aspects:

1. New neutral current interactions are best parameterized model independently at low energies by effective four-fermion interactions via the quantity Λ/g, where g characterizes the strength and Λ is the scale of the new dynamics. The proposed A_{PV} measurement is sensitive to interaction amplitudes as small as 1.5×10^{-3} times the Fermi constant, G_F, which corresponds to a sensitivity of $\Lambda/g = 7.5$ TeV. This would be the most sensitive probe of new flavor and CP-conserving neutral current interactions in the leptonic sector until the advent of a linear collider or a neutrino factory.

2. As noted above, within the Standard Model, weak neutral current amplitudes are functions of the weak mixing angle $\sin^2\theta_W$. The two most precise independent determinations of $\sin^2\theta_W$ differ by 3σ. While the world average is consistent with other electroweak measurements and constraints on the Higgs boson mass M_H, choosing one or the other central value ruins this consistency and implies very different new high energy dynamics. The proposed A_{PV} measurement, which would achieve a sensitivity of $\delta(\sin^2\theta_W) = \pm 0.00029$, is the only method available in the next decade to directly address this issue at the same level of precision and interpretability.

A_{PV} in Møller scattering measures the weak charge of the electron Q^e_W, which is proportional to the product of the electron's vector and axial-vector couplings to the Z^0 boson. The electroweak theory prediction at tree level in terms of the weak mixing angle is $Q^e_W = 1 - 4\sin^2\theta_W$; this is modified at the one-loop level [195, 196, 173] and becomes dependent on the energy scale at which the measurement is carried out, *i.e.* $\sin^2\theta_W$ "runs". At low energy, Q_W^e is predicted to be 0.0469 ± 0.0006, a $\sim 40\%$ change of its tree level value of ~ 0.075 (when evaluated at M_Z).

The prediction for A_{PV} for the proposed experimental design is ≈ 35 parts per billion (ppb) and the goal is to measure this quantity with a statistical precision of 0.73 ppb and thus achieve a 2.3% measurement of Q_W^e. The reduction in the numerical value of Q_W^e due to radiative corrections leads to increased fractional accuracy in the determination of the weak mixing angle, $\sim 0.1\%$, comparable to the two best such determinations from measurements of asymmetries in Z^0 decays in the e^+e^- colliders LEP and SLC.

At the level of sensitivity probed, the proposed measurement could be influenced by radiative loop effects of new particles predicted by the Minimal Supersymmetric Standard Model (MSSM) [197, 4]. In Fig. 7-8, the dots on the right-hand side show the results of a random scan over an allowed set of MSSM parameters. Deviations from the Standard Model as large as +8% are possible, corresponding to a potential deviation as large as 3.5 σ. If the assumption of R-parity conservation is relaxed (RPV), tree-level interactions could generate even larger deviations in Q_W^e. The left-hand side of Fig. 7-8 shows the allowed region after constraints from low energy precision data have been taken into account. In this case, relative deviations of up to -18% are allowed, a shift of almost 8 σ.

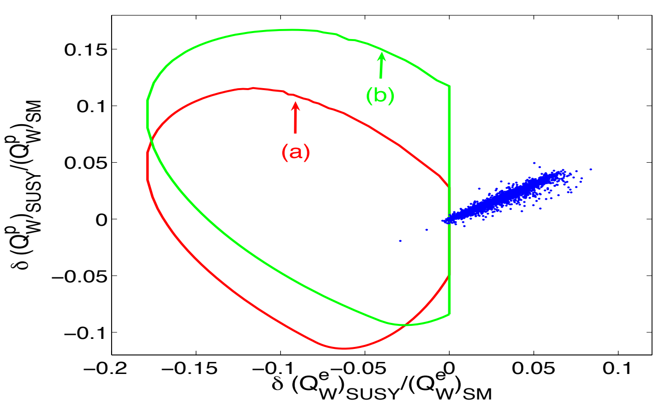

Figure 7-8. *Relative shifts in the electron and proton weak charges due to SUSY effects. Dots indicate the range of allowed MSSM-loop corrections. The interior of the truncated elliptical regions gives possible shifts due to R-parity violating (RPV) SUSY interactions, where (a) and (b) correspond to different assumptions on limits derived from first-row CKM unitarity constraints.*

