PROCEEDINGS OF SCIENCE

# Low energy precision experiments and extensions of the Standard Model

**Timothy Chupp***
*University of Michigan, Ann Arbor, Michigan, 48104 USA*
*E-mail:* chupp@umich.edu

A number of low-energy precision measurements are sensitive to Beyond Standard Model Physics because the standard model prediction for the measured quantity is precisely known - for example in the case of the anomalous magnetic moment of the muon $(g-2)$ - or because the Standard Model "background" is small - for example in the case of electric dipole moments (EDMs). I will discuss several studies underway that probe BSM including the muon $g-2$, EDMs and Beyond Standard Model Physics accessible from neutron decay.

*Xth Quark Confinement and the Hadron Spectrum,*
*October 8-12, 2012*
*TUM Campus Garching, Munich, Germany*

*Speaker.

## 1. Introduction

The Standard Model successfully describes nearly all measured elementary particle interactions and properties in terms of the weak, electromagnetic and strong interactions, yet there is strong evidence that the Standard Model is incomplete. Neutrinos with non-zero masses, the abundance of non-baryonic dark matter, and the baryon asymmetry of the universe are not directly accounted for in the Standard Model. Beyond Standard Model Physics (BSMP) that could accommodate these phenomena also generally introduce new particles and phenomena which suggest where to look. The search for new particles at the highest energies is one avenue; however this talk is about searches at lower energy, where one or both of the following can be exploited: 1) the Standard Model prediction is of comparable precision to the experiment, 2) the Standard Model background is small so that the observable stands out. The anomalous magnetic moment of the muon [1] is an example for which the Standard Model prediction and experiment are similarly precise. Time-reversal invariance (T) or equivalently charge-conjugation and parity (CP) violating electric dipole moments (EDMs) of the neutron, nuclei, atoms and molecules [2] are examples where the Standard Model background is small compared to current experimental sensitivity. A combination of precision predictions and low background is provided by measurements of neutron decay including the lifetime and correlations which measure both SM parameters such as the CKM matrix element $V_{ud}$ and probe BSMP couplings, for example in the T-violating triple correlation involving the neutron spin and momenta of the decay particles [3, 4]. Here I will briefly review several of these opportunities to probe BSMP that comprise the field we call "Fundamental Symmetries."

## 2. Anamolous magnetic moment of the muon

The magnetic moment of a charged lepton, *i.e.* the electron, muon or tau is $\mu_l = \frac{g}{2}\frac{e\hbar}{2m_l}$, where $g = 2(1+a_l)$, with $a_l$ the anomaly due to QED, electroweak interactions and strong interaction effects as well as possible new physics contributions. BSMP that enters at a mass scale $\Lambda$ contribute to $a_l$ proportional to $(\frac{m_l}{\Lambda})^2$, and thus the muon anomaly is about 40-thousand times more sensitive to new physics at scale $\Lambda$ than the electron. The electron magnetic moment has been measured to the astonishing precision of $0.76\times10^{-12}$, which corresponds to a measurement of the anomaly of 0.6 ppb (part per billion). A measurement of the muon anomaly at the proposed 140 ppb level, as discussed below, would be about 180 times more sensitive to new physics than the electron anomaly extracted from the electron-magnetic-moment measurement.

The Standard Model contributions to $a_\mu$ are given in Table 1. The dominant contribution from QED ($\approx 1.16\times10^{-3}$) is calculated up to four loops with estimated uncertainties at the four-loop level, from five loops and from the uncertainty in $\alpha$. The electroweak correction has been calculated at the two loop level [11] with uncertainty dominated by considering a range of Higgs masses $114 \le m_H \le 700$ GeV; however if the Higgs mass is constrained by experiment, this uncertainty would become negligible and the remaining uncertainty would be solely due to QCD [7, 8, 9, 10]. Hadronic effects, which contribute the largest uncertainties to the Standard Model calculation of $a_\mu$, are separated into leading-order and higher order corrections and a calculated light-by-light contribution. The leading-order contribution is found from a dispersion relation based on

**Table 1:** Standard Model contributions to $a_\mu$. For the 4-loop QED contribution, the first error (in parenthesis) is due to uncertainty in the 4-loop correction, and the second error is due to 5-loop effects; the third QED error is due to the uncertainty in $\alpha$. For the electroweak correction, the first error is due to hadronic 1-loop effects, while the second in parentheses is due to a broad range of possible Higgs-boson masses and would become negligible with definite $m_H$. For the hadronic vacuum-polarization effects, the first error is from experimental input and the second errors are due to perturbative QCD uncertainties for leading order and radiative corrections for higher order contributions. The light-by-light contribution uncertainty is from ref. [13].

| Source | Contribution ($10^{-11}$) | uncertainties ($10^{-11}$) | references |
|---|---|---|---|
| QED - 4 loop | 116 584 717.09 | 0.02, 0.14, 0.04 | [5][6] |
| Electroweak | 154 | 1, (2) | [7][8][9][10][11] |
| Hadronic VP - leading order | 6 955 | 40, 7 | [12] |
| higher order | -98 | 0.9, 0.3 | [12] |
| Hadronic light-by-light | 105 | 26 | [13] |
| **Total - SM** | **116 591 834** | **49** | |
| **E821 Result** | **116 592 089** | **63** | |

estimating the integral of $R(s) = \frac{e^+e^- \to (\text{all hadrons})}{e^+e^- \to \mu^+\mu^-}$, which is determined by experiment. The total Standard Model contribution is $1.16591834 \times 10^{-3}$ with an uncertainty of $49 \times 10^{-11}$ or 420 ppb. A great deal of activity, in particular in assessing incoming data on $R(s)$ and the theory of hadronic-vacuum polarization is ongoing and will be essential in reducing the 420 ppb uncertainty to the 250 ppb level.