A comprehensive analysis of the MOLLER experiment's sensitivity to TeV-scale Z's has recently been carried out [198] for a fairly large class of family-universal models contained in the E_6 gauge group. While models with full E_6 unification are already excluded by existing precision electroweak data, the Z' bosons in these

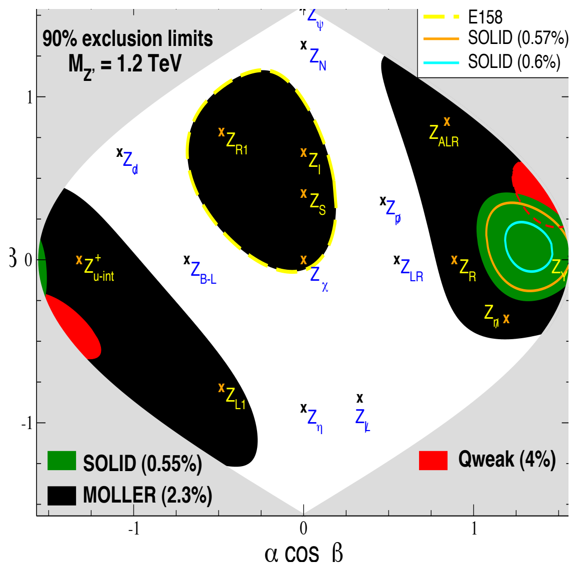

Figure 7-9. *90% C.L. exclusion regions for a 1.2 TeV Z' (E_6 gauge group) for MOLLER, Qweak and SOLID, assuming they obtain exactly the SM predictions. Also shown is the contour from the E158 result.*

models with the same electroweak charges to SM particles are still motivated because they also arise in many superstring models as well as from a bottom-up approach [199]. The MOLLER reach for a 1.2 TeV Z' from this model class, assuming the value predicted by the SM is measured, along with the current region excluded by E158, is shown in Fig. 7-9.

The measurement would be carried out in Hall A at JLab, where a 11 GeV longitudinally polarized electron beam would be incident on a 1.5 m liquid hydrogen target. Møller electrons (beam electrons scattering off target electrons) in the full range of the azimuth and spanning the polar angular range 5 mrad $< \theta_{lab} <$ 17 mrad, would be separated from background and brought to a ring focus $\sim$ 30 m downstream of the target by a ???spectrometer system consisting of a pair of toroidal magnet assemblies and precision collimators. The Møller ring would be intercepted by a system of quartz detectors; the resulting Cherenkov light would provide a relative measure of the scattered flux. The experimental techniques for producing an ultra-stable polarized electron beam, systematic control at the part per billion level, and calibration techniques to control normalization errors, including the degree of electron beam polarization at the 1% level, have been continuously improved over 15 years of development at JLab.

7.4.4 Atomic Parity Violation

Atomic parity violation (APV) comes from the mixing of opposite parity states by the weak interaction that allows forbidden electromagnetic (EM) transitions. The smallness of the weak interaction is enhanced experimentally by interference of an allowed and a forbidden transition, that then changes as the parity of the apparatus where it is measured changes. It has a rich history that spans more than 30 years [200, 201], but continues to attract attention as it has been identified as a low energy area where it is possible to search for physics beyond the Standard Model (SM) [202].

APV arises from the parity-violating exchange of Z^0-bosons between electrons and the quarks in the nucleus [203]. The most precise measurement to date of APV was completed during the 1990s in ^{133}Cs by the the group of Wieman in Boulder [204]. The extraction of weak interaction physics requires a theoretical input that has been improving significantly during the last decade (*e.g.*, [205, 206]).

APV measures the strength of the weak neutral current at very low momentum transfer. There are three types of such "low energy" weak neutral current measurements with complementary sensitivity. The atomic weak charge is predominantly sensitive to the weak charge of the neutron, as the proton weak charge is proportional to $(1 - 4\sin^2\theta_W)$, which accidentally is near zero. The Qweak electron scattering experiment on hydrogen will be sensitive to the weak charge of the proton (see [172, 173, 207] for recent results on weak charge calculations). The SLAC E158 Møller scattering is sensitive to the electron's weak charge. Different Standard Model extensions then contribute differently [208]. The atomic weak charge is relatively insensitive to one-loop order corrections from all SUSY particles, so its measurement provides a benchmark for possible departures by the other low energy observables. Møller scattering is purely leptonic and has no sensitivity to leptoquarks, so APV can then provide the sensitivity to those.

Current efforts: APV scales with the nuclear charge roughly as Z^3, favoring experiments in heavy atoms (see the recent results in Yb in [209]). Ongoing efforts in APV include, but are not limited to: Yb (Berkeley [209]), Fr (FrPNC Collaboration at TRIUMF, and the Ferrara, Legnaro, Pisa, Siena collaboration), Ra^+ (KVI), and Dy (Berkeley). There is an overall plan to work with different isotopes as a way to understand possible neutron distribution effects [210], but also for studies of the weak interaction inside the nucleus, through anapole moment measurements (see for example [211] and references therein).

Exploration of new methods to measure APV: All successful experiments that have measured APV have used an interference between an EM-allowed transition and the weak, parity mixing, amplitude. The result then comes from the extraction of a rate of transitions with one or the other parities. This applies also to the experiments that measure optical rotation. The measurements are subject to many complications, which have been overcome. Many atomic physics and precision metrologists have developed great tools to measure frequency and frequency shifts. However, there is no frequency shift associated with a transition dipole. An electric dipole P-odd and T-even cannot give rise to a frequency shift in a stationary atomic state perturbed by homogeneous E and B dc fields. Important proposals have appeared, and are beginning to be followed, that change the measurement of APV from a rate to a frequency shift, with the use of quadrupole transitions in a single ion [213] or by using light shifts that can create a linear Stark shift measurable with matter-wave interferometry [214, 215].

Intensity frontier: The successful APV experiments require as many atoms as possible (N). Current efforts with rare isotopes incorporate laser trapping and cooling to ensure large samples for interrogation [211], ensuring the large N regime. Methodologies for the measurement are exploring many new avenues – for example, two-photon transitions [212] and the proposals of Fortson and Bouchiat. For radioactive ions, large numbers may be more complicated, given the effects of space charge on a cloud of ions; but care can be taken to pursue this avenue. The planned energy and current for nuclear studies in Project X at FermiLab would allow to produce many orders of magnitude more rare isotopes than in any other facility in the world. If the design allows for parallel operations. To achieve this will require development of appropriate targets and handling facilities. The flux, together with the multiuser parallel operation mode, has the potential to become a fantastic tool for APV research in the future.

7.4.5 Electroweak Physics at an EIC

Over the last decade, the Electron Ion Collider (EIC) has been considered in the US nuclear science community as a possible future experimental facility (beyond 12 GeV upgrade of the CEBAF at Jefferson Laboratory, and the FRIB at MSU) [216] for the study of QCD. The EIC will help us explore and understand some of the most fundamental and universal aspects of QCD [216, 217]. This physics program requires the EIC to have a variable center-of-mass energy from about $\sqrt{s} = 30 - 140$ GeV, luminosities of $\sim 10^{33-34}\text{cm}^{-2}\text{sec}^{-1}$ for ep collisions (100-1000 times that achieved at HERA), polarization in both beams, and a wider range in nuclear species. The planned precision studies of QCD and the partonic dynamics also require the construction of a comprehensive detector system capable of excellent particle identification over a large momentum range, high momentum and energy resolutions and almost full (4π) acceptance. Currently there are two designs under consideration for the EIC in the US:

1. eRHIC [218] at Brookhaven which will use the hadron and nuclear beams of the existing Relativistic Heavy Ion Collider (RHIC). The plan is to build an ERL-based electron beam facility of variable energy 5-30 GeV in the existing RHIC tunnel to collide with one of the RHIC beams.
2. ELIC at JLab [219] which will use the electron beam from the 12 GeV upgraded CEBAF under construction now. This will require construction of a hadron/nuclear beam facility to be built next to the upgraded CEBAF complex to enable such collisions.