The muon magnetic-moment anomaly has been measured with muons stored in a magnetic ring with electrostatic-quadrupole focusing, most recently at Brookhaven National Lab (BNL experiment E821 [1]). For relativistic particles of energy $E_\mu = \gamma m_u c^2$, the momentum and spin of the stored muons precess at different frequencies with the difference given by $\vec{\omega}_a = -\frac{q}{m}[a_\mu \vec{B} - (a_\mu - \frac{1}{\gamma^2-1})\frac{\vec{v}\times\vec{E}}{c}]$. At the special muon energy of 3.1 GeV, $\gamma = 29.3$, and the second $\vec{v}\times\vec{E}$ term is negligibly small. Thus $a_\mu$ can be determined by measuring the frequency $\omega_a$ and the magnetic field. The frequency $\omega_a$ is measured making use of the parity-violating asymmetry of positron emission in $\mu^+$ decay, which provides an angular distribution proportional to the cosine of the angle between the spin and $e^+$ momentum. Positrons emitted parallel to the muon momentum are kinematically boosted so that the rate above a threshold measured in an array of calorimeters is modulated at the frequency $\omega_a$ once background and rate-dependent corrections are taken into account. The magnetic field is determined from a set of proton-NMR measurements. About 360 NMR probes permanently mounted in the ring structure near the muon beam continuously monitors the field. A set of probes mounted in a moving "trolley" is periodically moved around the entire ring inside the vacuum chamber to determine the magnetic field distribution. The probes in the trolley are, from time to time, calibrated with respect to a spherical, pure $H_2O$ reference cell. The NMR measurements are combined and appropriately averaged across the muon beam to produce an average proton-NMR frequency $\omega_p$ with a systematic error of 170 ppb due to a number of contributions including temperature dependence of the diamagnetic shielding of the proton in $H_2O$, cross calibrations, time dependence and the convolution of the muon beam and magnetic field measurements. In terms of $\omega_a$ and $\omega_p$, the anomaly can be expressed as $a_\mu = \frac{\omega_a/\omega_p}{\mu_\mu/\mu_p - \omega_a/\omega_p}$, where $\mu_\mu$ and $\mu_p$ are, respectively, the magnetic moments of the muon and proton. For E821, the frequency $\omega_a$ was a determined with statistical and systematic errors of 465 ppb and 210 ppb, respectively. The final E821 result for $a_\mu$ is given in Table 1. The difference of Standard-Model prediction and the result of combining $\mu^+$ [14, 15] and $\mu^-$ [16] results is $(255 \pm 80) \times 10^{-11}$ or about $3.2\sigma$. This discrepancy has generated a great deal of interest and over 2300 citations. Many possible BSMP scenarios have been investigated including SUSY [17] and Dark Photons [18].

A new collaboration is working to improve the measurement by moving the ring to Fermilab (experiment E989) with the goal of reducing the uncertainty by a factor of about four to 140 ppb [19]. This improvement requires improved statistical uncertainty, mostly due to increasing muons per proton at higher energy (from 465 ppb to 100 ppb) and improved systematic errors for both $\omega_a$ and $\omega_p$ t (70 ppb and 70-100 ppb, respectively). A number of rate-dependent effects that contributed to the E821 systematic error on $\omega_a$ will be improved by decreasing the instantaneous rate and segmenting detectors. The hadronic background will be mitigated by the pion-decay path through the Fermilab accelerator complex, and improved beam dynamics are expected to affect the betatron oscillations of the stored muons. There are a number of straight-forward improvements to the determination of $\omega_p$ including reducing temperature fluctuations, measurement of the muon distribution and more frequent calibrations to mitigate the effects of time-dependence of the magnetic field distribution.

The importance of measuring the muon magnetic moment anomaly at the 100-200 ppb level has led to a proposal to J-PARC to make the measurement in a compact storage ring injected with accelerated cold muons extracted from monium by laser ionization [20]. One advantage of this approach is that there would be no need for electric fields to stabilize the storage ring. The compact ring would allow accurate determination of the magnetic field strength averaged over the muon distribution and address other systematic limitations of the BNL/Fermilab approach. The rates needed for such a measurement would be $10^6$ s$^{-1}$ or more, and developments at J-PARC and TRIUMF are promising.

Finally we discuss the muon EDM. As described in the next section, observation of an EDM would be direct evidence of T violation. For a charged particle such as the muon, an EDM means the separation of the the center of mass from the center of charge. The interaction of an EDM with an electric field leads to an energy shift or change in precession frequency. For the E821 storage ring, the EDM $d_\mu$ leads to an additional motion of the muon spin given by $\vec{\omega}_d = -\frac{q}{2m} d_\mu (\frac{\vec{v} \times \vec{B}}{c} + \vec{E})$. The first $\vec{v} \times \vec{B}$ term is perpendicular to the anomaly precession. Thus $\vec{w}_d$ rotates the muon spin out of the plane of the storage ring, and the EDM would be detected by out-off plane detectors. The E821 collaboration analysed data from detectors designed to help determine the muon beam distribution, and found $d_\mu = (0.0 \pm 0.9) \times 10^{-19}$ e-cm [21]. This about 7 orders of magnitude less sensitive than limits on the electron EDM set by atomic and molecular experiments, however the new $g-2$ experiment at Fermilab is expected to improve on the E821 EDM result by several orders of magnitude. Some models predict EDMs of leptons may scale proportional to $m_l$, $m_l^2$, *etc.*.

## 3. EDMs

An EDM in a quantum mechanical system can be defined as the projection of the charge distribution along the total angular momentum $\vec{J}$ in the state having magnetic quantum number $m_J = J$, *i.e.* $\int z\rho_{jj}(\vec{r})d^3r = dJ_z$. Thus $\vec{d} = d\vec{J}$, where $d$ is analogous to the magnetic-moment $\mu$. Under P, $\vec{d}$ changes sign, but $\vec{J}$ does not, and under T, $\vec{J}$ changes sign, but $\vec{d}$ does not. Thus $d$ must be odd under both P and T transformations. We can think of the EDM as arising from an electrical polarization of the system along $\vec{J}$ that is induced by elementary particle interactions that violate P and T, and, assuming CPT invariance, must violate CP.