With the experimental conditions available at the EIC − a) center of mass energy ($\sim 100 - 140$ GeV), b) $\sim 100 - 1000$ times larger luminosity in e-p collisions than HERA, c) polarization in electron and proton/deuteron/helium beams, and d) a comprehensive detector system − it is only natural to explore what measurements would be possible at the EIC in the electroweak physics sector and of possible physics beyond the Standard Model. Three possible physics topics were considered so far:

1. Precision measurement $\sin^2\theta_W$ as a function of Q, the momentum transfer, in e-p collisions [220]. This would be the next-generation experiment beyond the SLAC-E158, 6 GeV Q-Weak, 6 GeV PVDIS and the currently planned 12 GeV experiments (Møller [221] & SoLID-PVDIS [222]) and would be complementary to atomic parity violation searches planned in the future. The Q range of the EIC would be between the fixed-target experiments and the measurements from LEP at the Z-pole. Any deviation from the expected running of the $\sin^2\theta_W$ would be a hint of physics beyond the SM.
2. Possible exploration of charged lepton flavor violation, particularly transitions between the 1^{st} and the 3^{rd} generation leptons ($e - \tau$) [223] at the highest energy and highest luminosity e-p collisions [224] at the EIC. This would extend searches made at HERA, in different ranges of the leptoquark couplings and masses, and will be complementary to future searches at the LHC, LHeC and the Super-B factories. The ∼100-1000 times more luminous collisions compared to HERA will be key to success in these searches. The angular correlations in the final state decay particles in the known Standard Model interactions involving taus in the final state and those in which taus are created in leptoquark interactions will form the tell-tale signs of the existence of leptoquarks interactions. Such studies were performed at HERA in the last decade, so the requirements of detector acceptance and the methods of analyses are fairly well defined[225].
3. Exploration of nucleon spin structure using the electroweak probes *i.e.*, the Z boson (and its interference with γ) and $W^{+/-}$[227]. Due to their different couplings to the quarks and anti-quarks, these measurements will enable us to explore different combinations of partons, and hence allow a determination of parton distribution functions different from those accessible through conventional deep inelastic

scattering with virtual photons. There is ample experience with W production in e-p scattering from HERA, where detailed studies of the structure function xF_3 have been performed. Since the HERA proton beam was unpolarized, only unpolarized heavy quark distributions were ever measured. With the polarized proton and neutron (via either deuteron or helium) beams at the EIC, these studies can be extended to include not only the quark anti-quark polarization, but also details of their possible charge symmetry relations.

The above studies and considerations are preliminary. Detailed detector simulations are needed to confirm the feasibility of these, and are under way.

7.5 Other Symmetry Tests

Numerous tests of fundamental symmetries of nucleons, nuclei, and atoms – outside the main thrusts described above – are being pursued. Among those for which descriptions were discussed at this workshop are studies of antimatter and possible novel tests of time-reversal invariance.

7.5.1 Antiprotons and Antihydrogen

Matter-antimatter Symmetry and CPT

The discrepancy between the deviation from matter-antimatter symmetry on the cosmic scale, on one hand, and the so-far-observed perfect symmetry between particle and antiparticle properties on a microscopic scale, on the other hand, is one of the big mysteries that has not yet been satisfactorily explained by the SM. The observed baryon asymmetry in the cosmos of $(N_B - N_{\overline{B}})/N_\gamma \sim 10 \times 10^{-6}$ [228] is in the SM thought to originate from the three Sakharov conditions: (1) baryon number violation, (2) C and CP symmetry violation, and (3) deviations from thermal equilibrium during the expansion of the universe. The so-far-observed violations of CP symmetry in the K and B meson sector are, however, too small to quantitatively explain the observed baryon asymmetry, and thus other sources of matter-antimatter asymmetry may be explored. Notably, if CPT symmetry is violated, then Sakharov's third criterion need not be invoked. As a concrete illustration, one may consider the Standard Model extension by Kostelecky *et al.* [229], wherein it is possible to generate a large baryon asymmetry through violations of CPT [230].