An EDM measurment is conceptually simple: the Zeeman splitting between adjacent sub–levels is measured in the presence of both electric and magnetic fields so that $H = \vec{J}\cdot(d\vec{E} + \mu\vec{B})$. When the electric field is reversed with respect to the magnetic field, the magnetic resonance frequency shifts by $2d\mathbf{J}\cdot\mathbf{E}/J$. One of the most important aspects of any EDM measurement arises because any system with an EDM, i.e. non-zero $\vec{J}$, also has a magnetic moment and thus magnetic field variations, specifically those that might be correlated with the applied electric field, must be minimal, or even better directly measured. Basically, it is necessary to measure both $d$ and $\mu$, and thus the EDM measurement must incorporate a co-magnetometer or other means of monitoring the magnetic field. In many cases, this is accomplished with a second or multiple species with intrinsically different sensitivity to CP violation.

The Standard Model allows CP violation via complex flavor mixing amplitudes of the Cabibbo-Kobayashi-Maskawa (CKM) matrix and via the strong-interaction parameter $\bar{\theta}$. The CKM phase would generate EDMs much smaller than the current experimental sensitivity, leading to the contemporary view of EDM measurements as probe new physics. EDM results from the neutron and $^{199}$Hg are interpreted as suggesting that $\bar{\theta}$ is surprisingly small, though it is also possible that other sources of hadronic CP violation described below contribute to cancellations.

Among the most interesting contemporary motivations for the measurement of EDMs is the connection to baryogenesis laid out in the Sakharov criteria [22] requiring 1) baryon number violation, 2) CP violation and 3) non-equilibrium expansion. Standard Model sources are not sufficient to generate even the observed baryon asymmetry, and thus new forms of BSMP-CP violation are expected [23, 24, 25]. Most significant extensions of the Standard Model introduce additional phases that could produce the baryon asymmetry and lead to an EDM many orders of magnitude larger that the CKM values [26]. For example, supersymmetric models introduce phases that could produce the baryon asymmetry at the electroweak scale and produce EDMs of atoms or the neutron close to the current limits of sensitivity [27]. CP violation is also a valuable observable for probing physics beyond the Standard Model more generally - that is, CP violation can be used to reveal a weaker interaction in the presence of the dominant strong and electroweak interactions of the Standard Model.

There are several ways in which BSMP can contribute to the EDM of a system. For example for the neutron and nuclei the hadronic contributions include, in addition to $\bar{\theta}$, intrinsic quark EDMs ($d_{u/d}$, induced quark EDMs (chromoEDMs-$\tilde{d}_{u/d}$), 4-quark interactions and 3-gluon interactions. Diamagnetic systems including $^{199}$Hg, $^{129}$Xe and TlF have dominant contributions from hadronic interactions that generate the Schiff moment of the nucleus and from semi-leptonic interactions of the electron with tensor components of the nuclear current characterized by a coupling $C_T$.

For paramagnetic atoms the dominant contributions are from the electron EDM and semi-leptonic scalar interactions ($C_{S_{u/d}}$). Pseudoscalar nuclear contributions are suppressed in the limit of infinite mass of the nucleus.

In general, one can write the EDM of any system, labeled by $i$, as $d_i = \sum_i \alpha_{ij} C_j$, where $j$ labels the effective-physics parameter ($j$=$\bar{\theta}$, $d_{u/d}$, $\tilde{d}_{u/d}$, quark-quark, 4-quark, 3-gluon, $S_{u/d}$, $T$, and $d_e$) and $\alpha_{ij}$ are the coefficients reflecting sensitivity of $d_i$ to each physics parameter. The coefficients $\alpha_{ij}$ have been calculated for many systems of experimental interest (see, for example, reference [28]), but one sees that there are many CP-violating parameters that contribute to the EDM of any experimentally accessible system other than a bare lepton - *e.g.* the muon, and it would appear that we need experiments in at least as many systems as there are parameters. Fortunately there are classes of system for which just a few of the CP-violating parameters dominate. For example, paramagnetic atoms and molecules, *e.g.* Tl [30] and YbF [31], have dominant contributions from just three parameters, and it is in principle possible to set model-independent limits on $d_e$ and $C_{S_{u/d}}$ using data from three or more experiments with different relative sensitivities to $d_e$ and $C_{S_{u/d}}$. Allowing for both contributions to the EDMs of paramagnetic systems, we estimate that the limit on $d_e$ may be an order of magnitude or more larger than one would conclude from considering a single contribution to the EDM of Cs, Tl or YbF.

The situation with hadronic systems is more difficult, given the large number of CP violating parameters that contribute to the EDM. For example the neutron EDM is most sensitive to $\bar{\theta}$ and the EDMs of the two quarks while a diamagnetic atom such as $^{199}$Hg have additional contributions requiring, in principle, at least ten additional EDM measurements to constrain the individual sources of CP violation. In Table 2 we list the systems that have results along with ongoing and proposed endeavors that have the potential to ultimately provide a suite of measurements that will effectively constrain the sources of CP violation. In the remainder of this section, we anticipate results over the coming decade that will significantly advance the field.

**Paramagnetic atoms and molecules**

In paramagnetic atoms, the unpaired electron moves in the potential due to electric forces and the spin-orbit force so that the an external electric field, which effectively polarizes the atom, can be significantly amplified. The cesium EDM was measured in a cell, and the thallium EDM was measured with a pair of counter propagating vertical atomic beams. For the thallium experiment, the co-magnetometer was an additional pair of sodium beams. The Tl experiment is not likely to be improved; however work on Cs in an optical lattice and Fr in a cold atom fountain are progressing.