CPT symmetry ensures that particles and antiparticles have perfectly equal properties. It is the result of a proof based on mathematical properties of the quantum field theories used in the SM, but certain of these properties, like point-like particles, are not valid in extensions of the SM such as string theory. Thus tests of CPT by precisely comparing particle and antiparticle properties constitute a sensitive test of physics beyond the SM. Antiprotonic atoms and especially antihydrogen offer the most sensitive tests of CPT in the baryon sector.

CPT Tests with Antiprotonic Atoms and Antihydrogen

For more than 20 years, low energy antiprotons have provided the most sensitive tests of CPT in the baryon sector. The TRAP collaboration at LEAR of CERN has determined the maximal deviation of the charge-to-mass ratio of protons and antiprotons to $(Q_{\overline{p}}/M_{\overline{p}})/(Q_p/M_p) + 1 = 1.6(9) \times 10^{-10}$ [231, 232] using a Penning trap. The ASACUSA collaboration at CERN's Antiproton Decelerator has been performing precision laser and microwave spectroscopy of antiprotonic helium, an exotic three-body system containing a helium nucleus, an antiproton, and an electron exhibiting highly excited metastable states [233]. By comparing the experimentally observed transition frequencies between energy levels of the antiproton with state-of-the-art three-body QED calculations, the most precise values for the equality of proton and antiproton mass and charge ($(Q_p + Q_{\overline{p}})/Q_p = (M_p - M_{\overline{p}})/M_p < 7 \times 10^{-10}$ [234]) and the antiproton magnetic moment ($(\mu_p - \mu_{\overline{p}})/\mu_p < 2.9 \times 10^{-3}$ [235]) have been obtained.

Antihydrogen ($\overline{\mathrm{H}} \equiv \overline{p}e^+$), the simplest atom consisting only of antimatter, promises the highest sensitivity because its *CPT* conjugate system, hydrogen, is one of the best-studied atoms in physics. Currently three collaborations at CERN aim at forming antihydrogen and performing precision spectroscopy of its structure. ATRAP and ALPHA have the goal of measuring the two-photon 1S–2S laser transition in antihydrogen, which has been determined to a relative precision of 10^{-14} in hydrogen, and ASACUSA aims at measuring the 1.4 GHz ground-state hyperfine transition that is known to 10^{-12} relative precision from the hydrogen maser.

The progress – as is typical for precision experiments – is slow: the first formation of antihydrogen was reported in 2002 by ATHENA [236] (the predecessor of ALPHA) and ATRAP [237] using a nested Penning trap technique [238], the next major step happened in 2010 when ALPHA reported the first trapping of neutral antihydrogen atoms in a Joffe-Pritchard trap [239] (and later announced trapping times of 1000 seconds [240]), and ASACUSA announced the first formation of antihydrogen in a different trap named "cusp trap" [241] which is expected to provide a polarized $\overline{\mathrm{H}}$ beam [242] useful for measuring the ground-state hyperfine structure in an atomic beam [243]. Given these major achievements, first spectroscopy results can be expected within the next few years.

To reach the full potential of the measurements, *i.e.*, a similar precision to that obtained in hydrogen, a much longer time will be needed. The only facility in the world now providing low energy antiprotons, the AD at CERN, will be upgraded by an additional storage ring ELENA to decelerate antiprotons further and thus increase the number of trapped antiprotons. By the end of this decade another facility called FLAIR may go into operation at the FAIR facility under construction at Darmstadt.