Polar molecules have large intrinsic dipole moments and are highly polarizable due to closely spaced opposite parity levels. In a molecule, CP violation would induce this polarization along the angular momentum of a constituent, either the nucleus of an atom, as in TlF, or an unpaired electron as in paramagnetic molecules. Experiments are currently underway in several paramagnetic molecules including WC[39], metastable PbO[40], ThO[41] and a result has recently been presented for YbF[31]. One feature of several molecular systems is the co-magnetometer built in to the molecular levels. For example, in WC the frequency splitting in both Ω-doublet levels can be measured; the magnetic field shift is the same for both levels, while the EDM effect changes sign. Thus the sum and difference of frequencies serve to measure the magnetic dipole coupling and the electric dipole coupling, respectively.

**Table 2:** Summary of EDM results along with ongoing and proposed experiments in systems discussed in this section.

| System | Result (e-cm)/status | |
|---|---|---|
| Paramagnetic ($d_e$, $C_{S_{u/d}}$) | | |
| Cs atom | $(-1.8 \pm 6.9) \times 10^{-24}$ [29] | cold atom effort underway |
| Tl atom | $(-4.0 \pm 4.3) \times 10^{-25}$ [30] | |
| Fr atom | proposed | |
| YbF | $(\ \ 3.5 \pm 8.6) \times 10^{-22}$ [31] | |
| WC, ThO, PbF | running | |
| Hadronic (quark EDMs, chromoEDMs, $\bar{\theta}$, $C^T_{u/d}$, 4-quark, 3-gluon) | | |
| $n$ | $(\ \ 0.2 \pm 1.7) \times 10^{-26}$ [32] | new efforts underway |
| $^{199}$Hg atom | $(\ \ 0.5 \pm 1.5) \times 10^{-29}$ [33] | improvement expected |
| $^{129}$Xe atom | $(\ \ 0.7 \pm 3.3) \times 10^{-27}$ [34] | new efforts underway |
| TlF | $(-1.7 \pm 2.9) \times 10^{-23}$ [35] | |
| Octupole enhanced Schiff moment | | |
| $^{225}$Ra | ongoing [36] | |
| $^{223}$Rn | in development [37] | |
| Storage ring | | |
| $p$ | proposed [38] | |
| $^2$H | " | |
| $^3$He | " | |

**$d_e$ in solid state systems**

In solid-state systems, the EDM of the unpaired electrons is detectable either through the magnetic field produced when the electron is polarized by the strong internal electric field[42] or through the electric field induced when the electrons are polarized by a strong magnetic field[43]. For example, in $PbTiO_3$, a ferroelectric crystal, sensitivity to the electron EDM is enhanced due to the large number of electrons in the solid and due to the strong internal electric field, provided the crystal can be effectively cooled to maintain the electron polarization. A similar measurement in gadolinium-gallium garnet is under way[44]. Another approach using ferromagnetic gadolinium-iron garnet would detect the electric field produced by the electron EDMs aligned with the magnetically polarized spins[45].

**Neutron EDM**

The neutron EDM is measured using ultra-cold neutrons (UCN), which are long-wavelength neutrons that can be contained in material bottles. The best measurement to date at Institute Laue-Langevin (ILL) in Grenoble follows the steady evolution of UCN source development[46] and the incorporation of a $^{199}$Hg co-magnetometer [32]. The EDM measurement takes place in a storage cell placed inside four layers of passive magnetic shielding the co-magnetometer greatly reduces the effect of magnetic field variations. The statistical error can be improved only with more UNC or a higher electric field. Since the UCN enter the measurement cell as a gas, the figure of merit for UCN production is the density, which is 10-100 UCM/cm$^3$ for the ILL source. A great deal of progress in UCN production has been realized using superfluid helium[46, 47, 48] and solid deuterium[49, 50, 51]. Systematic errors generally arise because the co-magnetometer does not measure the same magnetic-dipole effects as the neutron due to the way the two species move in the measurement cell. These effects include motional effects (i.e. a $\vec{v}\times\vec{E}$ effect that averages differently[52]) and the geometric phase effect[53].

Future experiments are planned at several sites. The next generation ILL experiment operates at 500 mK in order to produce UCN by down scattering in superfluid helium and will use squid magnetometers[54]. The PSI group will develop a next-generation EDM experiment around their source, which is projected to produce 1000 UCN/cm$^3$. At the FRM reactor at the Technical University of Munich (TUM), an experiment is being mounted that plans to use UCN produced from a frozen deuterium source closely coupled to the reactor core. Sources based on superfluid helium are being developed at ILL and in KEK [48] with plans to move the KEK source to TRIUMF. A US group has gained a great deal of momentum on its way to developing an EDM experiment that will use a $^3$He co-magnetometer with an in-situ superfluid helium UCN source[55]. The level of activity and the scale of these efforts has increased greatly in recent years, and the expectation is that the neutron-EDM sensitivity will steadily improve by a factor of 10-100 in the next decade.

**Diamagnetic atoms**

Diamagnetic atoms, *i.e.* atoms with closed electron shells, acquire EDMs from several possible sources. In general, the largest contribution would be induced as the electrons probe the nuclear dipole distribution, giving rise to an atomic EDM proportional to the Schiff moment of the nucleus: $\vec{S}=\frac{1}{10}<er^2\vec{r}>-\frac{1}{6}<r^2><e\vec{r}>$ . Sensitivity to this Schiff moment increases as Z$^2$ to Z$^3$ due to the electron momenta, relativistic effects, and the size of the nucleus. Diamagnetic atoms are also sensitive to CP violating tensor neutral current interactions between the electrons and the nucleus[56]. The EDM of a diamagnetic atom can also be induced, at higher order, by the electron's EDM. Diamagnetic atoms have the experimentally attractive feature that they can be contained in room-temperature bottles or cells because the angular momentum of the atom, which resides in the nucleus, is well shielded by the closed electron shell, even as the atom sticks to the wall for short times.