Gravity of Antimatter

Using neutral antihydrogen, the gravitation between matter and antimatter can be experimentally investigated for the first time. Scenarios exist where a difference in the gravitational interaction of matter and antimatter can arise, which are part of a general search for non-Newtonian gravity [244]. The AEgIS experiment has been approved at CERN-AD and is about to start, aiming initially at a percent-level measurement of the gravitational acceleration of the antiproton. A second collaboration, GBAR, has submitted a letter of intent and is preparing a proposal, so that enhanced activities in this field can be expected in the future.

7.5.2 Antihydrogen: ALPHA

The goal of the Antihydrogen Laser Physics Apparatus (ALPHA) collaboration is to conduct fundamental studies of matter-antimatter asymmetry. Until recent successes [245, 246] with the current ALPHA apparatus, no group had ever trapped neutral antimatter. In 2009, the collaboration first had a hint of success, reporting [247] 6 ''candidate" antihydrogen atoms. In 2010, they demonstrated trapped antihydrogen, reporting 38 [245] antiatoms with trapping times of 0.17 s, subsequently optimizing performance and increasing the trapping numbers to 309 [246] trapped antiatoms during the 2010 antiproton season, and hundreds more during 2011, while simultaneously extending the confinement time of these antiatoms from 0.17 s to 1000 s. These results received significant coverage in the scientific press and were enthusiastically received by the general public [248]. The ALPHA apparatus was primarily designed to demonstrate that cold antihydrogen could be trapped, and this has been accomplished. Motivated by this rapid progress towards achieving conditions required for physics studies of antihydrogen, the collaboration is rebuilding the experiment. The new apparatus, ALPHA-II, is specifically designed to be a production machine on which physics studies of antimatter are conducted.

The success to date is only a first step on a long road of scientific exploration. Lessons from the five years of operation of the ALPHA apparatus are being incorporated into the new apparatus. ALPHA-II will be designed, constructed, and commissioned during the next three years. The ALPHA-II design will allow one to perform microwave and laser spectroscopy, antihydrogen charge neutrality measurements, and antimatter gravity studies. Though unlikely, any discovery of a fundamental difference between matter and antimatter in CPT or gravity experiments may shed light on baryogenesis or dark energy.

Key to these future physics studies with ALPHA-II is improving its performance over that of ALPHA. The ALPHA-II design goals are (a) a significant increase in trapping rates, from a peak rate of about 4 antihydrogen atoms per hour to a peak of order 40 antihydrogen atoms per hour, (b) improved trap geometry, allowing for enhanced diagnostics and laser and microwave spectroscopic access, and (c) improved shot-to-shot reliability. ALPHA-II will incorporate the techniques that the collaboration has developed on the original ALPHA apparatus, including evaporative cooling [252] of antiprotons and positrons, autoresonant injection [253] of antiprotons into the positron plasma, rotating wall plasma compression [254] and an octupole-mirror magnetic-well [255] neutral confinement scheme. The experiment will increase the production rate by separating catching and mixing functionalities, enhanced antiproton capture, creating and maintaining lower positron, antiproton, and electron plasmas, and developing new simulation tools for fast optimization of a wide range of system parameters. The collaboration is working on improved plasma diagnostics to reliably measure temperature at sub-Kelvin resolution, and on new, preferably non-invasive, temperature diagnostics.

The AD at CERN is the only facility that can provide low energy antiprotons for trapping experiments. The AD currently provides $\sim$5 MeV antiprotons to the experiments. ALPHA sends them through a degrader and traps about one in 10^3. CERN is building a new decelerator ring that will take the AD beam and lower its energy while providing the needed additional cooling, to 100kV. The construction of ELENA should begin in 2013 and the first physics injection should follow about three years later. This will significantly enhance antiproton capture rates, and, consequently, antihydrogen production. New positron-antiproton mixing schemes may be developed to best utilize increased antiproton numbers.