The most sensitive atomic EDM measurement is in $^{199}$Hg[33]. The experiment uses a stack of four cells such that the electric field in the middle two cells is opposite, and the electric field in the outer two cells is zero. The EDM signal is a difference of the precession frequencies for the middle two cells, and other combinations of the four cells' frequencies measured the averaged magnetic field and its gradients. There is no co-magnetometer species, but the leakage current from the single, central high-voltage electrode is monitored and found to be below the level that would produce a false signal due to the magnetic field produced by the current flowing in a loop around one of the central cells.

Another approach to co magnetometry has been provided by the spin-exchange pumped noble-gas maser [34]. Spin exchange with optically pumped alkali-metal vapors can be used to polarize and pump a population inversion in multiple species. We used the combination of $^{129}$Xe and $^3$He which have very different sensitivity to the Schiff moment and other sources of an atomic EDM due to the $Z^2$-$Z^3$ dependence. The co-magnetometer occupies nearly the identical volume for the two species. The statistical sensitivity was limited by instability of the masers, which could be greatly improved, and one to two orders of magnitude improvement seems feasible. Polarization by spin-exchange can also be used to produce significant volumes of polarized liquid $^{129}$Xe. An experiment under way at TUM, which uses squids to monitor the difference of precession frequencies for two samples in opposite electric fields, may provide several orders of magnitude improvement compared to $^{199}$Hg. An active maser approach using $^{129}$Xe is under development in Tokoyo Institute of Technology [58].

**Octupole Deformed Rare Isotopes**

In nuclei, collective effects produce higher order vibrations and deformations. The combination of quadrupole and octupole collectivity can lead to a large intrinsic dipole moment, and a T-non-invariant interaction can align this moment with the nuclear spin $\vec{J}$. The result is an expected enhancement[59, 60] of the Schiff moment by factors of several hundred to a thousand with respect to $^{199}$Hg[61, 62, 63]. This enhancement arises because of the large intrinsic moment and also because of the mixing of opposite parity levels with the same $J$, which arise near threshold in octupole deformed systems: $S \propto eZr_0^3 \frac{\beta_2\beta_3^2}{E_+ - E_-}\eta$. Here $\beta_2$ and $\beta_3$ are the quadrupole and octupole deformation parameters, $E_+$ and $E_-$ are the energies of the two opposite parity levels in the two-state approximation and $\eta$ is a parameter representing the strength of the CP-violating nucleon-nucleon interaction.

Two different systems provide experimental opportunities to extend the sensitivity to CP violaiton: laser cooled $^{225}$Ra in an optical trap[36] and spin-exchange polarized $^{223}$Rn in a cell[37]. Both of these techniques have progressed significantly toward the realization of an EDM measurement. A magneto-optical trap (MOT) of $^{225}$Ra and $^{226}$Ra with $N = 20$ and $N = 700$ atoms, respectively, has been established. One interesting feature of this MOT is that black-body radiation is an effective repump source[36]. The 1 mCi $^{225}$Ra is currently provided by alpha decay from a laboratory source of $^{229}$Th, though the planned EDM experiment at the $10^{-26}$ e-cm level and beyond will require a 10 mCi source. Further advances in statistical precision may be possible with production rates at a rare-isotope facility, and ultimately at FRIB. Studies with both radioactive xenon isotopes and radon isotopes at TRIUMF and Stony Brook have advanced progress toward a radon EDM measurement. Efficient transfer of the radioactive noble gas to a measurement cell[65] and polarization of about a million $^{209}$Rn atoms by spin exchange at Stony Brook[37] as well as relaxation measurements establish two of the requirements for an EDM measurement. Gamma-ray anisotropies, beta-asymmetries and possibly laser magnetometry can be used to monitor the nuclear spin precession, and projections at TRIUMF and FRIB are $4 \times 10^{-27}$ e-cm and $5 \times 10^{-28}$ e-cm respectively.

**Storage ring experiments**

A charged particle in a storage ring is guided by the magnetic field normal to the plane of the ring and additional electromagnetic fields to constrain the particle as described in section 2. For a particle with a magnetic moment aligned with the momentum at some time, the spin will precess with respect to the momentum in the plane of the ring at a rate that depends on the anomalous magnetic moment and the velocity. In direct analogy to the muon, the EDM of a stored nucleus will also lead to a torque that causes spin precession that is out-of phase with the magnetic moment precession and is perpendicular to the plane of the ring. Measurements on stored protons, deuterons and $^3$He nuclei with projected sensitivity at the $10^{-28}$ e-cm level or better have been proposed [38].

## 4. Correlations in Neutron Decay

While the most general formulation of beta-decay allows for vector (V), axial-vector (A), scalar (S), pseudoscalar (P) and tensor (T) amplitudes, the Standard Model is written with only V and A interactions. Allowing for T-violation, there is one arbitrary overall phase and three free parameters labeled $|g_V|$, $|g_A|$ and the relative phase of $g_A/g_V = |\lambda|e^{i\phi_{AV}}$ which vanishes in the absence of T violation. The value of $|g_V| = G_F|V_{ud}|$ follows from CVC (an assumption of the Standard Model) with $G_F$ determined from the muon lifetime and $V_{ud}$ most precisely determined from super-allowed beta decays. The parameter $|g_A| = |\lambda|g_V$ is determined from correlation-coefficient measurements, *i.e.* $a$, $A$ and $B$. The importance of accurately and precisely measuring the neutron lifetime and $\lambda$ has been magnified in recent years with the precision determination of the CKM matrix elements. The neutron lifetime depends on $V_{ud}$ and $\lambda$, while $\lambda$ can be independently determined from correlation-coefficient measurements described below. Thus $V_{ud}$ can be independently determined. Results of super-allowed beta decays are currently consistent with CKM matrix unitarity for 3 quark generations [66], and neutron decay should ultimately serve to corroborate the super-allowed beta decay analysis or reveal new physics. The goal for neutron decay must be similar precision, i.e. measurements at the 0.1% level and better. This can also be viewed as a test of Standard-Model assumptions, specifically CVC and no second-class currents [67].