Antimatter experiments have one advantage over experiments with normal matter: One can detect, with more than 60% efficiency, the interaction of each antihydrogen on the trap wall. Thus, with only a few antiatoms, one can perform experiments that would be impossible with normal atoms. For example, a microwave-induced spin flip to a high-field state can be detected on almost a per atom basis. If the flip is successful, the antihydrogen hits the trap wall and the resulting shower is detected. The detector has both spatial and temporal resolution and serves as a critical diagnostic for inferring the temperature of the trapped antiatoms.

Exploration of CPT Invariance in Antihydrogen Studies: Antihydrogen studies open up CPT physics in a new, previously unexplored sector. Projected resolution achievable on ALPHA-II should reach that achieved in the kaon measurements. The CPT experiments can be conducted in two ways: (i) by measuring the microwave transitions of the hyperfine interaction and (ii) $1S \rightarrow 2S$ atomic transitions. We are currently testing microwave equipment on ALPHA, and will be operational with microwaves and lasers on ALPHA-II. The collaboration believes it can reach the level of kaon-sector precision in five years of physics operation, with ultimately higher precision depending on the level of laser cooling that can be reached. These spectroscopic measurements, as well as the neutrality measurements and gravity measurements discussed below, are direct measurements on antimatter. They are not model dependent.

Charge Neutrality Measurements: Measurements of charge neutrality constitute a novel method to test for CPT violation. The charge neutrality of antihydrogen can be tested, without spectroscopic techniques, using ideas from accelerator physics. Currently, the charge of the positron and antiproton are known only [256] to a factor of 4x10^{-8} and 2x10^{-9}, respectively. Experiments on ALPHA-II should reach a higher level of precision. For example, with a 300s lifetime and roughly 40 antiatoms, the expected precision is 1x10^{-10}. With a longer Hbar lifetime (300s $\rightarrow$ 2700 s) the precision is 3x10^{-11}, and with a much longer Hbar lifetime (36,000 s) the precision is 1x10^{-11}.

Gravity Measurements: Direct measurement of the gravitational interaction with antihydrogen is a unique and important experiment. Antigravity studies on ALPHA-II do not require high-precision laser or microwave spectroscopy, though laser cooling will enhance the sensitivity of the gravity measurements. With laser cooling, the collaboration believes ALPHA-II can reach a precision of unity or better in the ratio of the inertial to gravitational mass of antihydrogen. (This would rule out, for example, the possibility that the sign of the matter-antimatter gravitational force is opposite to the matter-matter gravity).

7.5.3 Neutron Beam Tests of Time Reversal

One advantage of the search for time-reversal invariance violation (TRIV) in neutron nuclei interactions is the possibility of an enhancement of T-violating observables by many orders of magnitude due to the complex nuclear structure (see, *i.e.* [257] and references therein). Moreover, the variety of nuclear systems for measuring T-violating parameters provides assurance that a possible "accidental" cancelation of T-violating effects due to unknown structural factors related to the strong interaction in the particular system would be avoided. Taking into account that different models of the CP violation may contribute differently to a particular T-odd or CP-odd observable, which may have unknown theoretical uncertainties, TRIV nuclear effects could be considered valuable complementary experiments to electric dipole moment (EDM) measurements.

One of the promising approaches to the search for TRIV in nuclear reactions is the measurement of TRIV effects in transmission of polarized neutrons through a polarized target. For the observation of TRIV and parity violating effects, one can consider effects related to the $\vec{\sigma}_n \cdot (\vec{p} \times \vec{I})$ correlation, where $\vec{\sigma}_n$ is the neutron spin, $\vec{I}$ is the target spin, and $\vec{p}$ is the neutron momentum, which can be observed in the transmission of polarized neutrons through a target with polarized nuclei. This correlation leads to a difference between the total neutron cross sections $\Delta\sigma_{\not{T}\not{P}}$ for $\vec{\sigma}_n$ parallel and anti-parallel to $\vec{p} \times \vec{I}$ and to neutron spin rotation angle $\phi_{\not{T}\not{P}}$ around the axis $\vec{p} \times \vec{I}$

$$\Delta\sigma_{\not{T}\not{P}} = \frac{4\pi}{p}\mathrm{Im}(f_+ - f_-), \qquad \frac{d\phi_{\not{T}\not{P}}}{dz} = -\frac{2\pi N}{p}\mathrm{Re}(f_+ - f_-). \tag{7.10}$$