For polarized neutrons, the decay rate can be written:[68]:

$$\frac{d\Gamma}{dE_e d\Omega_e d\Omega_\nu} = \frac{1}{\tau_n}G(E_e)\{1 + a\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_eE_\nu} + b\frac{m_e}{E_e} + \vec{P}_n\cdot(A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e\times\vec{p}_\nu}{E_eE_\nu})\} \tag{4.1}$$

where $\vec{P}_n = \frac{\langle\vec{J}_n\rangle}{J_n}$ is the ensemble average of the neutron spin. In the Standard Model, the coefficients $a$, $A$ and $B$ depend only on $\lambda$, while BSMP due to scalar and tensor currents may also contribute. Thus a set of measurements over constrains Standard Model Physics and can be viewed as a search for BSMP. A finite $D$ coefficient would arise in the event of T-violation, and thus can be viewed as a measure of the phase of $\lambda$.

The emiT experiment [3, 4, 69, 70] measured the triple correlation $D\langle\vec{J}_n\rangle\cdot(\vec{p}_e\times\vec{p}_\nu)$ by measuring proton-electron coincidences. This triple correlation is T violating, P conserving, and is small in contrast to the the T-even/P-odd beta asymmetry ($A \approx -0.1$) and neutrino asymmetry ($B \approx 1$). The experiment was designed to optimize the tradeoffs of maximum coincidence decay rate, sensitivity to $D$, and symmetry to cancel the effects of the A- and B-coefficient correlations. Four electron detectors consisting of plastic scintillators with phototubes at either end alternated with four proton-detector planes in an octagonal array surrounding the neutron beam. The proton detectors consisted of 16 separate silicon surface barrier detectors (SBDs) arranged in two rows of eight detectors. The low energy protons from neutron decay ($E_p < 750$ eV) are delayed by times of order microseconds and are accelerated and focused onto the SBDs, which are biased by voltages in the range -25 to -31 kV. A total of more than $3\times10^8$ events formed the data set from which $D$ was extracted; significant additional data were used for calibrations and systematic studies. A blind analysis approach was adopted that required that all aspects of the data analysis including event definition, cuts, analysis techniques and all systematic effects to be finalized before revealing an artificial offset to $D$. A large range of systematic effects were identified and studied using the data, background studies, experimental details such as maps of neutron-beam and neutron-polarization distributions and a detailed Monte Carlo simulation of the experiment. Analysis included study of the effects of backgrounds, detector non-uniformities, polarization and beam distributions and a number of cuts on experimental parameters including magnetic fields, leakage currents, beta-detector multiplicity, proton acceleration voltage and a software threshold on the beta energy. The final result, $D = [-0.94 \pm 1.89(\text{stat}) \pm 0.97(\text{sys})] \times 10^{-4}$, represents the most sensitive measurement of $D$ in nuclear beta decay and can be interpreted in terms of possible extensions of the Standard Model. Assuming no scalar or tensor currents, this result constrains the complex phase between the axial-vector and vector currents to $\phi_{AV} = 180.012^\circ \pm 0.028^\circ$ (68% confidence level). If all currents are allowed there are four additional phases from scalar and tensor amplitudes, which can be constrained under specific assumptions. A more detailed discussion is presented in reference [4].

An improved experiment with the same apparatus would need both more neutron decays and reduced systematic effects. A new beam-line (NGC) under construction at NIST and the PF-1 beam at ILL could provide a factor of 10 or more increase of neutron decay rate. Reducing the three major systematic corrections requires eliminating the proton-threshold variations, a more symmetric neutron beam, and smaller magnetic field. The symmetry of the neutron-beam was most strongly affected by the supermirror-bender neutron polarizer, while the 560 $\mu$T magnetic field was chosen to effect sufficient velocity averaging of transverse-neutron polarization produced in the current-sheet spin flipper. An alternative polarizer is a steady-state polarized $^3$He spin filter [71], and the guide field can be reduced by using an adiabatic-fast-passage neutron spin flipper and effective shimming of the magnetic field along with shielding of external field perturbations. Extending the sensitivity to the level of final-state-effects ($10^{-5}$) and beyond is a well motivated goal that would require an apparatus with greater geometric efficiency for both proton and electron detectors.

To measure $a$ with unpolarized neutrons and $A$ and $B$ with polarized neutrons, a new spectrometer has been developed by the Nab/abBA/PANDA collaboration. The Nab spectrometer measures the proton velocity and electron energy in coincidence [72]. The first measurement planned is beta-neutrino correlation correlation with the goal of a 0.1% measurement of $a$. The Fierz-interference coefficient $b$, which arises in neutron decay due to a combination of scalar and tensor currents, will also be extracted by accurately measuring the electron energy spectrum. The neutrino asymmetry $B$, which is sensitive to scalar and tensor contributions in first order, can be separated from $A$ by measuring the electron-energy ($E_e$) dependence of the proton asymmetry $C$. Radiative corrections to $C$ have been calculated [73]. Contributions from new physics, for example scalar leptoquarks have been proposed [74], and a detailed study of the sensitivity of $C$ to new physics has recently been completed by Gudkov[75].

In the Nab detector, charged particles produced in neutron decay are confined by magnetic field lines that expand rapidly so that the transverse momentum is converted to longitudinal components while the energy remains constant. Thus the proton time of flight becomes a good measure of the proton velocity and therefore energy. A highly pixelated silicon detector has been developed. Each detector pixel maps to a specific $x$-$y$ position in the beam. Electron energy is measured in the energy-calibrated silicon detectors. The principle of the measurement of $a$ can be understood by writing $\vec{p}_p = -(\vec{p}_e + \vec{p}_\nu)$ and thus $p_p^2 = p_e^2 + p_\nu^2 + 2\vec{p}_e \cdot \vec{p}_\nu$. The energy released in neutron decay is $E_{max}$=782 keV, and the maximum proton energy is 750 eV, so to an accuracy of approximately

0.1%, $p_\nu = E_\nu \approx E_{max} - E_e$. We can therefore write $\vec{p}_e \cdot \vec{p}_\nu \approx \frac{1}{2}[p_p^2 - p_e^2 - (E_{max} - E_e)^2]$, for each neutron-decay event. The spectrum of events with respect to $\vec{p}_e \cdot \vec{p}_\nu$ has slope $a$. The crux of the spectrometer design is therefore to understand the relationship of the measured proton time-of-flight and proton velocity and any distortions to the spectrum that can arise. The spectrometer response has been studied through simulations and will be verified by measurements with the final apparatus.

The beta-neutrino asymmetry measurement will take place at the Oak-Ridge Spallation Neutron Source (SNS) Fundamental Neutron Physics Beamline (FP13). With expected data rates of 600 $s^{-1}$ for proton-electron coincidences, statistical precision of $\frac{\sigma_a}{a} = 10^{-3}$ should be possible in about 6 weeks or running; therefore Nab should not be statistics limited. A large number of systematic effects related to the spectrometer magnetic fields, stray electric fields, non-uniformities and calibrations have been studied in detail and are presented in reference [72]. One interesting possible systematic effect would arise if the neutron beam is polarized. This has never been measured, but is crucial for Nab: a neutron polarization of 0.01% ($10^{-4}$) would produce an error on $a$ of $6 \times 10^{-4}$ due primarily to the neutrino asymmetry ($B$ term). Measurement of the expected small polarization of the SNS FP-13 beam with an absolute precision less than $10^{-4}$ is a significant challenge, and we plan to use a polarized $^3$He cell. The $^3$He polarization will be flipped with losses less than $10^{-4}$ by adiabatic-fast-passage NMR (AFP) in a "magic box" magnetostatic cavity similar to that described in reference [76]. The basic polarimetry ideas are presented in reference [77]. With the intense FP13 neutron beam, statistics for a $10^{-4}$ measurement for all practical neutron velocities can be acquired in a short time. One important issue for the $P_n$ measurement is the guide field for neutrons. The Nab-spectrometer magnetic field is vertical, and the field reverses as the neutron beam enters and exits the spectrometer. Assuming neutrons emerging from the FP13 guide are polarized along the local field, the worst case scenario would be adiabatic transport into the Nab-spectrometer decay region. One promising way to investigate this is to set-up a guide field that would adiabatically transport polarized neutrons into the spectrometer and use a neutron spin flipper based on AFP to flip the spins of all neutron velocities with high precision. The spin transport would be set up and tuned with neutrons polarized by a $^3$He spin filter. The $a$ measurement would then be the average of the two neutron spin states, and if $P_n$ is sufficiently large ( e.g. $10^{-3}$), the neutron polarization would also be revealed.

## 5. Summary

The search for Beyond-Standard-Model Physics at low energies, the field also called Fundamental Symmetries continues to thrive. I have given three examples of ongoing efforts: the muon magnetic moment anomaly $g-2$, electric dipole moments and measurements of correlations in neutron decay, which have had significant impact in constraining BSMP and are poised to make significant improvements in sensitivity in the near future. I have, of course, left out many other activities that follow in the tradition of Fundamental Symmetries including neutrino masses and oscillation parameters, double beta decay, neutron oscillations, hadronic parity violation, parity-violating electron scattering, short and intermediate range interactions and dark matter searches. While no one knows how or where new physics will show up, these experiments are all highly motivated, technically challenging and a lot of fun.

## Acknowledements

It has been a pleasure and privilege collaborating with a large number of exceptional scientists working on the $^{129}$Xe and Radon EDM efforts, emiT and more recently Nab, and most recently the New Muon $g-2$ collaboration. This has led to many very productive discussions and arguments as well as several of successful experiments.

## References

[1] G.W. Bennett, et al. Phys. Rev. D **73**, 072003 (2006).

[2] T.E. Chupp, Nuclear Physics A, **827**, 428c-35c, (2009).

[3] H.P. Mumm *et al.*, Phys. Rev. Lett. **107**, 102301 (2011)

[4] T.E. Chupp, *et al.*, Phys. Rev. C **86**, 035505 (2012).

[5] T. Kinoshita, B. Nizic, and Y. Okamoto, Phys. Rev. D 41, 593 (1990).

[6] A. Höcker and W.J. Marciano, "The Muon Anomalous Magnetic Moment" in J. Beringer et al. (Particle Data Group), Phys. Rev. D86, 010001 (2012).

[7] R. Jackiw and S. Weinberg, Phys. Rev. D 5, 2473 (1972).

[8] G. Altarelli, N. Cabibbo, and L. Maiani, Phys. Lett. B 40, 415 (1972).

[9] I. Bars and M. Yoshimura, Phys. Rev. D 6, 374 (1972).

[10] W. A. Bardeen, R. Gastmans, and B. E. Lautrup, Nucl. Phys. B46, 315 (1972).

[11] T. Gribouk and A. Czarnecki, Phys. Rev. D **72**, 052016 (2005).

[12] M. Davier, A. Höcker, B. Malaescu, C.Z. Yuan and Z. Zhang, arXiv:0908.4300v2 [hep-ph] .

[13] J. Prades, E. de Rafael, A. Vainshtein, arXiv:0901.0306v1 [hep-ph].

[14] G. W. Bennett et al. , Phys. Rev. Lett. **89**, 101804 (2002).

[15] G. W. Bennett et al. , Phys. Rev. Lett. **89**, 129903(E) (2002).

[16] G. W. Bennett et al., Phys. Rev. Lett. **92**, 161802 (2004).

[17] A. Czarnecki and W.J. Marciano, Phys. Rev. D **64**, 013014 (2001).

[18] M. Pospelov, Phys. Rev. D **80**, 095002 (2009).

[19] B.L. Roberts, arXiv:1001.2898v2 [hep-ex] (2010).

[20] K. Ishida, AIP Conf. Proc. 1222, 369 (2010).