Here, $f_{+,-}$ are the zero-angle scattering amplitudes for neutrons polarized parallel and anti-parallel to the $\vec{p} \times \vec{I}$ axis, respectively; z is the target length and N is the number of target nuclei per unit volume. The unique feature of these TRIV effects (as well as the similar effects related to TRIV and parity conserving correlation $\vec{\sigma}_n \cdot (\vec{p} \times \vec{I}) \cdot (\vec{p} \cdot \vec{I})$) is the absence of false TRIV effects due to the final state interactions (FSI) (see, *e.g.*, [257] and references therein), because these effects are related to elastic scattering at a zero angle. The general theorem about the absence of FSI for TRIV effects in elastic scattering was first proved by R. M. Ryndin [258] (see, also [259, 260, 257, 272]). Therefore, an observation of a non-zero value of TRIV effects in neutron transmission directly indicates TRIV, exactly as in the case of neutron EDM [261].

Moreover, these TRIV effects are enhanced [262] by a factor of about 10^6 in neutron-induced nuclear reactions (a similar enhancement was observed for PV effects related to $(\vec{\sigma}_n \cdot \vec{p})$ correlation in neutron transmission through nuclear targets). Since TRIV and PV effects have similar enhancement factors, it is convenient to consider the ratio λ of TRIV to PV effect at the same nuclei and at the same neutron energy as the measure of TRIV effect, because for this ratio, most nuclear structure effects cancel each other out. As a result, one can estimate $\lambda \sim g_T/g_P$, where g_T and g_P are TRIV and PV nucleon-nucleon coupling constants. Theoretical predictions for λ are varying from 10^{-2} to 10^{-10} for different models of CP violation (see, for example, [263] and references therein). Therefore, one can estimate a range of possible values of the TRIV observable and relate a particular mechanism of CP violation to their values. These estimates show that these effects could be measured at the new spallation neutron facilities, such as the SNS at Oak Ridge National Laboratory or the J-SNS at J-PARC in Japan.

7.6 Strong Interaction Issues

An important consideration for the interpretation of the aforementioned studies is the robustness of theoretical Standard Model predictions against which one makes comparisons. Obtaining sufficiently reliable computations in strongly interacting systems, such as the neutron or nuclei, as well as robust atomic many-body computations, remains an important thrust for the field. In some cases – such as electric dipole moment searches – theoretical uncertainties are unlikely to substantially affect the discovery potential, but may influence the interpretation of the results in terms of the specific underlying mechanism of CP violation. In others, such as the tests of CKM unitarity, tiny deviations from Standard Model expectations can only be interpreted as arising from new physics to the extent that uncertainties in the Standard Model predictions are sufficiently small.

Achieving these robust Standard Model computations requires progress on a number of fronts. Lattice QCD computations are now being used to compute the "θ"-term contribution to the neutron EDM as well as various scalar and tensor form factors associated with possible non-Standard Model contributions to neutron decay. Similarly, there is continued scrutiny of nuclear wavefunction uncertainties entering extractions of $V_{\rm ud}$ from superallowed nuclear Fermi transitions, while work is ongoing with refinements of nuclear Schiff moment computations needed for the interpretation of atomic EDM searches. And novel aspects of nucleon structure associated with heavy quarks may affect expectations for dark matter direct detection experiments.

The vast subject of strong interaction issues related to probes for new physics – not to mention those of intrinsic interest to the QCD community – exceeds the scope of what we are able to provide here. Several important contributions were received from the community, including discussion of possibilities for new probes of nucleon spin structure, the role of "intrinsic" heavy quarks in the nucleon wavefunction, and efforts to sharpen lattice QCD input. We refer the reader to the working group website for detailed write-ups and links to other material[2].

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