[21] G. W. Bennett et al., Phys. Rev. D **80**, 052008. (2009).

[22] A.D. Sakharov, *JTEP Lett.* 5, 24 (1967).

[23] A.D. Dolgov, arXiv hep-ph/9707419 (1997).

[24] M. Trodden, *Rev. Mod. Phys.* 71, 1463 (1999).

[25] A. G. Cohen, D. B. Kaplan, and A. E. Nelson, Ann. Rev. Nucl. Part. Sci. **43**, 27 (1993).

[26] M. Pospelov and A. Ritz, *Phys. Rev.* D63, 073015 (2001).

[27] S. Abel, S. Khalil, O. Lebedev , *Nucl. Phys.* B606, 151 (2001).

[28] J.S.M. Ginges, V.V. Flambaum, *Phys. Rep.* **397** 63 (2004).

[29] S.A. Murthy, D. Krausse, Z.L Li, L.R. Hunter, *Phys. Rev. Lett.* **63**, 965 (1989).

[30] B.C. Regan, E.D. Commins, C.J. Schmidt, D.DeMille, *Phys Rev. Lett.* **88**, 071805 (2002).

[31] J.J. Hudson, D.M. Kara, I.J. Smallman, B.E. Sauer, M.R. Tarbutt, E.A. Hinds, Nature **473** 493 (2011).

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

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

[34] M.A. Rosenberry and T. E. Chupp, *Phys. Rev. Lett.* 86, 22 (2001).

[35] Cho, D., Sangster, K., Hinds, E., Phys. Rev. A **44**, 2783Ð 2799 (1991).

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

[37] E.R. Tardiff, *et al.*, *Phys. Rev.* **C 77**, 052501(R) (2008).

[38] Y.K. Semertzidis *et al.*, arXiv:hep-ex/0308063 (2003).

[39] Aaron Leanhardt, private communication.

[40] D. DeMille, *et al.*, *Phys. Rev.* **A 61**, 052507 (2000).

[41] E. R. Meyer, J. L. Bohn, M. P. Deskevich, *Phys. Rev.* **A73**, 062108 (2006).

[42] F.L. Shapiro, Sov. Phys. Usp. 11, 345 (1968).

[43] T.N. Mukhamedjanov, O.P. Sushkov, *Phys. Rev.* **A**, 034501 (2005).

[44] C.-Y. Liu, S.K. Lamoreaux, *Mod. Phys. Lett.* **A 19**, 1235 (2004).

[45] B.J. Heidenreich et al., Phys. Rev. Lett. 95, 253004 (2005).

[46] A. Steyerl, *et al.*, *Phys. Lett.* **A116**, 347 (1986).

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

[48] Y. Masuda, *et al.*, *Phys. Rev. Lett.* **89**, 284801 (2002).

[49] A.P. Serebrov, *Nucl. Inst. Meth. in Phys. Res.* bfA440, 653 (2000).

[50] A. Saunders et al., Phys. Lett. B 593, 55 (2004).

[51] M. Wohlmuther, G. Heidenreich, *Nucl. Inst. Meth. in Phys. Res.* **A564**, 51 (2006).

[52] S.K. Lamoreaux, R. Golub, *Phys. Rev.* **A71**, 032104 (2005).

[53] E.D. Commins, *Am. J. Phys.* **59**, 1077 (1991).

[54] Rutherford Appleton Laboratory, Particle Physics Experiments Report RAL-TR-2003-006.

[55] T. Ito, arXiv:nucl-ex/0702024v1 (2007).

[56] A. Martensson–Pendril, Phys. Rev. Lett. **54**, 1153 (1985).

[57] M. V. Romalis, M. P. Ledbetter, *Phys. Rev. Lett.* **87**, 067601 (2001).

[58] A. Yoshimi *et al.* Phys. Lett. A, **376**, 1924 (2012).

[59] W.C. Haxton and E.M. Henley, *Phys. Rev. Lett.* 51, 1937 (1983).

[60] N. Auerbach, V.V. Flambaum, and V. Spevak, *Phys. Rev. Lett.* 76, 4316 (1996).

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

[62] J. Engel, M. Bender, J. Dobaczewski, J.H. de Jesus, P. Olbratowski, *Phys. Rev.* C68, 025501 (2003).

[63] J.H. de Jesus, J. Engel, *Phys. Rev.* C72, 045503 (2005).

[64] B.C. Regan, E.D. Commins, C.J. Schmidt, D.DeMille, *Phys Rev. Lett.* **88**, 071805 (2002).

[65] S.R. Nuss-Warren *et al.*, *Nucl. Instr. and Meth. in Phys. Res.* **A533**, 275 (2004).

[66] J.C. Hardy, I.S. Towner, *Phys. Rev.* **C71**, 055501 (2005)

[67] N. Sevrijns, M. Beck, O Navialiat-Cuncic, Rev. Mod. Phys. **78** (2006).

[68] J.D. Jackson, S.B. Treiman, H.W. Wyld Jr. *Nucl. Phys.* **4**, 206 (1957).

[69] L. J. Lising *et al.*, *Phys. Rev.* **C62**, 055501 (2000).

[70] H. P. Mumm *et al.*, *Rev. Sci. Inst* **12**, 5343 (2004).

[71] T. Chupp *et al.*, Nucl. Inst. and Meth in Physics Res. A **574**, 500 (2007).

[72] S. Baeßler for the Nab Collaboration, (arXiv:1209.4663) (2012).

[73] F. Gluck *Phys. Lett.* **B376**, 25-28 (1996).

[74] P. Herczeg, *Prog. Part. Nucl. Phys.* **46**, 413 (2001).

[75] V. Gudkov, *Phys. Rev.* **C 77**, 045502 (2008).

[76] E.Babcock, *et al.*, Physica B **404**, 2655 (2009).

[77] T.E. Chupp, *et al. Nucl. Inst. Meth.* **A 574**, 500 (2007).